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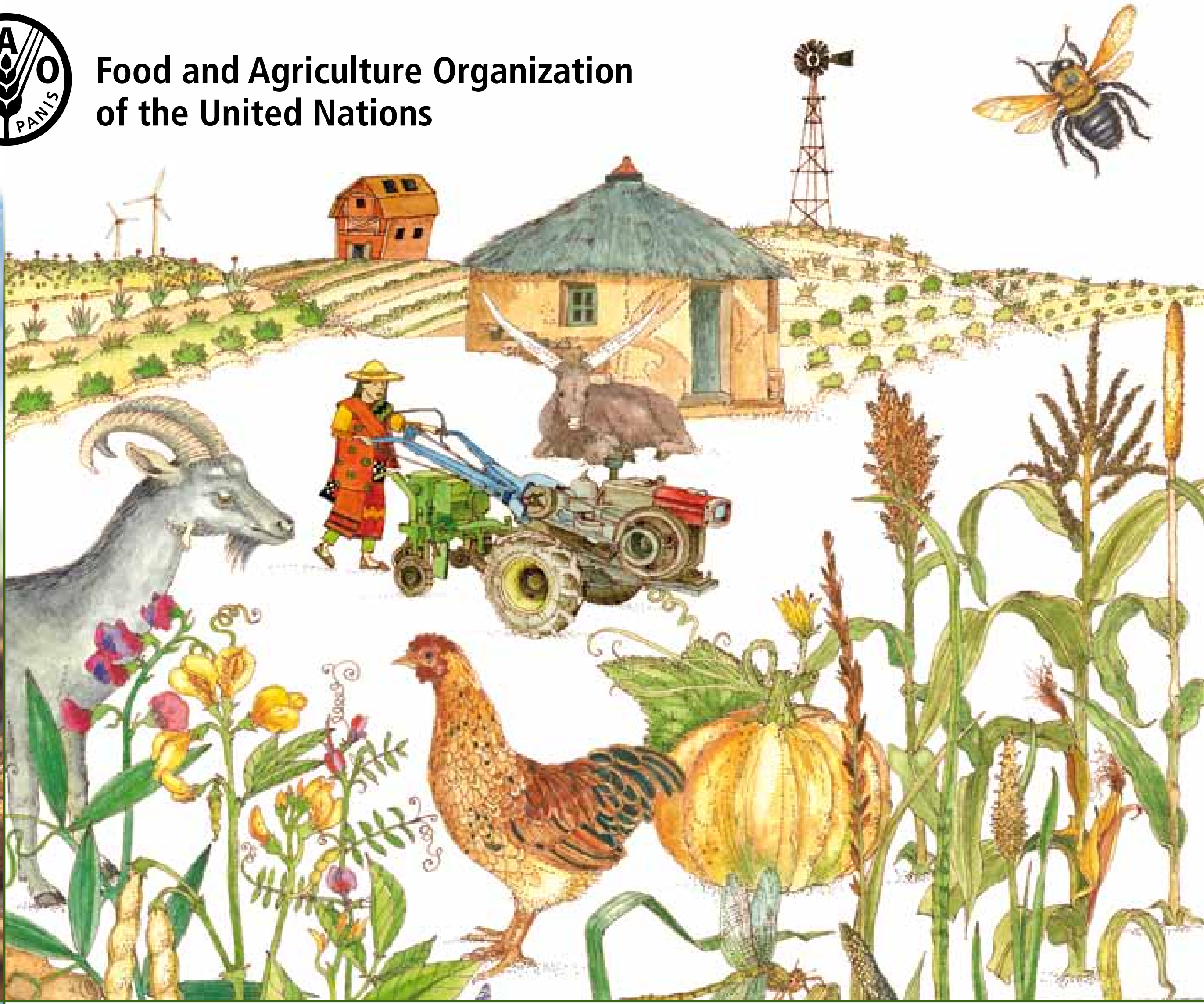

AGROECOLOGY FOR FOOD SECURITY AND NUTRITION

PROCEEDINGS OF THE FAO INTERNATIONAL SYMPOSIUM

18-19 September 2014, Rome, Italy

BIODIVERSITY & ECOSYSTEM SERVICES IN AGRICULTURAL PRODUCTION SYSTEMS

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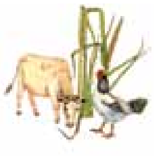

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FOREWORD TO THE PROCEEDINGS

Our global food system is at a crossroads. Agriculture must meet the challenges of hunger and malnutrition – against a backdrop of population growth, increased pressure on natural resources including soils and water, the loss of biodiversity, and the uncertainties associated with climate change. While past efforts focused on boosting agricultural output to produce more food, today's challenges – including climate change – demand a new approach.

We need to shift to more sustainable food systems – food systems that produce more, with less environmental cost. In many countries agriculture has been seen as an enemy of the environment, but there is increasing recognition that a regenerative, productive farming sector can provide environmental benefits while creating rural employment and sustaining livelihoods.

Agroecology offers the possibility of win-win solutions. By building synergies, agroecology can increase food production and food and nutrition security while restoring the ecosystem services and biodiversity that are essential for sustainable agricultural production. I firmly believe that agroecology can play an important role in building resilience and adapting to climate change.

During the *International Symposium on Agroecology for Food Security and Nutrition*, held at FAO headquarters in Rome on 18 and 19 September 2014, stakeholders representing governments, civil society, science and academia, the private sector, and the UN system gathered to discuss the contribution of agroecology to sustainable food systems. The Symposium provided an opportunity to share experiences, and build the evidence base on agroecology. These Proceedings bring together the lessons learned as well as scientific research and case studies of agroecology in practice.

Agroecological experiences can be found in all regions, and agroecology policies are already in place in many countries in Latin America and Europe. Agroecological approaches have been also recognized by international bodies such as the Committee on World Food Security.

FAO sees agroecology as a positive contribution to the eradication of hunger and extreme poverty, and a means to facilitate the transition to more productive, sustainable and inclusive food systems. FAO will continue to work with member countries to harness the benefits of agroecology by strengthening the evidence base and identifying and sharing examples of successful policies, strategies and approaches.

As I stated during the Symposium, the day-to-day experiences and knowledge of family farmers are the basis for our survival. We must walk together towards a more sustainable path.

José Graziano da Silva
Director-General, FAO

ACKNOWLEDGEMENTS

FAO would like to thank all those who contributed to the success of the International Symposium on Agroecology for Food Security and Nutrition, held at FAO headquarters in Rome on 18-19 September, 2014. Thank you to the participants, speakers, delegates, the Secretariat and those who worked behind the scenes on many aspects – without their contributions the International Symposium would not have been possible.

In particular, we acknowledge the support of France and Switzerland, who provided financial contributions to the International Symposium through the French Ministry of Agriculture, Agrifood, and Forestry, the Swiss Development Cooperation and the Foreign Office of Agriculture of Switzerland.

Special thanks to the members of the Scientific Committee, Miguel Altieri, Irene Cardoso, Barbara Gemmill-Herren, Etienne Hainzelin, Salman Hussain, Masa Iwanaga, Paul Mapfumo, Ephraim Nkonya, Jean-François Soussana, Pablo Tittonell and Fusuo Zhang for their leadership in laying the foundations for the International Symposium and these Proceedings.

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LIST OF ABBREVIATIONS

ABA	Brazilian Association of Agroecology
ACAO	Cuban Association for Organic Agriculture
ACT	African Conservation Tillage network
AEZ	agroecological zones
AFTD	Agroforestree Database (ICRAF)
AFZ	French Association for Animal Production (Association Française de Zootechnie)
AKST	Agricultural Knowledge, Science and Technology
AMF	arbuscular mycorrhizal fungi
ANA	National Articulation of Agroecology (Brazil)
ANAP	National Association of Small Farmers (Asociación Nacional de Agricultores Pequeños de Cuba)
APOT	Association of Organic Farmers of Turrialba
ARS	United States Agricultural Research Service
ASA	Brazilian Semi-arid Articulation (Articulação Semiárido Brasileiro)
ASAL	arid and semi-arid lands
ASDP	Agricultural Sector Development Programme (Tanzania)
AWM	agricultural water management
BAP	public water pump (bomba d'água popular)
BAU	business as usual
BNF	biological nitrogen fixation
CA	conservation agriculture
CAC	campesino-a-campesino ('farmer-to-farmer' or 'peasant-to-peasant')
C.A.F.E.	Coffee and Farmer Equity
CAP	Common Agricultural Policy
CATIE	Tropical Agricultural Research and Higher Education Center (Centro Agronómico Tropical de Investigación y Enseñanza)
CBO	community-based organization
CEBs	Grassroots Ecclesial Communities (Brazil)
CGIAR	Consultative Group for International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIMMYT	International Maize and Wheat Improvement Center
CIPAV	Centre for Research in Sustainable Agricultural Production Systems
CIRAD	Centre de coopération Internationale en recherche agronomique pour le développement
CIVAM	Centres d'Initiatives pour Valoriser l'Agriculture et le Milieu rural
CLORPT	climate, organisms, relief, parent material and time (soil properties)
CNPq	Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazil)
CONACYT	Consejo Nacional de Ciencia y Tecnologia (Mexico)
CPT	Pastoral Land Commission (Brazil)
CRSA	Climate Resilient Sustainable Agriculture (ActionAid)
CTA	Centre for Alternative Technologies of the Zona da Mata

DADO	District Agriculture Development Office (Nepal)
DFID	Department for International Development (UK)
DHA	double high sustainable agriculture
DHT	double high technology
ECOSUR	El Colegio de la Frontera Sur (Mexico)
EFI	Equitable Food Initiative
ETH	Swiss Federal Institute of Technology
FAO	Food and Agriculture Organization of the United Nations
FAPEMIG	Fundação de Amparo à Pesquisa do estado de Minas Gerais
FFS	Farmer Field School
FiBL	Research Institute of Organic Agriculture (Switzerland)
FMNR	farmer managed natural regeneration
FST	Rodale Farming Systems Trial
GHG	greenhouse gas
GIRAF	Belgian Interdisciplinary Agroecology Research Group
GWP	global warming potential
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
ICIPE	International Centre of Insect Physiology and Ecology
ICRAF	World Agroforestry Centre
IDRC	International Development Research Centre (Canada)
IFAD	International Fund for Agricultural Development
IFOAM	International Federation of Organic Agriculture Movements
IFS	International Foundation for Science
IITA	International Institute of Tropical Agriculture
INRA	L'Institut national de la recherche agronomique (France)
INTA	Instituto Nacional de Tecnología Agropecuaria (Argentina)
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
ISFM	integrated soil fertility management
iSPS	intensive silvopastoral systems
ITK	indigenous technical knowledge
KALRO	Kenya Agricultural and Livestock Research Organisation
LCA	life cycle assessment
LED	Liechtenstein Development Service
LEG	organic legume system
LGEFR	Leadership Group for Environmentally Friendly Rubber (China)
LSMS-ISA	Living Standards Measurement Study – Integrated Surveys on Agriculture
LTE	Long Term Experiment
LVC	La Via Campesina
MASIPAG	Magsasaka at Siyentipiko para sa Pag-unlad ng Agrikultura (Philippines)
MBC	Mesoamerican Biological Corridor
MDA	Ministério do Desenvolvimento Agrário (Brazil)
MLND	maize lethal necrosis disease
NDVI	normalized difference vegetation index

NGO	non-governmental organization
NPK	nitrogen, phosphorus, potassium
NTFPs	non-timber forest and rangeland products/non-timber forest products
ORD	Organic Resource Database
PDS	Public Distribution System (India)
PLANAPO	National Plan for Agroecology and Organic Production
POR	Participatory On-farm Research
PRA	Participatory Rural Appraisal
PTA	Project of Alternative Technologies
RAS	recirculating aquaculture systems
REDAGRES	Red Iberoamericana de Agroecología para el desarrollo de Sistemas Agrícolas Resilientes al Cambio Climático
RP	rock phosphate
RR	response ratio
RWH	rainwater harvesting
SAB	Scientific Advisory Board (SysCom programme)
SDC	Swiss Agency for Development and Cooperation
SFR	soil fertility replenishment
SL	Sustainable Livelihoods
SOC	soil organic carbon
SOCLA	Latin American Scientific Society of Agroecology (Sociedad Científica Latinoamericana de Agroecología)
SOFECSA	Soil Fertility Consortium for Southern Africa
SOM	soil organic matter
SPS	silvopastoral systems
SRI	System of Rice Intensification
SSA	sub-Saharan Africa
STB	Science and Technology Backyards
STR	Rural Workers Union (Brazil)
SWC	soil and water conservation
SysCom	Farming Systems Comparison in the Tropics
TEEB	The Economics of Ecosystems and Biodiversity
TEEBAgFood	TEEB for Agriculture and Food study
TLU	tropical livestock units
TME	Tecnología de Manejo Extensivo
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commissioner for Refugees
USDA	United States Department of Agriculture
VCR	value–cost ratio
VCTBC	Volcanica Central Talamanca Biological Corridor
WFP	World Food Programme
WHO	World Health Organization
ZIMSOFF	Zimbabwe Organic Smallholder Farmers Forum
ZNBF	Zero Budget Natural Farming movement (India)

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INTRODUCTION
AGROECOLOGY: A GLOBAL MOVEMENT FOR FOOD SECURITY AND SOVEREIGNTY

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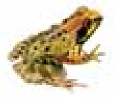
One of the most complete definitions of agroecology today is the "ecology of the food system" (Francis *et al*., 2003). It has the explicit goal of transforming food systems towards sustainability, such that there is a balance between ecological soundness, economic viability and social justice (Gliessman, 2015). However, to achieve this transformation, change is needed in all parts of the food system, from the seed and the soil, to the table (Gliessman and Rosemeyer, 2010). Those who grow the food, those who eat it, and those who move the food between the two – must all be connected in a social movement that honours the deep relationship between culture and the environment that created agriculture in the first place. Our current globalized and industrialized food system does not provide convincing evidence that it is sustainable in any of the three aspects of sustainability (economic, social or environmental) (Gliessman, 2007; 2015). With a deep understanding of what a holistic, ecological view of the food system can be, the change needed to restore sustainability to food systems can occur.

THE EVOLUTION OF THE AGROECOLOGICAL VISION FOR FOOD SYSTEM CHANGE: FROM THE FARM TO THE FOOD SYSTEM

Looking back to one of the first places where the current agroecology movement put down roots in the 1970s – the lowland tropics of southeastern Mexico in the state of Tabasco – it is evident that these roots were grounded in deepening ecological foundations as much as providing resistance to the pressures being applied by the so-called Green Revolution (Gliessman, 2013). When an agroecological lens was focused on the monoculture production of crops such as corn, beans, rice, or sugar cane, it quickly became evident that they were causing ecological degradation (soil erosion, loss of agrobiodiversity, pest outbreaks, etc.) as well as social duress (poverty,



malnutrition, dependency, loss of livelihood diversity, etc.) (Barkin, 1978; Hart, 1979; Kimbrell, 2002). When it became apparent that ecological knowledge could be combined with the rich local culture and experience of agriculture inherent in traditional farming systems (Gliessman, 1978; Gliessman *et al.*, 1981), the interdisciplinary roots of agroecology began to flourish.

With the establishment of the first formal academic programme in agroecology in 1982 at the University of California, Santa Cruz, the agroecological approach was backed up with in-depth research and education (Gliessman, 1984). Its ecosystem focus allowed for the development of research approaches that were interdisciplinary and field-based, and linked the more production-oriented focus of the agronomist with the more systems-oriented viewpoint of the ecologist (Gliessman, 1990). Different methodologies for quantifying and evaluating agro-ecosystem sustainability began to emerge, and examples of the design and management principles needed to develop a sustainable basis for land use, management and conservation began to appear worldwide (Gliessman, 2001).

The publication of an undergraduate textbook with an accompanying field and laboratory manual (Gliessman, 1998a; 1998b), followed by new editions in 2007 and 2015, have been strong steps forward in recognizing agroecology as an academic discipline. Students are given an in-depth introduction to the ecological principles and processes that form the foundation for sustainable agriculture, with opportunities to gain hands-on experience as part of the learning process. In order to understand and promote changes by farmers in their practices and farming approaches, the textbook originally adopted MacRae *et al.*'s (1990) three levels of agro-ecosystem conversion to sustainability (described in the following section and summarized in Table 1). Together with the ecological knowledge needed to make these transitions, important concepts were developed that provided a protocol for the study of agro-ecosystems. Since the appearance of the first edition of the book, the focus and field of agroecology has expanded and matured. By the mid-2000s, the focus of agroecology had moved from the field and farm scale to the entire food system, emphasizing the importance of building food networks that link all parts of the food system. Today this has evolved to the point where agroecology has more fully embraced its role as a networked movement for social change and food system transformation.

USING AGROECOLOGY IN THE TRANSFORMATION OF FOOD SYSTEMS

Farmers have a reputation for being innovators and experimenters, willingly adopting new practices when they perceive that some benefit will be gained, yet retaining those that have proven themselves over time. This is especially true of smallholder farmers around the world (Altieri, 2004; Altieri and Toledo, 2011). But over the past 50-60 years, innovation in agriculture has been driven mainly by an over-emphasis on high yields and visionless, short-term farm profit, resulting in remarkable returns for some, but too often at the cost of an array of negative environmental and social side effects. Despite the continuation of strong pressure to focus on the (economic) bottom line, however, many farmers are choosing to make the transition to practices that are more environmentally sound and have the potential for contributing to long-term sustainability for agriculture. Others are starting agricultural enterprises from the beginning that incorporate a variety of ecologically informed approaches. Yet others are using agroecological principles to strengthen local knowledge, experience and networks in farming that have accumulated over centuries (Altieri and Toledo, 2011). All of these types of efforts represent ‘transition’ or ‘transformation’ of agriculture in the broad sense.

The transition to ecologically based management is grounded in the principles of agroecology. These principles can come into play initially in the actual process of changing the way food is grown. Farmers engaged in the transition process know, through intuition, experience and knowledge, what is *un*-sustainable and what is, at the very least, *more* sustainable. Nevertheless, there is a clear need to understand the process in more detail. As a contribution towards this change, a protocol for converting industrial/conventional systems into more-sustainable systems is proposed below and summarized in Table 1.

The transition process

The transition process can be complex, requiring changes in field practices, day-to-day management of the farming operation, planning, marketing and philosophy. The following principles can serve as general guidelines for navigating the overall transformation:

- Shift from through-flow nutrient management to a nutrient recycling model, with increased dependence on natural processes such as biological nitrogen fixation and mycorrhizal relationships;
- Use renewable sources of energy instead of non-renewable sources;
- Eliminate the use of non-renewable, off-farm human inputs that have the potential to harm the environment or the health of farmers, farm workers, or consumers;
- When materials must be added to the system, use naturally occurring materials instead of synthetic, manufactured inputs;
- Manage pests, diseases and weeds instead of ‘controlling’ them;
- Re-establish the biological relationships that can occur naturally on the farm instead of reducing and simplifying them;
- Make more appropriate matches between cropping patterns and the productive potential and physical limitations of the farm landscape;
- Use a strategy of adapting the biological and genetic potential of agricultural plant and animal species to the ecological conditions of the farm rather than modifying the farm to meet the needs of the crops and animals;
- Value most highly the overall health of the agro-ecosystem rather than the outcome of a particular crop system or season;
- Emphasize conservation of soil, water, energy and biological resources;
- Respect local knowledge and experience in agro-ecosystem design and management;
- Incorporate the idea of long-term sustainability into overall agro-ecosystem design and management.

The integration of these principles creates a synergism of interactions and relationships on the farm that eventually leads to the development of the properties of sustainable agro-ecosystems. Emphasis on particular principles will vary, but all of them can contribute greatly to the transition process. We should not be satisfied with an approach to transition that only replaces industrial/conventional inputs and practices with environmentally benign alternatives; nor should we be satisfied with an approach dictated solely by market demands, or one that does not take into account the economic and social health of agricultural communities. Transition must be part of ensuring long-term food security for everyone, in all parts of the world.

Levels of transition

For many farmers, a rapid shift to sustainable agro-ecosystem design and practice is neither possible nor practical. As a result, many transition efforts proceed in small steps towards the ultimate goal of sustainability, or are simply focused on developing food production systems that are somewhat more environmentally sound. The first three levels of conversion to a sustainable food system focus on the farm scale (MacRae *et al.*, 1990; Gliessman, 2015). Two additional levels go beyond the farm scale. The first three levels help us describe the steps that farmers actually take in shifting from industrial or conventional agro-ecosystems, and all five levels taken together can serve as a map outlining an evolutionary change process for the entire global food system.

Level one:

Increase the efficiency of industrial/conventional practices in order to reduce the use and consumption of costly, scarce, or environmentally damaging inputs.

The goal of this approach is to use inputs more efficiently so that fewer inputs will be needed and the negative impacts of their use will be reduced as well. This approach has been the primary emphasis of much conventional agricultural research, through which numerous agricultural technologies and practices have been developed. Examples include optimal crop spacing and density, improved machinery, pest monitoring for improved pesticide application, improved timing of operations and precision farming for optimal fertilizer and water placement. Although these kinds of efforts reduce the negative impacts of conventional agriculture, they do not help break its dependence on external human inputs.

Level two:

Substitute industrial/conventional inputs and practices, replacing them with alternative practices.

The goal at this level of transition is to replace resource-intensive and environment-degrading products and practices with those that are more environmentally benign. Organic farming and biological agricultural research have emphasized such an approach. Examples of alternative practices include the use of nitrogen-fixing cover crops and rotations to replace synthetic nitrogen fertilizers, the use of biological control agents rather than pesticides, and the shift to reduced or minimal tillage. At this level, the basic agro-ecosystem structure is not greatly altered; hence many of the same problems that occur in industrial and conventional systems also occur in those with input substitution.

Level three:

Redesign the agro-ecosystem so that it functions on the basis of a new set of ecological processes.

At this level, fundamental changes in overall system design eliminate the root causes of many of the problems that still exist at levels one and two. Thus, rather than finding sounder ways of solving problems, the problems are prevented from arising in the first place. Whole-system conversion studies allow for an understanding of yield-limiting factors in the context of agro-ecosystem structure and function. Problems are recognized, and thereby prevented, by internal site- and time-specific design and management approaches, instead of the application of external inputs. An example is the diversification of farm structure and management through the use of rotations, multiple cropping and agroforestry.

Level four:

Re-establish a more direct connection between those who grow the food and those who consume it.

Transition occurs within a cultural and economic context, and that context must support the shift to more-sustainable practices. At a local level, this means consumers value locally grown food and support with their food dollars the farmers who are striving to move through transition levels one, two and three. This support turns into a kind of ‘food citizenship’ and becomes a force for food system change. The more this transformation occurs in communities around the world, the closer we move towards building the new culture and economy of sustainability that is the prerequisite for reaching level five.

Level five:

On the foundation created by the sustainable farm-scale agro-ecosystems of level three and the sustainable food relationships of level four, build a new global food system, based on equity, participation and justice, that is not only sustainable but also helps restore and protect Earth’s life-support systems.

Unlike levels one through four, level five entails change that is global in scope and which reaches so deeply into the nature of human civilization that it transcends the concept of ‘transition’. Nevertheless, the path to level five necessarily passes through the farm-scale, down-to-earth transition process that is presented above.

In terms of research, agronomists and other agricultural researchers have done a good job of working on the transition from level one to level two, and research on the transition to level three has been underway for some time. Work on the ethics and economics of food system sustainability that are involved in levels four and five, however, has only just begun (Berry, 2009; Jackson, 2011). Agroecology provides the basis for the type of research and community-based action that is needed. Eventually it will help us find answers to larger, more abstract questions, such as what sustainability is and how we will know we have achieved it.

WHAT IS A SUSTAINABLE FOOD SYSTEM ANYWAY?

What is the alternative to industrial agriculture? Despite being dedicated to developing forms of sustainable agriculture, the field of agroecology cannot answer this question as directly as we might wish. Agroecology consists of principles, concepts and strategies that must form the foundation of any system of food production that can make a legitimate claim to being a more-sustainable successor to industrial agriculture. These principles, concepts and strategies are more oriented towards offering a design framework for sustainable agro-ecosystems than they are prescriptions or blueprints for the construction or management of actual agro-ecosystems, and they do not dictate the specifics of an entire world food system.

Nonetheless, agroecological principles do suggest the general elements of a sustainable food system, and describing these elements will help us visualize some of the goals towards which the agroecological approach points.

Exploring the sustainability concept

In order to better understand the elements of a future food system that operates on a more sustainable basis than the industrial agriculture-based food system of today, it is helpful to explore what is meant by the term *sustainability*.

As scientists, analysts, activists and others point with increasing frequency to the *un*sustainability of human society's current systems and practices – everything from fossil fuel use and industrial agriculture to an economic system dependent on constant growth – it has become ever more common to adopt the label 'sustainable'. Everyone wants his or her product, industry, alternative method, or proposal to be considered 'sustainable'. As a result, the term sustainability has become increasingly vague, ambiguous and confusing.

In addition, as a framework for critical analysis of industrial agriculture and for development of alternatives, the concept of sustainability has a key weakness because it depends entirely on an inferred or hypothesized future. Condemning a practice or system as unsustainable is essentially to claim that it is bad because it will not last. This sidesteps the possibility that it is causing serious negative consequences right now, in the present. Conversely, arguing for the desirability of a system or practice because it is sustainable is really to say that its major benefit would be its durability over time – that we could expect it to still exist at some time in the future. This by itself does not ensure that the system or practice mitigates or reverses harms to people or natural systems or provides a benefit. Underlying these drawbacks is a very real practical problem with the concept of sustainability: because sustainability *per se* can never be demonstrated in the present, its proof always remains in the future, out of reach. Thus, it is almost impossible to know for sure if a particular practice is in fact sustainable, or if a particular set of practices constitutes sustainability.

Despite the drawbacks of the term sustainability, agroecology does not abandon it in favour of another term. In part, that is because there is no adequate alternative term. Moreover, used precisely and in accordance with its original meaning, sustainability really does convey the essence of what we hope to create as an alternative to industrial agriculture – a system of food production, distribution and consumption that will endure indefinitely because it does not sow the seeds of its own demise. But there is much more to sustainability than mere endurance. As used in agroecology, sustainability refers also to the many characteristics of an ostensibly sustainable practice or system that are responsible for endowing that practice or system with the self-sufficiency, resilience and balance that *allow it* to endure over time.

If we are going to use the term sustainable to indicate the essential feature of what we hope to create as an alternative to industrial agriculture, we should be quite precise about what is entailed in our use of the term. Based on our present knowledge, we can suggest that a sustainable food system would, at the very least:

- have minimal negative effects on the environment and release insignificant amounts of toxic or damaging substances into the atmosphere, surface water, or groundwater;
- minimize the production of greenhouse gases (GHGs), work to mitigate climate change by increasing the ability of managed systems to store fixed carbon, and facilitate human adaptation to a warming climate;
- preserve and rebuild soil fertility, prevent soil erosion and maintain the soil's ecological health;
- use water in a way that allows aquifers to be recharged and the water needs of the environment and people to be met;
- rely mainly on resources within the agro-ecosystem, including nearby communities, by replacing external inputs with nutrient cycling, better conservation, and an expanded base of ecological knowledge;
- work to value and conserve biological diversity, both in the wild and in domesticated landscapes;
- guarantee equality of access to appropriate agricultural practices, knowledge and technologies and enable local control of agricultural resources;
- eliminate hunger, ensure food security in culturally appropriate ways and guarantee every human being a right to adequate food;
- remove social, economic and political injustices from food systems.

Each of these features of a sustainable system can be demonstrated in the present, and each one involves undeniable benefits to people and the ecological and social systems on which people depend.

Elements of a sustainable food system

Using this list of characteristics of sustainability as a guide, we can envision what food systems of the future might look like – if humankind as a whole begins to follow 'the path towards sustainability'. Many elements of these systems are already beginning to appear in rough form, alongside industrial food systems, as agroecology grows and spreads.

- The sustainable food system of the future will largely be made up of innumerable small- to medium-scale agro-ecosystems, each relatively self-contained, adapted to local conditions, and focused primarily on satisfying the food needs, desires and priorities of a local population.

Only after they satisfy local demands and needs will these agro-ecosystems attend to the needs and desires of more distant communities.

- Food networks will replace food chains as all players in the food system (from the farm to the table) are reconnected and have a say in what is produced, how it is produced and how it is exchanged and distributed.
- Traditional, peasant-managed agro-ecosystems, despite being beleaguered by the encroachment of industrial-based systems, still provide more than two-thirds of the world's food. Already embodying many of the key attributes of sustainability, these systems will remain a fundamental basis of food production for much of the world, as their productivity and efficiency is improved through agroecological research.
- Cities – which will continue to provide homes for a large number of the world's people – will be supplied with food less by global markets and more by agro-ecosystems in the surrounding region and in the cities themselves.
- Agricultural knowledge will exist primarily in the public domain, where it will be widely dispersed and embodied more in farmers' practices than in technological products and systems.
- Farmers will be rewarded for the environmental services that their farms provide beyond the production of food. Protecting biodiversity, producing clean water, stopping soil erosion, sequestering carbon, and promoting the presence of living landscapes will be valued and rewarded.
- Because sustainability in agriculture is not just about growing and raising food, but about how that food is used, distributed and consumed, a sustainable food system will distribute food more equitably, reduce food overconsumption and waste, and insure that our precious agricultural land is used to feed people rather than automobiles and livestock.
- Food justice will be a common goal in sustainable food systems as food security, food sovereignty and the right to food become guiding social principles.

It is not an exaggeration to say that the sustainable food system of the future, considered as a whole, will represent a paradigm shift. Like traditional and indigenous agro-ecosystems, it will conserve resources and minimize exogenous inputs. Like industrial agriculture, it will be very productive. And unlike any system of food production that has heretofore existed on the planet, it will combine these attributes while distributing its benefits equitably among human beings and societies and refraining from displacing its costs onto natural ecosystems increasingly pushed to the brink of collapse. In order for this paradigm shift to come about, agroecology must become a force for change that integrates research, practice and social change in all parts of our food systems.

AGROECOLOGY AND THE FOOD SYSTEM OF THE FUTURE

Advocates for industrial agriculture argue that the only way to satisfy the food needs of the expanding world population is to continue to develop new agricultural technologies – particularly genetically modified crop varieties – that will increase yields, reduce insect damage and eliminate competition from weeds. They dismiss alternative, traditional, sustainable and ecologically based systems as inadequate to the task of growing the needed amount of food. This view is mistaken on at least two accounts.

First, this view exaggerates the need for increasing yields. Globally, the food system currently produces more than enough food calories to adequately feed every single living human being and more (Cassidy *et al*., 2013; FAO, 2013b). One problem is that 9 percent of these calories are diverted to make biofuels or other industrial products and another 36 percent are used for animal feed (less than 10 percent of which is recovered in the form of animal-based food calories), leaving only 55 percent to be eaten directly by humans. Another problem is that an estimated *one-third* of the food produced globally is lost to spoilage, spillage and other problems along the supply chain, or simply wasted at the household level (FAO, 2013a). Further, the calories that are eaten by humans directly and not lost as waste are distributed very unevenly, with many of them going to expand the waistlines of affluent populations. Thus, the need for more food is driven not as much by the increase in population as it is by wasteful patterns of food use and a shift towards richer diets – *both of which are social choices*. If people ate less animal-based food on average and food was used and distributed more equitably and efficiently, as noted above, more than enough extra food-production capacity would be freed up to feed everyone adequately, leaving a buffer for feeding an expanding population.

Second, this view ignores a growing body of research showing that small-scale, ecologically-based, organic and even traditional peasant systems can approach, match, and even exceed the productivity of industrial systems when measured by the number of people fed per unit of land or the food biomass produced per unit area (see for example Ponisio *et al*., 2014). These agro-ecosystems are usually the kinds of diverse, multi-layered and integrated systems that are most common in smallholder, traditional farming systems in the developing world, with a focus on meeting local needs, providing food for the larger communities in which they participate and maintaining the productive capacity of the soil for the long term. The emphasis of these systems is definitely not on monoculture yield maximization, nor the market. A comprehensive 2011 report, presented before the UN Human Rights Council and based on an extensive review of recent scientific literature, showed that agroecologically guided restructuring of agro-ecosystems has the capability of doubling food production in entire regions within ten years, while mitigating climate change and alleviating rural poverty (De Schutter, 2011).

Many scientists, researchers and educators in the field of agroecology, and their colleagues in disciplines like agronomy, have long believed that their role is to come up with agricultural methods and systems that are more sustainable, more environmentally friendly, less input-dependent and less technology-intensive than those of industrial agriculture. The assumption is that these methods and systems will then be adopted because they are superior when judged by any of various sets of criteria. Unfortunately, the experience of the last couple of decades has exposed the limitations of this view. Although we have accumulated a great deal of knowledge about the ecological relationships underlying sustainable food production, that knowledge has seen relatively little application, and industrial agriculture has meanwhile strengthened its dominance of the world food system.

Transforming agriculture in a fundamental way – putting it on a sustainable path – is going to be a tremendous challenge. A basic assumption of this chapter is that agroecologists can hope to meet this challenge only if we approach it on three different fronts simultaneously.

First, we require more and better knowledge of the ecological relationships among domesticated agricultural species, among these species and the physical environment, and among these species and those of natural systems. This need is satisfied by the science aspect of agroecology, which draws on modern ecological knowledge and methods to derive the principles that can be used to design and manage sustainable agro-ecosystems.

Second, we require effective and innovative agricultural practices, on-the-ground systems that work in the present to satisfy our food needs while laying the groundwork for the more-sustainable systems of the future. Satisfying this need is the practical aspect of agroecology, which values the local, empirical knowledge of farmers and the sharing of this knowledge, and which undercuts the distinction between the production of knowledge and its application.

Finally, circumstances demand fundamental changes in the ways that humans relate to food, the economic and social systems that determine the distribution of food, and the ways in which food mediates the relationships of power among populations, classes and countries. Serving this need is the social-change aspect of agroecology, which not only advocates for the changes that will lead to food security for all, but also seeks knowledge of the means by which these changes can be activated and sustained. A framework for linking these three areas of agroecology with the five levels of food system transition is presented in Table 1.

Each of these aspects of agroecology is critical. The FAO Symposium on Agroecology for Food Security and Nutrition in Rome in September 2014[1] allowed for the presentation of many examples of how the science of agroecology is being applied in farming systems around the world. The social-change aspect of agroecology was strongly voiced by the organizations supporting and promoting the rights and needs of food insecure and malnourished communities. If agroecologists and others seeking to put agriculture on a more sustainable basis fail to listen to these voices and link their science and practice with them, their efforts are likely to be for naught.

A few years ago, a strong call for this integrated approach to agroecology was made in the concluding remarks at the 3rd Latin American Congress of Agroecology sponsored by the Latin American Scientific Society of Agroecology (SOCLA) held in Mexico. It provides a strong call to action as a way of concluding this chapter:

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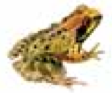
[1] For more information on the International Symposium on Agroecology for Food Security and Nutrition, see: http://www.fao.org/about/meetings/afns/en/.

> *"Agroecology must integrate science, technology and practice, and movements for social change. We can't let the artificial separation of these three areas be an excuse some may use to justify doing only the research or technology parts. Agroecology focuses on the entire food system, from the seed to the table. The ideal agroecologist is one who does science, farms, and is committed to making sure social justice guides his or her action for change. We must help the people who grow the food and the people who eat the food re-connect in a relationship that benefits both. We must re-establish the food security, food sovereignty, and opportunity in rural communities throughout Latin America that has been severely damaged by the globalized food system. We must respect the different systems of knowledge that have co-evolved for millennia under local ecologies and cultures. By doing this, we can avoid the eminent food crisis and establish a sustainable foundation for the food systems of the future."*
>
> (Gliessman, 2012)

Table 1. **The levels of transition and the integration of the three components of agroecology needed for the transformation to a sustainable world food system**

LEVEL	SCALE	Role of Agroecology's Three Aspects		
		Ecological Research	**Farmer Practice and Collaboration**	**Social Change**
1 Increase efficiency of industrial practices	Farm	**Primary**	**Important** Lowers costs and lessens environmental impacts	**Minor**
2 Substitute alternative practices and inputs	Farm	**Primary**	**Important** Supports shift to alternative practices	**Minor**
3 Redesign whole agro-ecosystems	Farm, region	**Primary** Develops indicators of sustainability	**Important** Builds true sustainability at the farm scale	**Important** Builds enterprise viability and societal support
4 Re-establish connections between growers and eaters, develop alternative food networks	Local, regional, national	**Supportive** Interdisciplinary research provides evidence of need for change and viability of alternatives	**Important** Forms direct and supportive relationships	**Primary** Economies restructured; values and behaviours changed
5 Rebuild the global food system so that it is sustainable and equitable for all	World	**Supportive** Transdisciplinary research promotes the change process and monitors sustainability	**Important** Offers the practical basis for the paradigm shift	**Primary** World systems fundamentally transformed

Source: adapted from Gliessman, 2015



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01

FOOD SECURITY AND ECOSYSTEM SERVICES IN A CHANGING WORLD:
IT IS TIME FOR AGROECOLOGY

02

ENHANCING THE FUNCTION AND PROVISIONING OF ECOSYSTEM SERVICES IN AGRICULTURE:
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04

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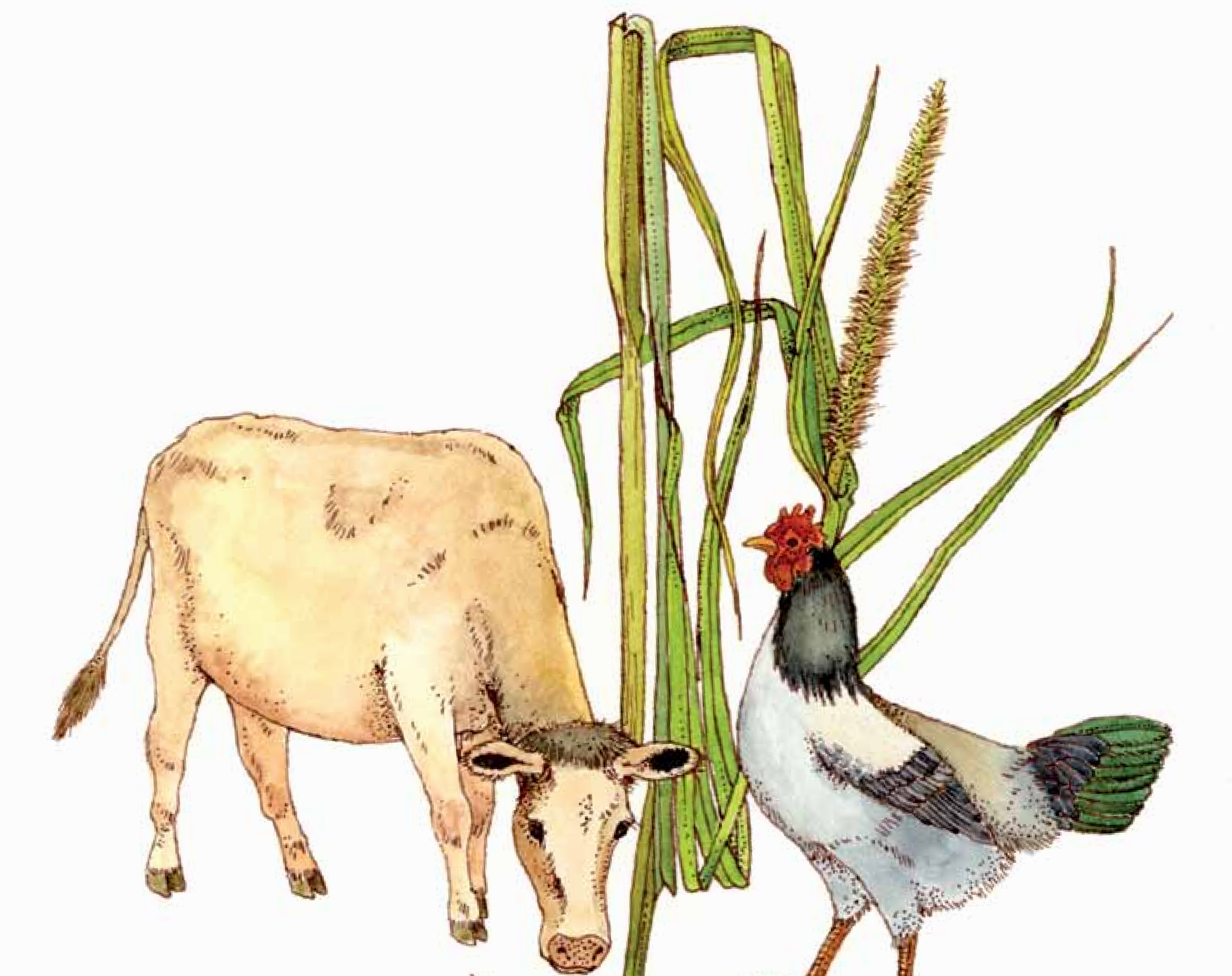
SCIENTIFIC KNOWLEDGE

Principles of Agroecology



01

FOOD SECURITY AND ECOSYSTEM SERVICES IN A CHANGING WORLD: IT IS TIME FOR AGROECOLOGY

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Abstract

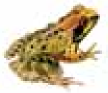
Agroecology offers technical and organizational innovations to lead the way to a restorative, adaptable, inclusive and resource use-efficient agricultural model at the global scale. But agroecology is defined differently by different schools of thought with implications for the roles that nature and social movements play in the resulting agricultural models proposed to address future food security and nutrition. Agroecology, defined as

the use of ecological principles for the design of agricultural systems, has great potential to contribute to global change adaptability. In this chapter, examples from around the world are examined to explore four important aspects of agroecology: (i) the design of complex adaptive smallholder systems through diversification and synergies; (ii) the potential of following agroecological principles to design alternative agricultural systems in large-scale farming; (iii) the ability of agroecology to restore degraded landscapes; and (iv) the crucial role of social movements and supportive policies in the dissemination of agroecology. By relying on biodiversity, agroecological systems are not only more productive and resilient than conventional ones; they also contribute to reducing production risks, as well as to the diversification of diets and of income sources for smallholder farming families.

INTRODUCTION

Most of the agricultural land in the world is currently producing below its capacity (e.g. van Ittersum *et al.*, 2013). At the global scale, the average yield of most major crops has increased steadily over the last 50 years (Tilman *et al.*, 2011). However, this growth has been unequal across the world and today's productivity tends to be lowest in the poorest regions of the world, where food is most needed, and even lower for the least resource-endowed farmers at any given location (UNCTAD, 2014). Although, globally speaking, the world produces enough food calories to feed everyone (2 700 Kcal person^{-1} day^{-1} produced vs 1 800-2 100 Kcal person^{-1} day^{-1} required), food production per capita remains at the same level as in the 1960s in the least favoured regions of the world (FAO, 2014). When more than just calories or macronutrients are considered, global trends indicate that three major cereals (maize, wheat and rice) have increased in importance in global diets, to the detriment of local and often better adapted and more nutritious food crops such as small grain cereals or pulses. This has had negative nutritional consequences for people in the developing world (Khoury *et al.*, 2014).

In such regions, inadequate models of agricultural development coupled with increasing (settled) population densities in rural areas has led to severe degradation of the natural resource base (e.g. Bationo and Waswa, 2011; Valbuena *et al.*, 2014; Andrieu *et al.*, 2015). Most farmers in these regions do not have access to, cannot afford or are unwilling to adopt 'modern' agricultural technologies. Such technologies were not developed to fit the reality of their systems and their social-ecological environment, and hence they are ineffective at increasing crop and livestock productivity (Tittonell and Giller, 2013). In contrast, in the most affluent regions of the world agricultural intensification through the use of inputs, in excess of what their factor elasticity would dictate, has led to environmental pollution with harmful consequences for human health and high costs for society as a whole (costs that are never internalized in the price paid for the agricultural produce).



Climate change presents a further threat to food production and increases environmental risks in both the South and the North (Reidsma *et al.*, 2009; Mapfumo *et al.*, 2010). Moreover, global food security has inherent vulnerabilities stemming from its dependence on fossil fuels, which are currently necessary for production and transport. The use of fossil fuels, together with deforestation, wetland drainage, enteric fermentation and soil organic matter (SOM) oxidation, create a net release of carbon to the atmosphere that contributes substantially to global warming (agriculture is responsible for more than 25 percent of all greenhouse gas emissions). In addition, because oil is an increasingly scarce resource, the inevitable price crises will automatically make many people food insecure.

The time has come to rethink our current agricultural model, one that has been conceived to address the world's problems in a completely different historical context (da Silva, 2014). It is time for a new agricultural model that ensures that enough nutritious food is produced *where it is most needed*, that is able to adapt to climate change and when possible contribute to climate change mitigation, that preserves biological and cultural diversity, and that delivers ecosystem services of local and global relevance. In other words, it is time for agroecology. This chapter will explore the concept as put forward by different schools of thought around the world, and provide evidence from science, practice and policy on the potential of agroecology to lead the way to restorative, adaptable, inclusive and resource use-efficient agriculture.

THE LANDSCAPE OF AGROECOLOGY

History, definitions and discourses

Agroecology has been appropriately defined as a realm where science, practice and social movements converge (e.g. Wezel *et al.*, 2009; Tomich *et al.*, 2011). A recent report put together by the International Institute for the Environment and Development with the objective of informing the international community on what agroecology is and what it can offer (Silici, 2014) made a useful attempt at describing its history. They trace the use of the term agroecology in science back to the 1930s, the emergence of agroecology as a farming practice to the 1970s, and the history of agroecology-related social movements to the 1980s. The most conspicuous of these movements is undoubtedly La Via Campesina, which federates a large number of independent family farmer groups around the world (Martinez-Torres and Rosset, 2014). Social organization is one of the pillars of agroecology. It is responsible for the dissemination of agroecological knowledge and technologies or, as Peter Rosset put it, "*the social organisation is the medium on which agroecology spreads...*". The actual extent of agroecology in terms of area occupied or number of farmers or consumers involved is not known with clarity. However large or small it may be, it is not the result of any dissemination campaign of governments, private parties or international organizations such as the UN institutes. It is the result of *campesino-a-campesino* (farmer-to-farmer) dissemination (Holt-Giménez and Altieri, 2013).

Yet agroecology is also a term used in several agricultural disciplines and by different schools of thought (Tittonell, 2014). In classical agronomy it is often used to refer to the set of climatic and soil conditions that define the productive potential of a certain location. The term has also been used to refer to the study of the ecology of agricultural systems (e.g. Dalgaard *et al.*, 2003; Francis *et al.*, 2003). Under these broader definitions, and responding to the increasing perception from different parties that agroecology is a sort of new buzzword in the development jargon, there is an increasing number of research groups in the world that claim to be working on agroecology, and of scientists who call themselves 'agroecologists', even though they are often not aware of the existence of an international agroecology movement or of the scientific discipline that grows along with it. Likewise, there are also plenty of examples of agroecological practice and knowledge worldwide that are not necessarily labelled as such (e.g. Khan *et al.*, 2010; Xie *et al.*, 2011; Khumairoh *et al.*, 2012; Nezomba *et al.*, 2015). In certain circles, agroecology tends to be seen as a lateral thinking discourse, one that can bridge the apparently insurmountable philosophical gap between 'conventional' and organic agriculture, for instance. The members of the agroecology movement do not necessarily welcome such developments. They argue, with evidence, that agroecology was first ignored, then criticised, and now co-opted (Altieri, 2014).

Two textbooks (Altieri, 1987; Gliessman, 1998) that appeared a couple of decades ago were extremely influential in the Americas, and later worldwide, in that they provided the scientific underpinning to agroecology. These were not strictly the only books that dealt with ecological principles in science or agricultural design, but they were largely popular among a generation of agronomists and agricultural scientists in the making – including myself. Both authors defined agroecology, in short, as the use of ecological principles for the design and management of sustainable agricultural systems. Later on, Gliessman (2007) proposed to refer to 'food systems' instead of 'agricultural systems' in a revised definition of agroecology, thereby enlarging the boundaries of agroecological systems to include not only farming but also distribution, processing, trading and consumption. Within the agroecology movement, there are also those who emphasize the social organizational aspect of agroecology as its central pillar and see ecological knowledge, science and practice as somewhat secondary (e.g. Sevilla-Guzmán and Woodgate, 2013).

Agroecology provides no recipes, no technical packages, no standards and no prescriptions. Rather, it relies on the application of five basic principles[1]: recycling, efficiency, diversity, regulation and synergies. The choice of management practices and technologies to achieve these principles is always location specific, shaped by a given social-ecological context. The absence of standards and certification systems differentiates agroecology from organic agriculture. Although discrepancies between both have been repeatedly pointed out in the past, I am convinced that (i) agroecology can offer the foundations for the design of sustainable organic farming systems by helping farmers escape the 'input substitution' trap; and (ii) that

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[1] These five principles are not meant as a dogma; they are proposed as a working definition in this chapter, and they correspond with principles proposed in the classical works of Altieri (2002) and Gliessman (2007).

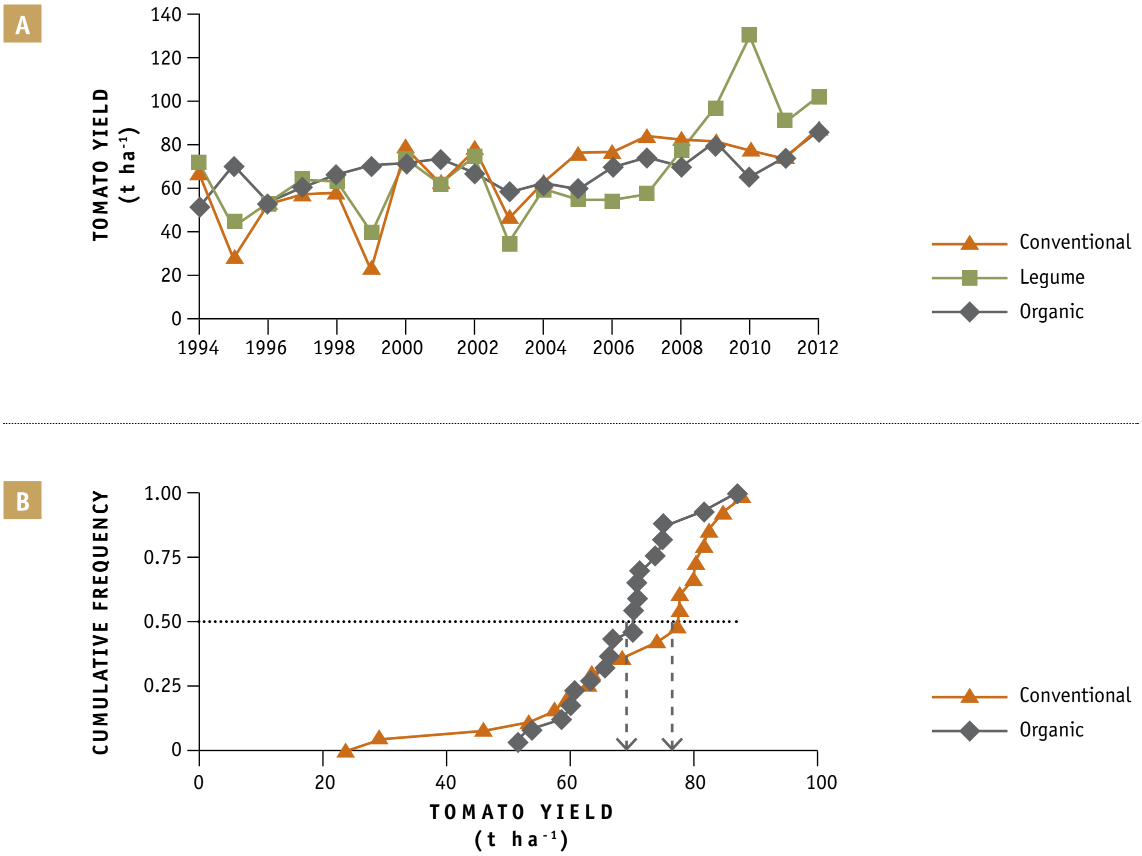
organic farming already offers excellent examples of the application of agroecological principles in a context of large-scale commercial farming in developed regions, as will be demonstrated below. It is also true that not all current organic farms can be described as agroecological, nor will all agroecological practices fit within current organic certification standards. Nevertheless, both movements are gradually converging. For example, the International Federation of Organic Agriculture Movements (IFOAM) launched a new concept in 2014 termed Organic 3.0 (www.ifoam.bio/en/what-organic-30), which proposes to broaden the spectrum of practices based on agroecological principles, to lead the way to more flexible certification standards and therefore increase the chances of scaling out organic farming.

Agroecology and adaptation to global changes

Global changes are threatening current and future food security. These include climate change, population growth, urbanization, trade globalization and dietary changes. In addition, environmental degradation is both a result and a driver of global change. It is imperative to design agricultural systems that are resilient in the face of increasingly frequent shocks and adaptable to the stresses and new sets of conditions imposed by these changes. There is ample evidence that agroecology can contribute to climate change adaptation and mitigation, to produce food with low environmental impacts in or around cities, and to produce greater yields in places where other models of agriculture do not perform (e.g. Pretty *et al.*, 2011). But globalization and dietary changes remain major global threats to agroecology. Trade globalization threatens local production, monopolizes genetic diversity and leads to uniform diets around the world, which consist largely of a few world commodities (i.e. wheat, rice, maize, soybean, oil palm, sugar cane) (Khouri *et al.*, 2014). Such dietary changes lead to a loss of diversity in agro-ecosystems, from genetic to landscape-level diversity, with consequences for ecosystem services, food production and the environment. Most importantly, there is increasing evidence that the loss of biodiversity in agro-ecosystems leads to less resilience and adaptability.

Information from long-term trials is of great value here. A number of them have been conducted comparing conventional, organic and other agroecological systems for more than 30 years already. The University of California Davis started a 100-year experiment in 1993 in their Russell experimental ranch, where they monitor yields, yield quality, soil biology and water and nutrient flows across management systems (http://asi.ucdavis.edu/rr). Long-term data from such an experiment shows how, for a drought sensitive crop such as field tomato grown in rotation with maize, organic soil management leads to more stable yields over time (Figure 1). Average yields over the entire period considered (1993-2012) were 66.7±18.2, 68.9±24.1 and 67.8±9.0 tonnes ha^{-1} respectively for conventional, legume–maize–tomato and organic systems. Figure 1B shows that the median yield of the organic system was 7.3 percent lower than the conventional one (69.9 vs 75.4 tonnes ha^{-1}), but in the 50 percent less favourable years, organic yields fluctuated between 51 and 70 tonnes ha^{-1}, whereas conventional yields fluctuated between 23 and 75 tonnes ha^{-1}. Similarly, the long-term results from the system experiment at the Rodale Institute in Pennsylvania show that organically managed crops yield better than conventional ones in dry years, leading to more favourable economic margins (Mirsky *et al.*, 2012).

Figure 1. **Yield data from the long-term systems experiment at Russell Ranch, UC Davis, California**



(**A**) Yield of field grown tomato in rotation with maize under conventional and organic management, and in rotation with maize and legumes; (**B**) Cumulative frequencies of tomato yields under conventional and organic management, indicating the 50th percentile with a grey dashed line. The data used in the analysis are available at: http://asi.ucdavis.edu/rr

Comparing the yields of conventional and organic agriculture has been common practice in recent years and two widely cited papers independently concluded that the average yield gap between both systems across crop types and locations was in the order of 20 percent (Seufert *et al.*, 2012; de Ponti *et al.*, 2012). A new publication that reanalysed the same data, using more sophisticated statistical techniques to account for co-variances, indicates that yield gaps between both systems are narrower when similar amounts of nitrogen were applied in both systems (9 percent), or when entire rotations were considered (7 percent) (Ponisio *et al.*, 2014). Furthermore, a quick glance at the data in Figure 1A serves to illustrate why considering long-term series rather than point measurements is important when comparing yields in both systems. If the Russell experiment would have been conducted in the year 1994 only, the conclusion would be that legume–maize–tomato and conventional systems yield better than organic. If only 1995 was considered, then the conclusion would be that organic yields better than the other two. If only 1996 was considered, then the conclusion would be that there are no significant differences between systems. Systems that contribute to the long-term buildup of soil quality tend to express their maximum potential after a number of years of implementation.

Long-term trials are thus an essential tool in the science of agroecology, not only when it comes to assessing adaptability to global change, but also the environmental impact and mitigation potential of alternative systems. A report by FAO summarized the results of a number of long-term agricultural trials worldwide in relation to climate change-relevant variables, showing that organic management of soils contributes substantially to carbon sequestration and significantly reduces the global warming potential (GWP) of agriculture compared with conventional management (Niggli *et al.*, 2009). Similar findings were reported earlier by Küstermann *et al.* (2008) from a study based on simulation modelling. Likewise, the long-term Rodale experiment cited above shows that organic management leads to a 64 percent reduction in GWP and 45 percent greater energy efficiency compared with conventional management (www.rodaleinstitute.org/our-work/farming-systems-trial). The long-term DOK trial[2] run since 1978 in Switzerland shows that organic management systems use 30-50 percent less energy per unit area, and 19 percent less energy per unit crop produce than conventional ones, and are the only systems that maintain SOM levels in the long term (Fliessbach *et al.*, 2007). Figure 2 provides a summary of the differences between organic and conventional systems recorded in this experiment over 21 years.

More recently, Rossing *et al.* (2014) summarized the scientific evidence on the ability of agroecological and organic farming systems to adapt to or mitigate climate change through a literature review including 97 references. They analysed several indicators and found statistically significant positive effects (better performance) of these systems as well as non-significant effects (equivocal performance) when compared with conventional practices. Significantly better performances of agroecological systems were found in terms of: (i) carbon sequestration down to 0.3 m depth; (ii) energy-use efficiency; (iii) soil water holding capacity; (iv) resilience to drought; and (v) resilience to hurricanes and heavy rainfall. Equivocal performance was found for (i) carbon sequestration down to 1 m depth; and (ii) GWP. There were only a few studies available that reported soil carbon measurements below 0.3 m depth (Gattinger *et al.*, 2012).

In terms of GWP, a major discrepancy was found between studies that reported CO_2 emission equivalents calculated through life cycle assessments per unit of product or per unit of area (Tuomisto *et al.*, 2012). Industrial agriculture performed better when emission equivalents were expressed per kg of produce (e.g. per kg of meat or cereal). Yet, what causes global warming is the total net emission of CO_2 and related gases per area, irrespective of the yields obtained. Calculating emissions or any other environmental impact per unit of produce, as often done through the methods of environmental accounting, is thus misleading. This exacerbates the sensitivity of environmental assessments to the definition of system boundaries.

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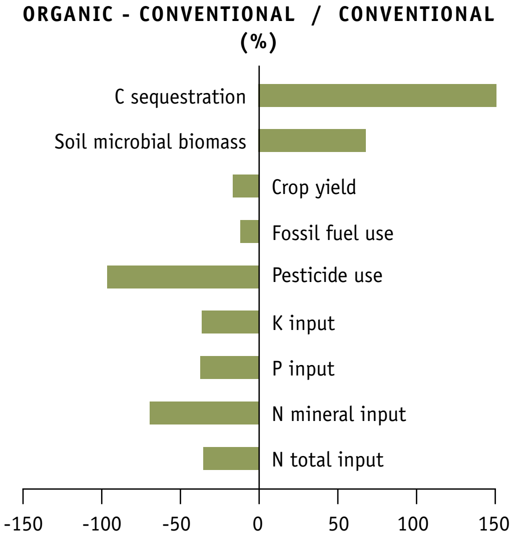
[2] The DOK trial compares biodynamic (D), organic (O) and conventional (K for German: "*konventionell*") production of arable crops such as wheat, potatoes, maize, soya and grass-clover leys since 1978, and has resulted in a number of scientific publications.

Figure 2. **Comparative environmental performance of organic versus conventional management systems in 21-year long rotations at the DOK experiment in Switzerland**



Organic management led to yields that were on average 17 percent smaller than conventional ones, but increased C sequestration and soil microbial biomass by 150 and 67 percent respectively, reduced fossil fuel and pesticide use by 13 and 96 percent, and nutrient inputs by more than 35 percent.

Source: data from Fliessbach *et al.*, 2007

CASE STUDIES AND EXAMPLES

Case studies from around the world were selected to illustrate four important aspects of agroecology:

1. The potential of combining biodiversity, traditional practices and alternative sources of knowledge for the design of complex adaptive agricultural systems that contribute to food security and nutrition in family agriculture;
2. The potential of using agroecological principles in the design and management of large-scale, mechanized agricultural systems in developed regions by adjusting agronomic practices and technologies;
3. The potential of agroecological practices to restore and sustain the productivity of presently degraded lands in sub-Saharan Africa, and the need for conducive conditions to make this happen at scale;
4. The transformative potential of agroecology to contribute to food security, nutrition and the empowerment of family farmers when social movements and conducive policies are aligned.

Documentary videos were produced to illustrate these four aspects with real cases and presented in the context of the First International Symposium on Agroecology for Food Security and Nutrition organized by the FAO in September 2014. They can be found at: www.fao.org/about/meetings/afns/en.

Complex adaptive agro-ecosystems

Complex adaptive agro-ecosystems that combine diverse cropping and animal production activities in space and time, aim to increase overall resource efficiencies, including labour and financial efficiencies. For example, complex rice agro-ecosystems that combine rice, azolla, duck, fish and border plants deliver ecosystem services that support ecological rice production systems (see video: Complex adaptive rice cultivation in Indonesia). Fish and ducks control weeds and pests directly through their feeding behaviour and movement (Figure 3A), foster nutrient cycling and contribute to diversify diets and family incomes (Xie *et al.*, 2011; Liang *et al.*, 2012; Long *et al.*, 2013). Complex adaptive rice experiments run on farmers' fields since 2010 in Malang, East Java, showed greater average rice yields and nutrient uptake than in monocultures in the first two years of the experiment, and increasing yields as complexity (i.e. the number of system components) increased (Khumairoh *et al.*, 2012). Rice yields of 10.2 tonnes ha^{-1} were observed in the second cropping cycle when rice, fish, ducks and azolla were combined. Recent measurements in 2013 also included ammonia volatilization, which is a major source of nitrogen losses from the system (Del Río, 2014). System complexity under organic management did not influence the NH_3 volatilization, which was in all cases smaller than under conventional rice with synthetic fertilisers. The systems were exposed to climatic variability, such as a prolonged wet season in 2010, and to an endemic pest outbreak in 2014. Measurements taken in 2010 revealed that significantly lower infestation levels of snails, maggots and plant hoppers both at the beginning and at the end of rice growing cycle (Table 1). The presence of ducks and fish reduced the population of major rice pests in 2010 and efficiently controlled stem borer in 2014 compared with the conventional system (that received 6 litres of pesticide per ha). Economic analysis shows that the increased costs associated with animal husbandry in complex systems are more than compensated by the reduction in costs associated with agrochemicals and by greater revenues and income diversification from the complex systems (Khumairoh, pers. comm.).

Complex adaptive agro-ecosystems are often inspired by traditional farming practices, as in the example above, but optimized using modern knowledge and technologies. Yet complex systems – or polycultures, in the broadest sense – have been also designed as goal-oriented

Table 1. **Infestation levels of snails, maggots and plant hoppers in rice (individuals per m^2) at initial and final stages of rice growth**

	SNAILS		MAGGOTS		PLANT HOPPERS	
Weeks after transplanting	*4*	*10*	*4*	*10*	*4*	*10*
Rice control	35	17	46	21.8	11	18
Rice + ducks	20	1	25	1.8	1	2
Rice + ducks + fish	21	1	25	1.1	2	2

Source: Khumairoh *et al.*, 2012

objects, responding to well-defined targets, adapted to their socio-technical context, and not necessarily drawing inspiration from traditional systems (e.g. Vereijken, 1997). Conspicuous examples of this are the combination of annual and perennial crops, or of these with grazing ruminants or free-ranging pigs or poultry, of agroforestry and silvopastoral systems, etc. While most of the investment in agricultural research in the last five decades has been directed towards oversimplified monocultures, it is time for scientists and technology developers to seriously recognize and embrace complex polycultures as a viable alternative to balance the goals of achieving agricultural productivity, nutritional diversity, global change adaptability and ecosystem service provision.

Figure 3. **Images from the various cases studies**

(**A**) Ducks foraging for weeds and insects in a complex adaptive rice system in Malang, Indonesia (photo: P. Tittonell); (**B**) A gigantic winter wheat plant grown at broad spacing in an innovative organic farm in Zeeland, The Netherlands (photo: K. Steendijk); (**C**) A degraded landscape exhibiting deep erosion gullies and almost no vegetation cover in Arusha District, Tanzania (photo: S. de Hek); (**D**) A restored landscape in Sahelian Burkina Faso (photo: G. Félix).

Agroecological principles in large-scale farming

Although agroecology has its origins in the *campesino* movements of Latin America, and has been embraced by family farmer movements around the world, the basic principles of agroecology are also of prime relevance for the design of sustainable large-scale agricultural systems. Several organic, biodynamic and even innovative 'conventional' farmers in Europe and the Americas have genuinely embraced agroecological principles for the design and management of their farms. This form of agroecology is not necessarily always linked to social movements – other than consumer movements such as community-supported agriculture, farmer trade unions, associations of concerned farmers, etc. National agricultural research organizations in countries like Argentina (INTA) or France (INRA) are increasingly opening up to agroecology, creating new research and development programmes that aim at translating its principles into management, technology and policy options targeting large-scale mechanized agriculture. Their target farms do not necessarily conform to the model of smallholder family agricultural systems that is the prime target of the agroecology movement. Nevertheless, their size and the volume of their production mean that their transition to agroecology can have large positive impacts on the global environment, on biodiversity and on the quality of food delivered to consumers, particularly for the majority of urban dwellers that are supplied by them.

Organic and other innovative farmers in The Netherlands are realizing the high yield potential of cereals on Dutch soils through smart ecological intensification techniques, producing yields that are as high as those obtained by their conventional neighbours (see video: Healthy Cereals, The Netherlands). The technique used by such farmers resembles the principles behind the System of Rice Intensification (Stoop, 2011): a reduction of plant population to allow ample tillering, a uniform sowing bed and emergence rate to facilitate mechanical weeding, selection of vigorous seeds, a synchronisation between crop demand and the supply from organic sources and, in some cases, minimum or no soil tillage. To this they add GPS-assisted controlled traffic of agricultural machinery to plant on permanent beds and avoid soil compaction, use of green manures and diversified crop rotations[3] (Oomen, 2012). Table 2 shows data on winter wheat yield and yield components collected from two neighbouring organic farms in Zeeland, one that grows wheat 'as usual' (i.e. with similar practices to those followed by conventional farmers in the region) and one that adapts wheat agronomy to organic cultivation. In spite of starting with less seeds and broader plant spacing, the crop under adapted management ends up with more fertile ears per unit area and greater average yields with less spatial variability (Figure 3B). This farmer reduced initial plant densities because he applied composted chicken manure, which releases nutrients much more slowly (especially in early spring) compared with the digested slurry applied by the conventional farmer. As shown by Delmotte *et al.* (2011) in their comparative analysis of conventional versus organic rice yields in France, organic farmers make major agronomic adjustments to their crops, considering fertility levels and forecasted weather at the initial phases of the crop. The resulting crops differ widely in their structure

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[3] For example, the Dutch organic farmer shown in the video farms 80 ha of land where he keeps as many as 18 different crops in rotation.

and eco-physiological attributes from conventional ones. This again proves that, contrary to the generally perceived notion, organic and agroecological farming is much more than simply conventional farming without inputs or with a different type of inputs. Agroecological production calls for an entirely different understanding of basic agronomy.

Table 2. **Agronomic variables and yield components of winter wheat cultivar *Tartarus* grown under organic cultivation by framers in Zeeland, The Netherlands, following current versus adapted agronomic management practices in 2011/12***

SYSTEM	PLANTING DENSITY (kg ha^{-1})	WEIGHT OF 1 000 SEEDS	PLANTS PER M^2 AT TILLERING (CV, %)	EARS PER M^2 (CV, %)	GRAINS PER EAR	WEIGHT OF 1 000 GRAINS	HARVEST INDEX (%)	GRAIN YIELD (t ha^{-1})
Current	200	52	111 (55)	277 (30)	50.5	47.7	47	6.7 ± 2.1
Adapted	60	60	84 (19)	317 (23)	51.2	47.3	51	7.7 ± 1.4

Source: G. Oomen, 2012

*The average wheat yield in conventional farms in the region was 8.5 t ha^{-1} in 2012.

Restoration of degraded ecosystems in sub-Saharan Africa

It is estimated that about 25 percent of the area of agricultural soils worldwide is in a severely degraded state (Bai *et al.*, 2010). This is certainly a challenge when it comes to thinking about meeting future food demands. But it is also an opportunity, as the restoration of such a vast area will not only result in 25 percent more land to produce food but also in thousands of megatonnes of carbon removed from the atmosphere and sunk back into the topsoil layer. The problem of soil degradation is aggravated in sub-Saharan Africa by the co-existence of soils that are inherently poor (formed on highly weathered Precambrian rock) or too coarse or shallow to hold water, large extensions of inherently erratic climatic conditions (e.g. 30-40 percent rainfall variability in semi-arid and 15-20 percent in humid regions), and increasing rural population densities with concomitant increases in cultivation intensity, livestock densities and land fragmentation. It has been estimated that 45 percent of the area in the continent is vulnerable to desertification (Reich *et al.*, 2001).

Yet a number of successful examples of restoration of degraded landscapes exist in the literature. A classic case is the restoration of soil productivity in the Sahel by means of the large-scale implementation of the traditional *zaï* planting basins system in combination with half-moon planting ditches and stone barriers to reduce soil erosion (e.g. Bationo *et al.*, 2005). More recently, interesting examples have been documented using land 'exclosures' in Ethiopia (Corral-Nuñez *et al.*, 2014), growing 'indifallows' in Zimbabwe (Nezomba *et al.*, 2015) or native shrubs and woody amendments in Burkina Faso (Lahmar *et al.*, 2012; Félix *et al.*, 2015; Figure 3D). Moreover, broad grain estimations of primary productivity at continental scale through repeated normalized difference vegetation index (NDVI) measurements show that the areas where crop and natural vegetation biomass production is improving are larger than those in which biomass

production is declining, particularly in arid regions (Table 3). However, most of the land that is 'greening', presumably as a consequence of increased annual rainfall with respect to the period of reference (the early-1980s), is associated with pastoralist systems rather than agricultural areas.

Table 3. **Areas (million km^2) of Africa that exhibit decreasing, neutral or increasing biomass production as estimated from the slope of annual NDVI, per climatic zone**

BIOMASS TREND	CLIMATIC ZONE			
	Arid (<500 mm)	**Semi-arid (500-800 mm)**	**Sub-humid (800-1 300 mm)**	**Humid (>1 300 mm)**
Decreasing	0.3	0.3	0.9	0.7
Neutral	2.2	1.5	2.8	2.2
Increasing	4.2	1.8	2.5	1.9
Total	**6.7**	**3.6**	**6.2**	**4.8**

Source: adapted from Vlek *et al.*, 2008

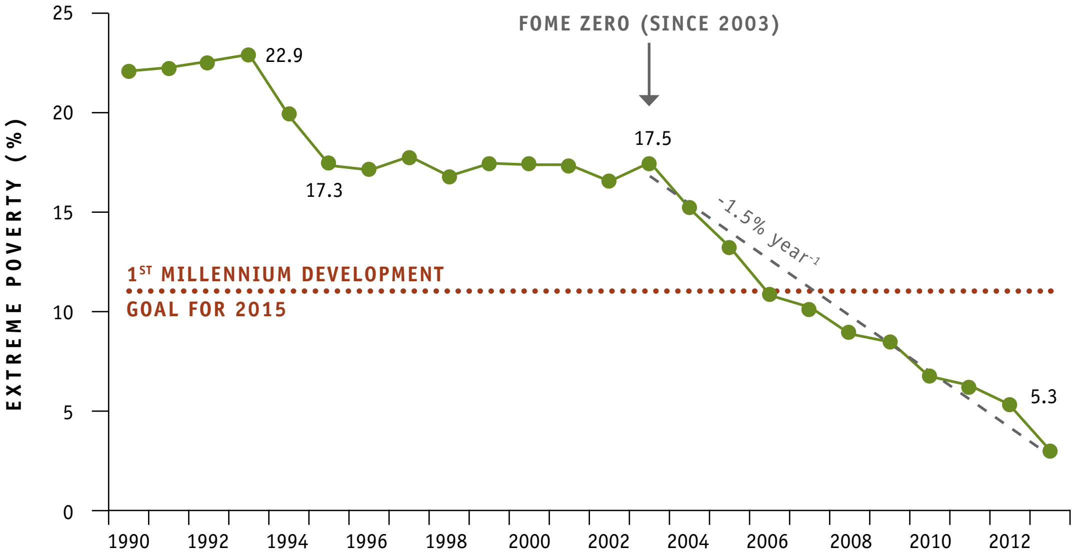
All the scientific evidence seems to indicate that restoring and sustaining land productivity, which is essential for future food security in sub-Saharan Africa, is not necessarily a technical challenge anymore but rather a matter of finding the right incentives for smallholder farmers to invest in it. The Tanzanian farmer in the case study video (see video: Restoring landscapes, Tanzania) is not an average smallholder farmer in his region. He used to be a local primary school teacher, well respected in his community, and with a natural curiosity for innovations. He has been receptive to a large number of technologies that were promoted in the region through various organizations nucleated by the African Conservation Tillage (ACT) network, and has selected and adapted them to fit his system. He created an oasis of agricultural productivity in an otherwise degraded, desertifying landscape (Figure 3C) by combining measures such as contour farming, agroforestry, conservation tillage, intercropping, cut-and-carry livestock feeding, composting and biogas production, and proper seed storage. This example shows that there is scope for restoring degraded landscapes and agricultural productivity by following basic agroecological principles. At the same time this example shows that single technologies or interventions will not work.

The big question ahead of the agroecology and related movements is how to scale up such successful examples. What are the incentives for farmers to invest time and resources in restoring degraded ecosystems? What forms of policy can create conducive conditions for wide scale agroecology adoption in remote areas with poor access to basic services, information, markets or education? Most strikingly, not all rural dwellers in sub-Saharan Africa are necessarily 'farmers' by choice or vocation, and only a small proportion of them regard farming as a viable form of livelihood for their children (Bryceson, 2002). When conducting household surveys in East Africa more than a decade ago, I used to pose questions to farmers regarding their motivations to be farming. To the question '*Why are you farming?*' their answer was, in a large number of cases, literally: '*Because I'm unemployed*' (cf. Tittonell *et al.*, 2010). It is obvious that restoring landscapes and sustaining productive agro-ecosystems requires much more than agronomic or technological fixes.

Agroecology movements and policies

Brazil is one of the few countries that in the space of one decade achieved the Millennium goals of reducing extreme poverty and eradicating hunger (Figure 4). Central to this achievement was the launching of the *Fome Zero* programme (Zero Hunger), which comprised a large number of policy and development instruments that were deployed all over the country and adapted to fit regional differences. Some of these policies led to emergent, unexpected positive outcomes. For example, through the creation of a programme on obligatory school meals, school managers all over the country are obliged by law to purchase at least 30 percent of the food from family farmers. When the food is organic, farmers receive a 30 percent price surplus. As the geographical distribution of schools covers all of Brazil's urban and rural areas (45 million school children), this policy created an enormous proximity market for the atomized production of smallholder farmers (4.3 million of them in the entire country), reducing transportation and transaction costs for both buyers and sellers, therefore contributing to lower food prices. Farmers that have to serve a school kitchen are stimulated to diversify their production, as schools demanded a diversity of ingredients for their meals. The resulting diversification of production on the farm has also had positive consequences on the diet of smallholder farming families themselves; clearly a win-win situation. Another indirect outcome from the programmes was the diversity of new forms of farmer organizations to aggregate and distribute their production, ensuring traceability, quality and fair pricing. These forms of organization were made possible through a certain tradition of farmer organization in rural Brazil (see video: Agroecology in movement, Brazil), but also through political support.

Figure 4. **Brazil's extreme poverty levels over the first ten years of implementation of the *Fome Zero* programme (2003-2013), indicating the Millennium Goal threshold set for 2015, which was already achieved by 2006**



For the World Bank, a 3 percent level is equivalent to eradication (Paes-Sousa and Vaitsman, 2014)

Source: IBGE, 2013

Brazil is the first country to have created a Ministry of Agrarian Development (Medaests *et al.*, 2003) to attend to the specific needs of the smallholder family farming sector and the first one to have launched a National Agroecology Plan, which rests on principles of territorial development. For example, this Ministry finances the construction of rural schools that train the youth using the principles of agroecology. There are many aspects still to be improved in Brazil's rural development policies, but the reason this case study is featured here is to emphasize the fact that conducive policies – backed by political will – are essential for agroecology to work and be a reality for a large number of family farmers. National policies such as the ones developed and implemented in Brazil are needed to scale out agroecology innovations from a niche position to becoming alternative socio-technical regimes. In a time in which agriculture and food security experts hypothesize, speculate and often disagree on what needs to happen in order to end world hunger, it is perhaps more sensible to analyse the example of countries such as Brazil that have effectively ended hunger within their borders in recent years. In particular, the experience of Brazil illustrates that ending hunger does not necessarily mean doubling crop yields.

CONCLUDING REMARKS

Agroecology offers technical and organizational innovations to promote a restorative, adaptable, inclusive and resource use-efficient agricultural model at global scale. There are several challenges ahead. An important one is to know with certainty the current extent of agroecology in the world in terms of the area and number of farmers adopting agroecological principles. If we can understand and document which types of farmers, and under which conditions, are switching to agroecology we will be able to better inform the development of public policies to support this transition. Scaling up agroecology from successful isolated examples of pioneer farmers to broad-scale dissemination is our next major challenge. Here is where social organization and movements have a major role to play. Investing in institutional and policy innovation will be at least as important as investing in generating new scientific knowledge on agroecology. Rather than policies that compel farmers to embrace agroecology, what we need are policies that set the rules of the game to make agroecological farming as competitive and economically viable as industrial farming, for example: (i) by internalizing the environmental externalities in production costs; (ii) through preferential allocation of subsidies to low environmental impact farming; (iii) through the protection of family farmers' rights to access agrobiodiversity, which is increasingly being restricted by patents and unethical claims on property rights; and (iv) through the promotion of short commercialization circuits and local food systems, including processing, that can guarantee quality and safe food for the poorest urban dwellers.

In a context of rapidly increasing population and dwindling farm sizes, small farms could play a more significant role by complementing and reinforcing diets through the production of a large diversity of nutritious crops, rather than focusing on producing only calorie-rich crops. Although modern human diets are more commonly determined by demand than by supply (Marie and Delpeuch, 2005), the case of smallholder rural families may constitute an exception in many

situations. The average diet of people in rural areas that are well connected to markets and urban hubs, or that have access to mass communication media, is increasingly determined by demand. It is almost commonplace to see rural people who live in mega-diverse environments consuming processed food produced in cities, using ingredients that come from far away. Yet, in regions that are less connected to markets or to mass media, or where poverty prevents people from affording foreign foods, the relationship between landscape and nutritional diversity is a much stronger one. The functional biodiversity that is necessary to sustain agroecological processes and functions also results in a greater diversity of crops and animal products that can improve the diet of farming families, as in the example of Brazil.

If we consider the composition of a recommended average diet to reduce food-related health risks and improve nutrition (Murray, 2014), and compare it with current global food production, it is evident that we are short of vegetables by 11 percent, fruits by 34 percent, fresh milk by 50 percent and nuts and seeds by 58 percent. These nutritional gaps indicate that there is a need to diversify production through, e.g. intensive vegetable rotations and associations, crop-livestock integration, or fruit tree agroforestry – all practices that are common in agroecology. Efforts should be directed towards the design of nutrition-sensitive landscapes by means of diversification. The good intention of increasing the yield of a few world commodities to reduce poverty and hunger has already shown its limitations. Particularly in smallholder family agriculture, when land sizes are as small as one acre or less, increasing the yield of staple crops will not result in families rising out of poverty. Given their small size, the total income they may receive from selling their harvest – even if they produce at potential yield levels – will still be meagre. The result is that a large number of farmers in developing regions are currently part-time farmers who are unable to pay enough attention to their farms and their landscapes. This trend will be exacerbated for future generations of family farmers unless we do something about it. It is time for agroecology.

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02

ENHANCING THE FUNCTION AND PROVISIONING OF ECOSYSTEM SERVICES IN AGRICULTURE:

AGROECOLOGICAL PRINCIPLES

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Abstract

Agroecology is essentially based on the use of biodiversity and ecosystem services in agricultural production, and thus represents a true rupture from the way agriculture has been seen and analysed by mainstream science for over a century. Agroecology does not have a consensual definition; it represents a conceptual space to think about agricultural sustainability through strong interactions between science and society with a wealth of new concepts, questions and tools. Among the diverse 'incarnations' of agroecology, the lowest common denominator is found at plot level. The basic and common principle is to increase biomass production by enhancing the services provided by living organisms and by taking the optimal advantage of natural resources, especially those which are abundant and free (e.g. solar radiation, atmospheric carbon and nitrogen, rainfall). Agroecology aims to manage, and in some cases to increase, production in a sustainable and resilient way that will maintain and improve the natural capital in the long term. It will enhance the ecological processes and interactions of functional biodiversity above- and below-ground, over space and in time, by both intensifying biological cycles for nutrients, water and energy, and controlling the aggressors of crops. Because ecosystem services are involved, agroecology has long been working on larger scales (i.e. farms, landscapes, watershed basins, value chains, food systems). Agroecology has had a deep engagement with interdisciplinary research, in particular focusing on some of the drivers of agricultural development such as food industries and distribution, consumer health, public policies, etc. Because agroecology strongly depends on locally available natural resources including agrobiodiversity, it cannot prescribe ready-to-use technical packages to farmers. Rather, agroecological models and solutions are built by mingling scientific and traditional knowledge and by strongly relying on local learning and innovation processes. With the many challenges ahead, agroecology represents a true alternative avenue for agricultural transformation; while it questions the role and practices of agricultural research and calls for a significant renewal.

INTRODUCTION

As the challenges that the world has to face are becoming overwhelming: food and nutrition security, biodiversity erosion and ecosystems integrity, climate change, energy transition and decarbonation of the economy, etc., there is an acute need for finding sustainability and an urgency to be able to build concrete way of implementing it. Agriculture of the world, as with all other human activities, must reflect on how it can genuinely increase its sustainability.

Agroecology is a concrete approach to transform the agriculture of the world, in its huge diversity, into more sustainable forms and systems.

Because agriculture uses nearly 40 percent of the Earth's land, over three-quarters of available freshwater, and provides livelihood and jobs to almost half of the world's labour force, it has intimate links with some of the most acute world challenges – as mentioned above (Hainzelin, 2014).

The future of agriculture is not written in stone; there is no universal law that requires agriculture in developing countries to follow the same steps of modernization by industrialization, as has happened in most of the rich countries. There is obviously a necessity to improve land and labour productivity to be able to cap the pressure on land, protect fragile ecosystems and avoid deforestation, but the intensification pathways and modalities is today's acute question. Agroecology represents a new vision of intensification, a 'family' of pathways of transformation that concerns all agricultural systems: from manual and 'organic by default' agriculture in regions that have not yet started any intensification process, to industrialized agro-systems that need to rethink their model because of its unsustainability.

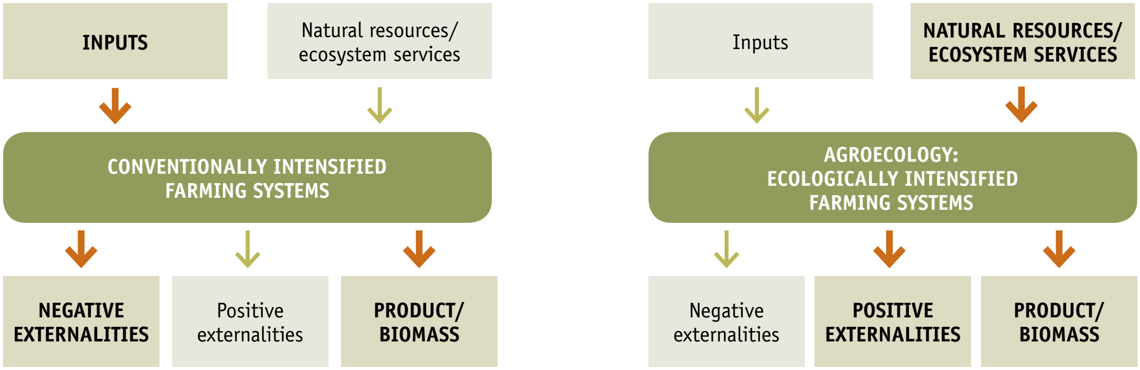
In this chapter, we will review the basic principles of agroecology, and discuss how its diverse incarnations mobilize ecosystem services to intensify production in a sustainable way. We will then see what these principles imply in terms of the consideration of local contexts and traditional knowledge. Finally, we will reflect on the role of scientific research in contributing to build agroecological intensification pathways.

AGROECOLOGY OPENS A WIDE RANGE OF SOLUTIONS TO TRANSFORM AGRICULTURE AND IMPROVE ITS PERFORMANCE AND SUSTAINABILITY

A shift of paradigm

Agroecology represents a rupture with the way agriculture has been seen and analysed by mainstream science for over a century – with an essentially reductionist viewpoint and an increasing dependence on external inputs. According to this mainstream perspective, the logical evolution of agriculture is one of yield intensification through the use of high-yielding varieties and high levels of external inputs (fertilizers, pesticides, irrigation, etc.). This model of 'conventional intensification' has been the base of industrialized, 'Green Revolution' agriculture. It promotes a strong specialization of crops, often reduced to a uniform and synchronous canopy, ultimately consisting of a single genotype of some major species, with the rest of the living organisms being systematically eliminated as 'limiting factors'. It has long been seen as the ultimate way to produce, but its sustainability is increasingly questioned, because it has forgotten the importance of biodiversity as the driving force of production and regulation processes in ecosystems. Despite spectacular gains in terms of productivity (economy of scale, homogeneity, mechanization, etc.), it has caused an extreme impoverishment in biotic interactions (Figure 1).

Figure 1. **Comparison of conventional and ecological intensification pathways in cropping systems**



Source: adapted from Griffon, 2013

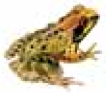
Acknowledging the absolute double necessity of intensification and sustainability, several authors including Pretty and Bharucha (2014) have been developing the concept of "sustainable intensification" as a "*process or system where agricultural yields are increased without adverse environmental impact*". This concept, on which everybody should easily agree, does not articulate a specific technological pathway; it emphasizes ends rather than means, which can be extremely diversified (Pretty and Bharucha, 2014).

On the other hand, agroecology is very focused on means: it is mainly based on a stronger provision and mobilization of natural resources and functionalities of biodiversity and the relevant ecosystem services that sustain agricultural production such as natural pest control, maintenance of soil fertility and pollination. In this way, it is an 'ecological intensification'. It represents a rupture with conventional intensification, but it is in tune with the other transformative evolutions that agriculture has known since it started in the Neolithic: domestication and breeding processes, and later on association animal-crops, rotation with legumes crops, soil tillage, then no-tillage, etc.

A new way of looking at performance

Given the need for sustainability, what exactly does the performance of agricultural production mean? It is now widely recognized that agriculture is multifunctional, as stated in the following passage from the International Assessment on Agricultural Knowledge, Science and Technology for Development:

> *"other important functions for sustainable development include provision of nonfood products; provision of ecological services and environmental protection; advancement of livelihoods; economic development; creation of employment opportunities; food safety and nutritional quality; social stability; maintenance of culture and tradition and identity" (IAASTD, 2009).*



Agricultural productivity cannot only be measured by labour or land productivity. Negative externalities as well as the supply of ecosystem services and amenities must enter into the calculation. Furthermore, they must be computed over time so that the long-term impact on ecosystem potentialities and resilience can be evaluated. This multi-criteria performance, a crucial element to evaluate sustainability, is being debated: numerous indicators are proposed but very few are agreed upon by consensus. A recent meta-analysis based on 49 research papers published in Europe identified over 500 sustainability indicators, of which the vast majority (431) were used only once (Buckwell, 2014). This illustrates the lack of agreed-upon tools to measure sustainability, although numerous research initiatives are in progress to be able to better characterize sustainability (Caron *et al.*, 2014).

The principles of agroecology lead to a re-analysis of all technical interventions in cropping systems. This analysis is based on a long-term vision of 'aggradation', building on existing foundations, where natural capital improvement is one of the goals. The example of tillage illustrates the balance that needs to be made between the expected positive effects (e.g. reducing weeds, opening soil porosity) and the negative effects (e.g. energetic and equipment cost, erosion susceptibility and perturbation of soil biodiversity) (Griffon, 2013).

AGROECOLOGY DOES NOT HAVE A CONSENSUAL DEFINITION BUT IT HAS MANY 'INCARNATIONS'

Although various scholars have described agroecology with considerable details and a sound conceptual basis (Altieri, 1995; Gliessman, 1998), today it has no consensual and clear definition. Its very nature is much discussed; it has been described as a science, a movement and a practice, showing how much its nature depends on the point of view of the author (Wezel *et al.*, 2009). Agroecology has 'incarnations' that are many and very diverse. Within the family of practice, we can include permaculture, organic agriculture, eco-agriculture, conservation agriculture, evergreen agriculture, minimum or no-tillage, etc. – each focusing on one specific feature of agroecology. The expression "ecological intensification" refers even more to the range of means to be mobilized in priority to transform agriculture though agroecology (Griffon, 2013; Tittonell, 2013; 2014). On the science side, scholars could engage in endless debates as to whether agroecology is a new scientific discipline, or a trans- or an inter-discipline, noting that its concepts and methods are still quite fluid.

The scope of topics addressed by published research on agroecology is also extremely large. Xavier Reboud (pers. comm.) analysed more than 2 500 references of scientific papers published between 1975 and 2010, either using the word "agroecology" or being related to agroecology without using the term. His attempt to group and map the scientific questions or themes linked to agroecology resulted in a large variety of fields, research objects, scales, etc.

Agroecology represents a conceptual space to think about agricultural sustainability through strong interactions between science and society, with a wealth of renewed concepts, questions and tools. The fact that the definition of agroecology is itself somehow fuzzy is considered by some authors as an opportunity and richness; the diversity of perspectives generates active debates, and is a promising source of new ideas and concepts (Griffon, 2013).

Among the large diversity of agroecology 'incarnations', the lowest common denominator is found at plot level. The basic and common principle of agroecology is to enhance the services provided by living organisms taking the optimal advantage of natural resources, especially those that are abundant and free (e.g. solar radiation, atmospheric carbon and nitrogen, rainfall).

HOW DOES AGROECOLOGY MOBILIZE BIODIVERSITY AND ECOSYSTEM SERVICES AT PLOT SCALE?

Three main levers of using ecosystem services to intensify

First, agroecology seeks to optimize functional biodiversity above-ground, at different scales over space and time, to intensify biological cycles for nutrients, water and energy (Malézieux *et al.*, 2009). The amplification of these cycles, each one of which is an ecosystem service, aims at increasing biomass production, focusing particularly on the harvested biomass (food, fibre, energy, etc.). Constant attention is paid to the need to maintain natural resources and increase the local ecosystem's potential. Experimenting with the complementarity of niches, canopy architectures and root systems among species (including the 'service species' grown to provide specific services), and planning annual and perennial combinations, etc., maximizes the uptake of resources, both below- and above-ground.

Second, functional biodiversity is utilized to limit the population of bio-aggressors like weeds, pests and soil-borne diseases that reduce the harvested crop biomass. There are innumerable examples of the use of biological control, augmentation of pest predators and aggressors, allelopathic effects and stimulo-deterrent diversion techniques to control aggressors. Agroecology advocates building knowledge on how biological spatio-temporal stands and interactions, trophic chains and specific ecology, can enhance the fight against crop aggressors (Ratnadass *et al.*, 2014).

Third, agroecology manages functional biodiversity below-ground by amplifying biogeochemical cycles in the soil, recycling the nutrients from deep profiles and increasing microbial activities. This is probably where conventional and ecological intensification differ the most; the former relies almost exclusively on fertilizers and amendments to provide the nutrient needs of the canopy, whereas the latter mobilizes and enhances the activity of the living communities of the soil to improve the nutrient cycles. Agroecology does not exonerate the need to compensate nutrient exports, but as it provides a larger and more active soil space, and reduces nutrient losses, fertilizers are used in a more parsimonious way. This is a completely different intensification mindset, but there is much to discover about the different ways to apply this principle. Soil cycles are a mostly unknown world and only 10 percent of the soil biodiversity – that represents one-quarter of the total living species – have been described. Moreover, little is understood about the way soil cycles and biodiversity work in different soils. The soil fauna and microbial biomass can reach up to 10 tonnes ha^{-1}, but can also be extremely ill-treated and depleted by modern cropping techniques (Eglin *et al.*, 2010).

The expected advantages

Agroecology obviously depends much more than conventional cropping on the locally available resources and environment. Climate, particularly rainfall amount and distribution, nature and richness of the soil, available biodiversity, etc., will affect the equation of agroecology. Therefore, the expected advantages will differ depending on the context, but will generally be of three kinds:

» Increased biomass production and carbon sequestration in plants and soil throughout the year in a way that will maintain and improve the natural capital (enhanced soil biology and fertility) in the long term;

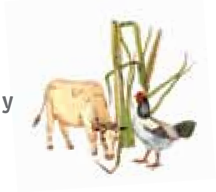
» Reduced input costs and technology dependency through agroecology by first tapping into free local resources, better energy balance of the crop and reduced externalities from inputs to human and environment health;

» Improved output stability and capacity to cope with and adapt to stress, perturbation and aggressors, because agroecology does not depend on synchronized and homogeneous mechanisms.

Agroecology is no magic bullet. It takes a considerable amount of both knowledge and innovative spirit to build these new systems and attain these advantages. One of the challenges will be to maintain the mineral balance as the system intensifies and the exported biomass increases. For some macronutrients, such as phosphorus, the equation will be particularly hard to solve, but this can be a common research venture between conventional and agroecological approaches, both having to apply the principle of parsimony. Most of the time, applying agroecological principles means a 'complexificaton' of cropping systems. This may be considered as a drawback, hampering the standardization and mechanization of techniques, especially on larger-scale farms. There is also an on-going argument about the comparison of performances between conventional and agroecological systems. If we limit this comparison to yield, the results can favour conventional intensification. However, when the analysis of production efficiencies is combined with the overall cost of the crop including negative externalities, the comparison is rarely in favour of conventional systems. Furthermore, agroecology applies the commonly accepted principle that there are trade-offs between short-term yield and long-term sustainability, whereas conventional systems are more short-term centred. This is why new multi-criteria tools are needed to measure the performances of different cropping systems.

Some concrete illustrations of applied agroecology

The basic principles that have been described above are already being applied with success at large scales, both in large mechanized farms and smallholders' farms. Planning and managing spatial and temporal biodiversity for functional optimization means dealing with genetic diversity but also species and ecosystem diversity. It always means 'complexification' of cropping systems, not only on the plot but also in the landscape around the plot. Among many possible examples, four illustrative cases of this 'complexification' are provided below.



No-tillage techniques in Mato Grosso, Brazil:

In the Amazonian regions of Mato Grosso (Brazil), no-tillage techniques associated with different combinations and the succession of multiple crops have been used over an area of 10 million ha. Rainfall is very high in these regions and the conventional monocropped soybean cultivation, after clearing the forest, leaves the ground uncovered and provokes high levels of erosion. Using service plants in intercropping with commercial crops, the principles applied are: (i) to keep the soil covered by a crop canopy or biomass on the ground; and (ii) develop a powerful and deep root system and ensure its viability all year-round, during very humid months as well as the dry months. These two applied principles permit the maintenance of soil biological activity and biomass production throughout the year, the elimination of erosion, and the amplification of nutrient cycles from very deep horizons (Séguy and Bouzinac, 2008). The total acreage under conservation agriculture (no-tillage, cover crops) in Brazil is now around 18 million ha, both within very large-scale farms and smallholders' farms (Scopel *et al.*, 2005).

'Push-pull' systems in Africa:

To control corn stem borer in Africa, the International Centre of Insect Physiology and Ecology (ICIPE) designed a combined use of 'trap plants' (Sudan grass or elephant grass) and 'repellent plants' (molasses grass, *Desmodium uncinatum*), which respectively attract and repel the borer for its oviposition, with a view to optimize their individual partial effects. Such processes are called 'stimulo-deterrent diversion of pests' or more simply 'push-pull' systems. They open innumerable combinations of species and designs of settings (intercropping, 'peri-cropping', etc.) to control crop aggressors (Ratnadass *et al.*, 2014). This family of techniques, which are not costly but mobilize farmers' intelligence and innovative spirit, are being used by a fast growing number of smallholders in Africa.

Temperate agroforestry systems in Europe:

Agroforestry is a traditional farming system in many tropical regions, as it used to be in the temperate regions before the process of intensification. The association between annual and perennial species can be very complex and brings a wealth of benefits: better exploitation of resources, diversity of products, complementarity over space and over time, improved capacity to buffer shocks, etc. Research has shown great interest to re-introduce tree species in large intensified and mechanized crops. The results from the large European project "SAFE" that worked in seven countries on the association between cereal crops and different tree species (walnut, cherry, poplar, oak) have been quite positive (i.e. one plus one can be more than two) in terms of global yield (up to 30 percent more than separate plots), with additional benefits for carbon sequestration, profitability, adaptive capacity, etc. The re-introduction of tree species in large mechanized monocrop farms in Europe will not happen overnight; it will take time as it requires a kind of a mental revolution, but eventually it might impact up to 65 million ha in Europe (Dupraz and Capillon, 2005).

Service species for pest control in the French West Indies:

In general, banana crops are heavily treated with different pesticides (up to 80 treatments per year in Central America) and this is a cause for serious concern with respect to human and ecosystem health. In the French West Indies, an original scheme of research and development with a producers' organization was launched to find ecological ways to reduce pesticide use without losing control over crop pests. A wide range of 'service species' to cover the ground at different stages of the banana crop, as well as crops to be grown between banana cycles, have been tested to reduce pest populations (nematodes, weevils), increase soil porosity, and contain weeds and erosion. Finely detailed research has been carried out in spatial and trophic ecology involving different species in association with other agroecological techniques (pheromone trap techniques, fallow management, varietal improvement, etc.). The results are quite encouraging; the pesticide dose has been reduced (from 12 kg ha^{-1} in 2006 to 4 kg ha^{-1} in 2012), especially for insecticides, while keeping control of nematodes and weevils, and reducing the overall production cost (Risède *et al.*, 2010).

AGROECOLOGY HAS LONG BEEN WORKING ON LARGER SCALES THAN THE PLOT

Because it is dealing with ecosystem services that are often mobilized at scales larger than plots, agroecology has long been working on innovations at higher scales – farms, landscapes, watershed basins, value chains and ultimately, food systems. These innovations generally go in the same direction, which means diversification and 'complexification' of production systems that require planning, management and coordination at higher scales (Tittonell, 2013). To deal with pests or insects at the plot level requires a consideration of the different trophic aspects, including the population of natural enemies occurring at the landscape level. To deal with soil erosion on a watershed slope, measures to increase the 'roughness' of the land across the slope are needed. To optimize crop production and the efficiency of the food system, communities may often need to better coordinate their different production strategies. Agroecology must consider the living communities in the plot, around the plots, and in non-cultivated ecosystems at the landscape level. This need for coordination, between farmers and between communities, may represent both a constraint and an opportunity in agroecology.

In fact, in regions where agroecology has been applied for a longer period of time, it is clear that there is a co-evolution between technical systems and rural societies – between ecological and social systems. Altieri and his colleagues have effectively shown the degree to which smallholders' initiative is central to agroecological innovation and outscaling (Altieri 1995; Altieri and Nicholls, 2012). This means that interactions between the social dynamics among farmers (organization, cooperation, learning process, connection with other stakeholders of the value chains, etc.) and technical innovations at different scales are crucial for a beneficial transformation.

Finally, many drivers of agricultural transformation are outside of the control of producers (e.g. the economy of agribusiness, agro-inputs upstream and value chains downstream), or even completely outside of the agriculture world (food industry and distribution systems, urban

consumers' markets, public policies and regulation, etc.). As a consequence, the transformation towards agroecology depends substantially on parameters that can be either 'enabling' or 'handicapping'.

For all these reasons, agroecology has been dealing with complex problems since its inception, mingling basic biological and ecological mechanisms, sometimes at a very fine scale, with human, social and political questions that can reach global scales (Wezel *et al.*, 2009). Integration of these extreme differences in scales generates radically new questions for which scientists are generally poorly equipped (Chevassus-au-Louis *et al.*, 2009).

AGROECOLOGY STRONGLY DEPENDS ON LOCALLY AVAILABLE NATURAL RESOURCES

Agroecology gives priority to the use of local resources including agrobiodiversity. Therefore, it strongly depends on the local context and potential. The different climatic, edaphic and biological parameters of a specific local context will affect the available resources and fashion the possible technical systems that will make the most of these resources. For this reason, agroecology does not prescribe ready-to-use technical packages but seeks to meet farmers' needs with an optimized range of technical options that farmers will combine and refine (Caron *et al.*, 2014). This is a crucial difference in approach from conventional intensification; models and solutions are built from a mingling of scientific and traditional knowledge and they strongly rely on learning and innovation processes among local stakeholders.

Some implications

A consequence of the importance of local context and the shift from 'ready-to-use' to 'custom-made' cropping systems, is that producers and their networks become the centre of local innovation systems. There is no longer a uniform technical prescription; farmers are being empowered in technical but also in social, organizational and political ways.

This means that science must be able to feed local innovation systems with pertinent scientific knowledge and provide new knowledge engineering, using the farmer's knowledge as a base. Agroecology needs cutting-edge science not only to be able to cross different disciplines and scales, but also to combine knowledge of different origins and reliability levels, in a way that enhances learning and innovation dynamics. Practical experiences, including through farmer field schools and sharing between innovative peasants, show how demanding these participatory processes are, but also how rewarding they can be.

Another important consequence of the transition towards agroecology is the status of agrobiodiversity. This key component of resilience is the principal lever that farmers can mobilize to intensify, and it must remain accessible to small farmers at no cost. Its erosion must be stopped because it is essential capital for future adaptation; *in situ* conservation of agrobiodiversity must be supported as an indispensable complement of *ex situ* conservation (Louafi *et al.*, 2014).

Agroecology is a radically new intensification avenue for most farmers of the world, but the pathways are diverse and many. These pathways could touch virtually any farmer in the world, including smallholders as well as larger producers. In some regions, agroecology has been applied with success for many decades by innumerable farmers. However, there are different policy environments, with some more enabling than others. Agroecology transitions will reinforce the resilience of agriculture and reduce the dependency on inputs, but it has a cost and will not happen without specific public policies, including transition policies for family agriculture, payment of environmental services, training, etc.

CONCLUSION: CRITICAL QUESTIONS ON THE ROLE AND THE PRACTICES OF AGRICULTURAL RESEARCH

With the many challenges ahead, agroecology represents a true alternative for an agricultural transformation while at the same time posing some critical questions on the role and practices of agricultural research; it calls for a significant renewal of what is expected of agricultural science. Because of the specificities of agroecology, there are direct consequences for the role and the practices of researchers (Caron *et al.*, 2014):

» Research should reflect on its role and input into agroecology – opening new questions of research, trying to shake the 'path dependency' wherever it may exist, and finding new and open ways of managing knowledge. This requires a reinforcement of the capacity of collective action among researchers, at team and project level, but also at institutional level, because a better research 'orchestration' of the many institutions working in this field is needed, to avoid redundancy and build critical mass.

» Researchers cannot be only knowledge producers and technology prescribers; together with engineers in charge of assembling existing knowledge, they should also become catalysers of change and innovation, which means to be able to work with different kinds of stakeholders, sometimes through asymmetric partnerships, with unbalanced strengths and powers. Scientists should take into consideration local knowledge and maintain strong personal interactions with agricultural realities and local innovation systems.

» Agricultural research will need more connections with basic knowledge to be instrumental in the implementation of agroecology (functional ecology, predictive biology[1], etc.), but also the capacity/tools to integrate and explore the long-term effects and consequences of the different options.

» Biologists, especially breeders that work to improve living organisms, must re-think their approaches and open up to the consideration of a broader range of species (domestication of 'service species' providing key ecosystem services, including animal species or micro-organisms) and new kinds of varieties (multi-crop and multi-genotype breeding, participatory

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[1] Predictive biology is a field of biological research centred on a fine understanding of gene expression (and therefore prediction) by integration of different disciplines and tools.

breeding, varieties-to-be-refined, etc.) (Ahmadi *et al.*, 2014). Genetic progress should be reassessed in the light of the multi-criteria concept of performance, as defined earlier. Making the most of biodiversity at different scales could open a new era for biotechnologies.

- Agronomists will have to deal with management of complex cropping systems, the combination of many species, cyclic successions and practices, and cope with multi-criteria performance. The diversity of points of view among the various agroecology movements is a source of richness, but we need to build common concepts, tools and metrics that encompass this diversity and facilitate constructive comparison and invention.

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03

CREATING VIRTUOUS CYCLES IN SMALLHOLDER PRODUCTION SYSTEMS THROUGH AGROECOLOGY

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Abstract

There are increasing global concerns about the failures of current food systems regimes and accelerated degradation of the natural resource base in the wake of rising pressures on agricultural production systems due to a growing human population and changing climate. These concerns raise questions about the appropriateness of conventional agriculture approaches (influenced by the Green Revolution) in fostering sustainable and resilient production and livelihood systems among the world's poor communities, such as those on the African continent. This chapter draws on examples of research and development interventions from sub-Saharan Africa to reveal how agroecological approaches at field, farm and landscape scales can create virtuous nutrient cycles, triggering higher-level socio-ecological dynamics that enhance the food security and livelihoods of smallholders. Interventions that involved the use of indigenous non-cultivated herbaceous legumes and planned sequences of integrated soil fertility management (ISFM) show potential for reversing soil carbon decline, nutrient depletion and falling crop yields under conventional agricultural systems. This chapter also highlights challenges in managing resource- and nutrient-use efficiencies, caused by intricate interdependences among agricultural production, natural resource pools, social safety net systems and patterns of access to knowledge, productive resources and technologies, all in a non-linear fashion. The research and extension approaches discussed here can create platforms for co-learning and co-innovation of farmers with diverse actors, including those beyond agriculture. These are critical factors for success. Such approaches open opportunities for farmers to share and pursue their livelihood objectives within and outside agriculture, reinforcing the virtuous cycles and broadening horizons for further collaboration as demands for new forms of resources, skills and technologies arise. Drawing on these experiences, we argue that inherent elements of resilience and visions of success among the predominantly smallholder farmers in Africa have largely been ignored in favour of current paradigms of agricultural research and development, often increasing the vulnerability of smallholders.

INTRODUCTION

The challenge of feeding a growing human population is not a new phenomenon in many parts of the world (UN, 1997). The agricultural Green Revolution of the 1970s is one of the most heralded development events of the 20th century, due to its success in easing the mounting challenge of feeding growing populations of hungry people, particularly in Asia and Latin America (Tribe, 1994; FAO, 1996; Evenson and Gollin, 2003; Pingali, 2012). Arguably, the Green Revolution's success story has eclipsed other success stories at local scales from which fundamental lessons could be drawn on how local populations have remained resilient against multi-faceted socio-ecological challenges, including population growth and diminishing natural resources. Millions of the world's population remain dependent on food systems anchored on agricultural production schemes outside the realms of classical Green Revolution approaches. This raises the question, *what is so unique in today's global fears about feeding the world's growing population?* Or alternatively, *why is food and nutrition insecurity still a major global concern with all the positive impacts and lessons of the Green Revolution and/or industrial agriculture*? While these queries may raise other critical and more compelling questions, they also point towards the broader problems of today's failing food systems, as well as the shortcomings of current agricultural production models in supporting resilient and sustainable livelihood systems. This chapter recognizes that current global concerns are justified by the enormity of the challenges of addressing food and nutrition insecurity and increasing agricultural production, particularly in developing countries. These challenges take place in the context of a ballooning global demand for food, feed and fibre, declining natural resources and climate change-induced impacts on production. We argue that the underlying problem rests with the limitations and narrowness of conventional agricultural production approaches that are premised on the technologies, institutions and policies of the Green Revolution. Conventional approaches to agricultural production have compromised opportunities to exploit ecological processes. Amidst the overall challenges of food insecurity, these ecological processes support the survival of some of the world's poorest populations, particularly those in sub-Saharan Africa.

Africa presents a paradox of hungry and malnourished farming families. The continent continues to be a global hotspot for food and nutrition insecurity and is home to some of the world's poorest populations. Food aid has virtually become a perennial feature, particularly in sub-Saharan Africa. More critically, in contrast to other continents, agricultural productivity in Africa has continued to decline (van Ittersum *et al.*, 2013). This has been primarily attributed to poor and diminishing soil fertility and farmers' lack of access to mineral fertilizers, good quality seeds and markets, within the context of climate variability and change. Africa has some of the world's oldest soils, which are characterized by poor fertility and are prone to wind and water erosion (World Soil Resource Base, 1998; Lal, 2007). The majority of sub-Saharan Africa's predominantly smallholder farmers have failed to apply Green Revolution-based agronomic practices (e.g. external inputs) or soil conservation measures, resulting in widespread nutrient mining and deterioration of soil/land quality. Research and extension have traditionally responded by 'pushing' agronomic technical solutions through blanket recommendations, which have often ignored indigenous/local knowledge and experiences. However, recent studies have shown that farming systems and conditions in Africa are too diverse and heterogeneous for any one size fits all, silver bullet solution (Tittonell *et al.*, 2010; Giller *et al.*, 2011). Therefore, context-specific solutions (e.g. indigenous mixed cropping, agroforestry systems) are required to support sustainable agricultural production systems that meet local food, nutrition and livelihood needs for otherwise vulnerable communities.

In the wake of mounting poverty and threats to food and nutrition security, reports of poor adoption of new or improved conventional agricultural production technologies are commonplace in Africa, particularly in sub-humid to semi-arid agroecological zones (Knowler and Bradshaw, 2007). Several reasons have been cited for the lack of adoption, including poor extension approaches, lack of capacity/resources, and economic and social risks (e.g. Mekuria and Siziba, 2003; Marenya and Barrett, 2007; Ajayi *et al.*, 2007). However, little is currently known about the negative consequences/costs of failed interventions and/or technologies, such

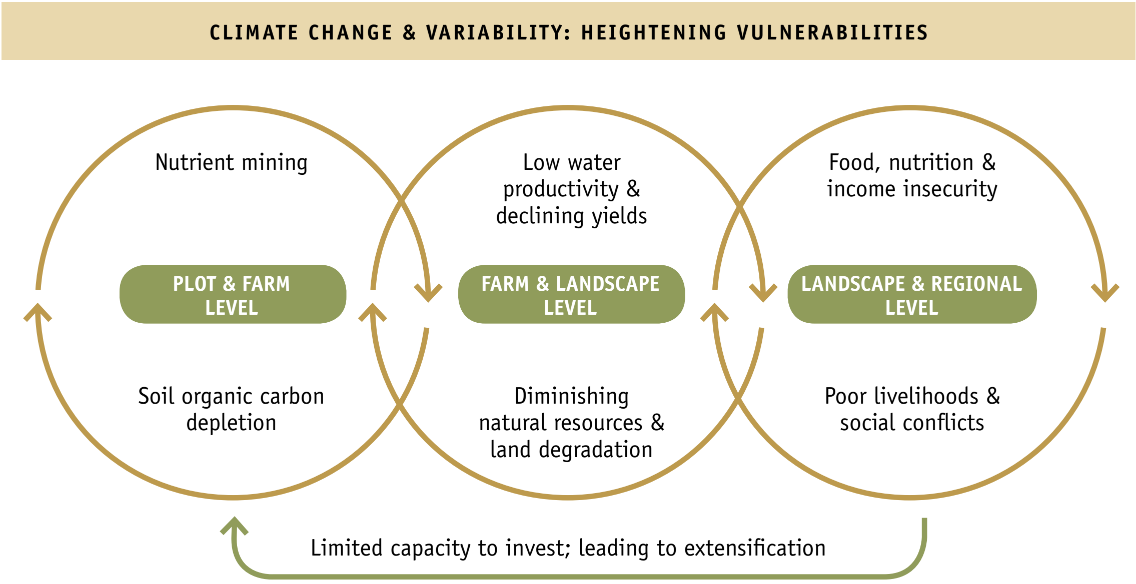
as the possible disruption of existing production and food systems. Because of its projected negative impacts on smallholder farming families and communities in Africa, climate change and variability now provides a new lens for assessing agriculture on the continent (e.g. IPCC, 2014). There are already increasing calls for the transformation of smallholder agricultural systems in Africa to make them more inclusive, resilient and sustainably productive (FAO, 2013). However, what has remained unclear is the 'how' part and its empirical basis. Drawing from experiences of the Soil Fertility Consortium for Southern Africa (SOFECSA), hosted by the University of Zimbabwe, this chapter seeks to show how an initial focus on addressing poor soil productivity through agroecological principles can open new opportunities for converting multilevel vicious cycles into virtuous cycles on smallholder farms.

FAILING CONVENTIONAL AGRICULTURE, VICIOUS CYCLES AND MULTIPLE POVERTY TRAPS

Research and development efforts driven by top-down extension approaches have promoted monocultures of a narrow range of food and cash crops in African smallholder farming systems. In southern Africa, these crops include maize, tobacco, cotton, soya bean and groundnut, as well as plantation tree crops such as tea. Monocropping was favoured because of its compatibility with diverse tillage operations, the use of chemicals for disease and pest control and mechanized crop harvesting, among other agronomic practices. The major consequences of these conventional agronomic approaches were the removal or exclusion of trees from croplands and a shift away from mixed cropping systems that had previously supported agrobiodiversity and household nutrition. This process disrupted the tight nutrient cycles that account for productivity of the *miombo* ecosystems from which most farming systems in southern Africa and parts of east Africa are derived (Swift *et al.*, 1989; Mapfumo and Mtambanengwe, 1999). An aggravating factor is that current conventional agricultural production systems are based on the premise of sustained use of external inputs, a requirement that has not been fulfilled in practice, primarily due to market failures and lack of access to productive resources by farmers. A major consequence of these processes has been a downward spiral in soil fertility due to nutrient mining (e.g. Smaling *et al.*, 1993; 1997), declining crop productivity, chronic food insecurity and widespread malnutrition (van Ittersum *et al.*, 2013). In turn, this has led to self-reinforcing mechanisms of land degradation and low productivity, as farmers are often preoccupied with the objective of achieving household food self-sufficiency (Mapfumo, 2009; Nyikahadzoi *et al.*, 2012) and therefore fail to invest in new technologies and innovations. In this situation, smallholders often focus primarily on short-term gains such as the production of staple maize through extensification approaches and encroaching into fragile and marginal areas, trapping farming households into multiple vicious cycles as yields continue to diminish (see Figure 1).

Maize occupies about 60-80 percent of cropped land area in any single cropping season in southern Africa (Aquino *et al.*, 2001; Smale and Jayne, 2003) and there are no established mechanisms to help these smallholder communities escape the *maize poverty trap*. For different socio-economic reasons, farmers continue to grow maize even with clear evidence that the crop fails especially under increased climate variability and limited access to nutrient inputs

Figure 1. **Schematic presentation of the interconnected vicious cycles driven by declining soil productivity and how they affect agricultural productivity and livelihoods in the face of climate change and variability**



(e.g. Mapfumo, 2011; Rurinda *et al.*, 2014). The focus on maize has also taken research and development attention away from other diverse crops and alternative production systems that may contribute to farmers' food security and livelihood objectives better than maize. There is no doubt that these challenges have effectively rendered maize as 'the problem'. These underlying factors show that declining soil fertility is central to the current and emerging vulnerabilities of rural communities to food and nutrition insecurity (Figure 1) and indicate the need for a change of paradigm in developing sustainable agricultural production systems.

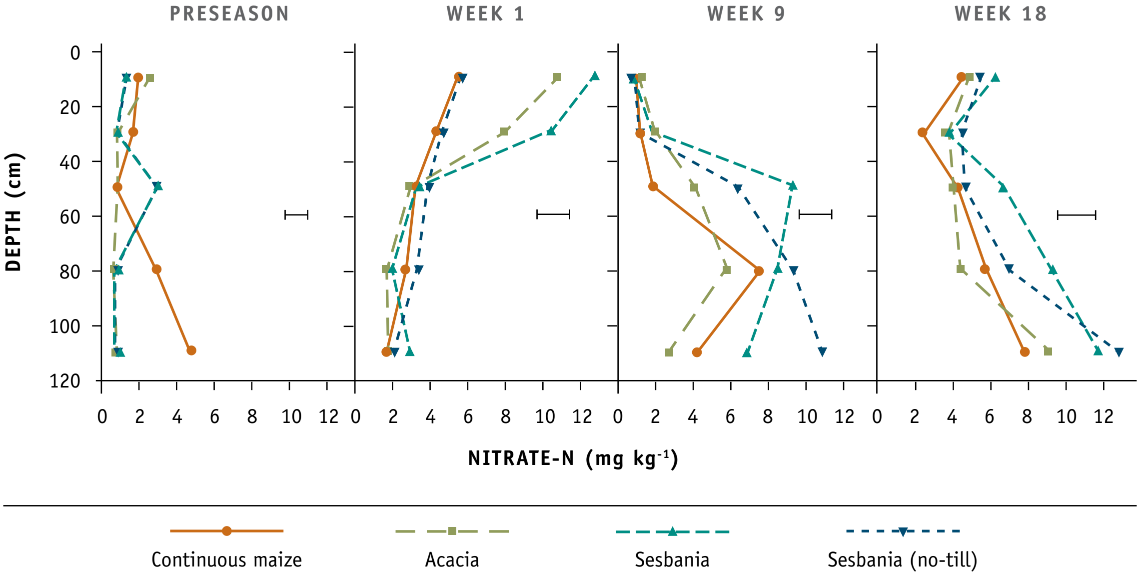
LESS OBVIOUS LINKS BETWEEN SOIL BIOGEOCHEMICAL PROCESSES AND POVERTY TRAPS

Poor and declining soil fertility has long been identified as the biophysical root cause for declining agricultural productivity in sub-Saharan Africa (Sanchez *et al.*, 1997). Although this has helped to create awareness among various stakeholders, including policy-makers and development partners at the national and global levels, about the importance of soil management in sustainable development (e.g. establishment of SOFECSA, the Tropical Soil Biology and Fertility Programme and the World Bank Soil Fertility Initiative), there are still critical knowledge gaps at the farmer level. Limited undertakings have been made to translate the experiences and findings of soil fertility research into the 'common' knowledge domain. The links between poor soil productivity and diminishing ecosystem services and socio-ecological problems are therefore often not recognized by farmers, development practitioners and policy-makers at the local level (Mapfumo *et al.*, 2013). For example, nutrient transfers between crop and livestock sub-systems (Giller *et al.*, 2011), nutrient resource subsidies from natural woodlands and grasslands supporting crop production, and depletion of soil carbon stocks and water resources in cultivated wetlands (Mtambanengwe and Mapfumo, 2008; Chagumaira *et al.*, 2015) have received little attention. Emerging evidence from research on climate change adaptation in Africa has revealed increased dependence on non-timber forest and rangeland products (NTFPs) for food (energy and protein) despite their decline due to climatic stress and excessive extraction (Woittiez *et al.*, 2013; Chagumaira *et al.*, 2015). However, no major investments have been made to promote component interactions that enhance the productivity of these systems and particularly in reinforcing nutrient cycles and empowering communities to conserve these resources. The only exception has been the efforts of the World Agroforestry Centre (Akinnifesi *et al.*, 2008).

UNDERSTANDING VICIOUS NUTRIENT CYCLES AND THEIR IMPLICATIONS UNDER CONVENTIONAL AGRICULTURE

Drawing examples from granite-derived coarse sandy soils in southern Africa, which present some of the most nutrient depleted and challenging agricultural soils on the continent, it is apparent that extraordinary innovations in soil fertility management are necessary to maintain or improve productivity. In these sandy soils, leaching is the most important nutrient loss pathway, particularly for nitrogen, which is lost very early in the growing season before crops such as maize have developed a sufficiently extensive rooting system (Figure 2; Chikowo *et al.*, 2003). Figure 2 shows that deep-rooted crops such as tree crops increase the capture of

Figure 2. **Nitrate-N measured at different soil depths in various maize cropping systems on a sandy clay soil in Zimbabwe**



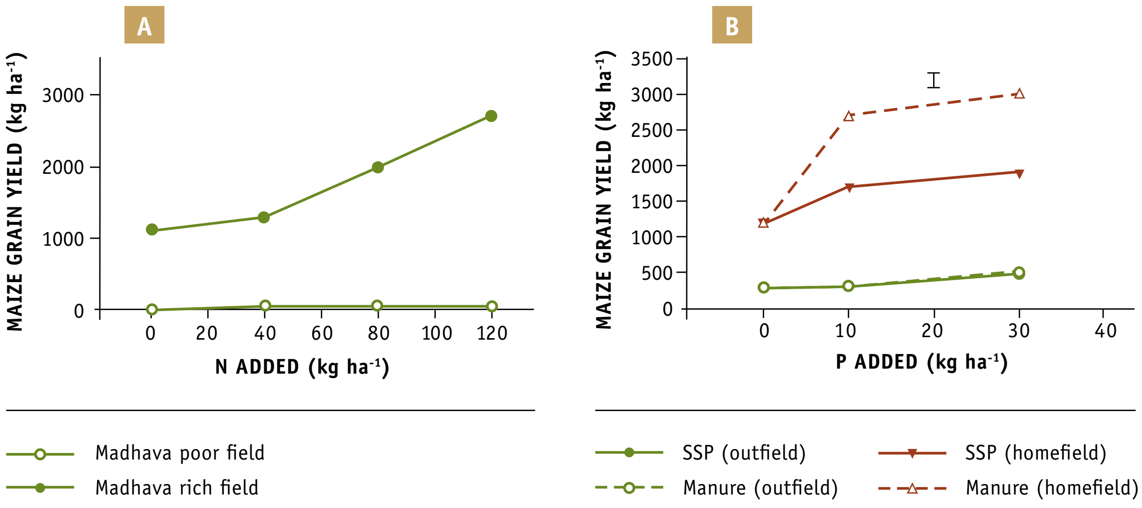
Source: Chikowo *et al.*, 2003

nutrients that would otherwise be leached. In contrast, cereal-based monocropping systems and non-systematic rotational systems are unlikely to result in efficient nutrient cycling options that are sufficient to improve productivity and increase returns to farmers' fertilizer investments.

Based on SOFECSA's research experience, soil organic matter (SOM) remains the single major determinant of nutrient-use efficiency on sandy soils. Soils with a soil organic carbon (SOC) content of less than 0.46 percent could not support any significant grain yield responses to nitrogen fertilization (Figure 3A) and the productivity gains following phosphorus fertilization were also limited (Figure 3B). Such soils have often been abandoned by farmers (Mapfumo *et al.*, 2005; Nezomba *et al.*, 2010) and can be classified as part of the groups of soils increasingly categorised as 'non-responsive' to fertilization under smallholder agriculture (Rowe *et al.*, 2006; Kamanga *et al.*, 2014; Chikowo *et al.*, 2014). When SOC levels are above 0.46 percent, use of traditional organic matter sources such as cattle manure and crop residues has often resulted in significant yield responses, while responses to the application of mineral fertilizer alone were most significant when SOC was greater than 0.65 percent (Figure 3; Mapfumo *et al.*, 2006; Kurwakumire *et al.*, 2014). These findings highlight the importance of organic matter management in influencing fertilizer-use efficiency, with critical implications for the fertilizer support programmes spearheaded by many governments, NGOs and development partners in the region. However, the major challenge is how to generate sufficient biomass on these nutrient-depleted and coarse-textured soils in order to increase SOC.

Research evidence has shown that relatively large amounts of organic matter inputs are required to achieve significant SOC increments, although there seems to be no additional benefits of application rates greater than 10 tonnes ha^{-1} on a dry matter basis (Mapfumo *et al.*, 2007). This is largely due to the poor capacity of sandy soils to physically protect the added carbon from microbial attack (Six *et al.*, 2002; Mtambanengwe and Mapfumo, 2008). On the

Figure 3. **Maize grain yield response to N and P application on sandy soils**

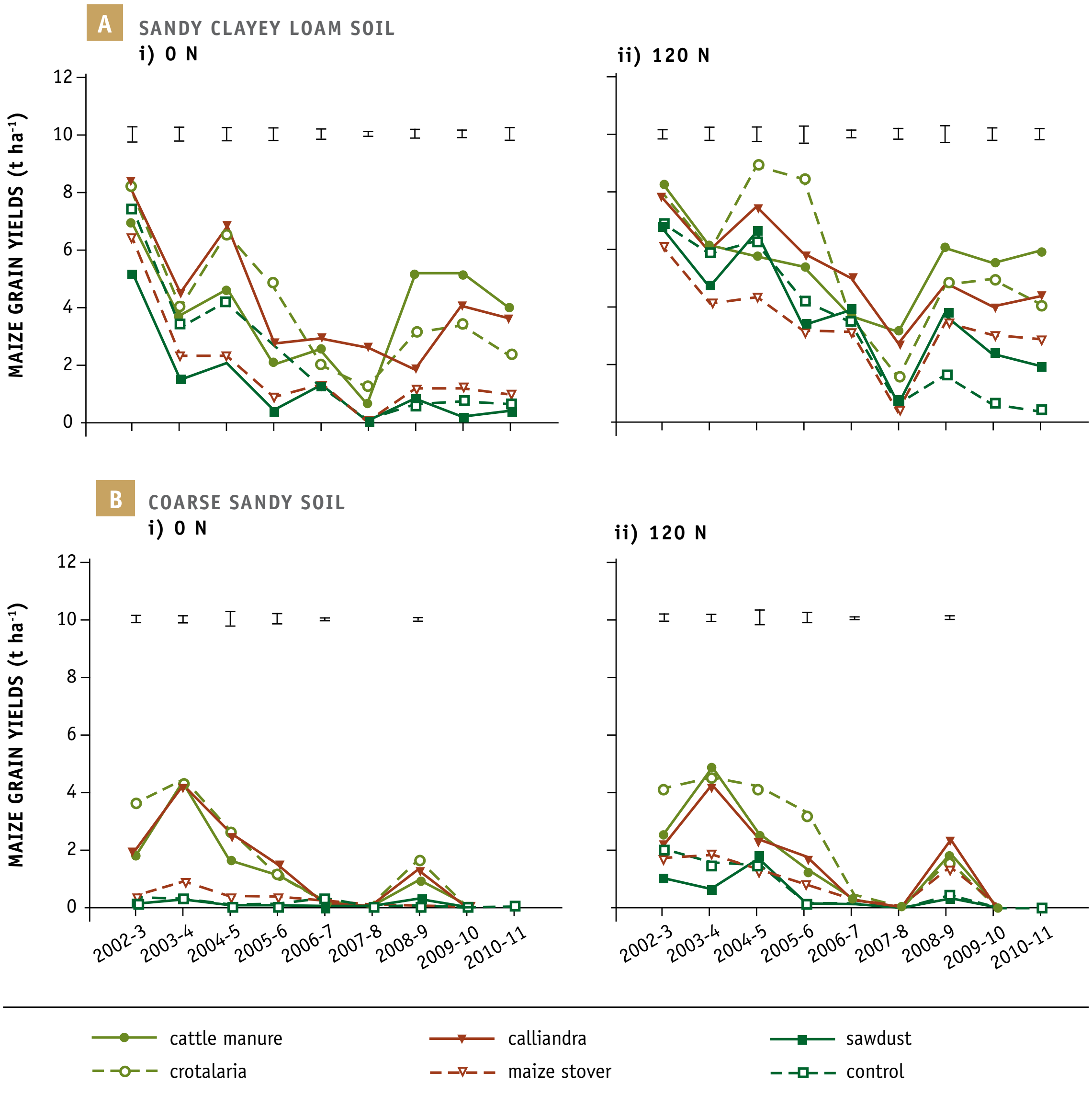


(**A**) Maize grain response to low (farmer Madhava's designated 'poor field' = 0.46% C) and moderate (designated 'rich field' = 0.65% C) soil organic carbon on a sandy soil in Zimbabwe; (**B**) Maize grain yield response to application of 100 kg N ha^{-1}, manure and single super phosphate (SSP) on a sandy soil.

Sources: Mapfumo and Mtambanengwe, 2006; Zingore *et al.*, 2007

other hand, most of the fields that are abandoned by farmers due to poor soil productivity often generate less than 3 tonnes ha^{-1} of dry matter even after more than two seasons of natural fallowing (Mapfumo *et al.*, 2005). This is consistent with small amounts of less than 1.5 tonnes ha^{-1} of dry matter of crop residue biomass that were measured in most of the farmers' fields (Mtambanengwe and Mapfumo, 2005), suggesting that current conventional production systems will fall short in arresting the downward spiral in SOC and hence productivity. Recent evidence from a long-term experiment in which low (1.2 tonnes C ha^{-1}) and high (4 tonnes C ha^{-1}) rates of different quality organic resources were repeatedly applied to both course sandy and sandy clay loam soils and monocropped with maize (Mapfumo *et al.*, 2007), showed a continued yield decline over nine years despite addition of NPK fertilizer on an annual basis (Figure 4). In part,

Figure 4. **Maize yield patterns following nine seasons of monocropping with and without N fertilization under different organic resource applications on soils of different texture**



Source: data from UZ-SOFECSA long-term experiment the long-term yield decline under maize monocropping was attributed to the loss of multiple other nutrients such as magnesium and calcium, as well as micronutrients such as zinc, which are not supplied in the common mineral fertilizers that are available to farmers (e.g. Manzeke *et al.*, 2014). This further explains why limited access to biomass is a major threat to sustainable cropping, particularly under low and variable rainfall conditions.

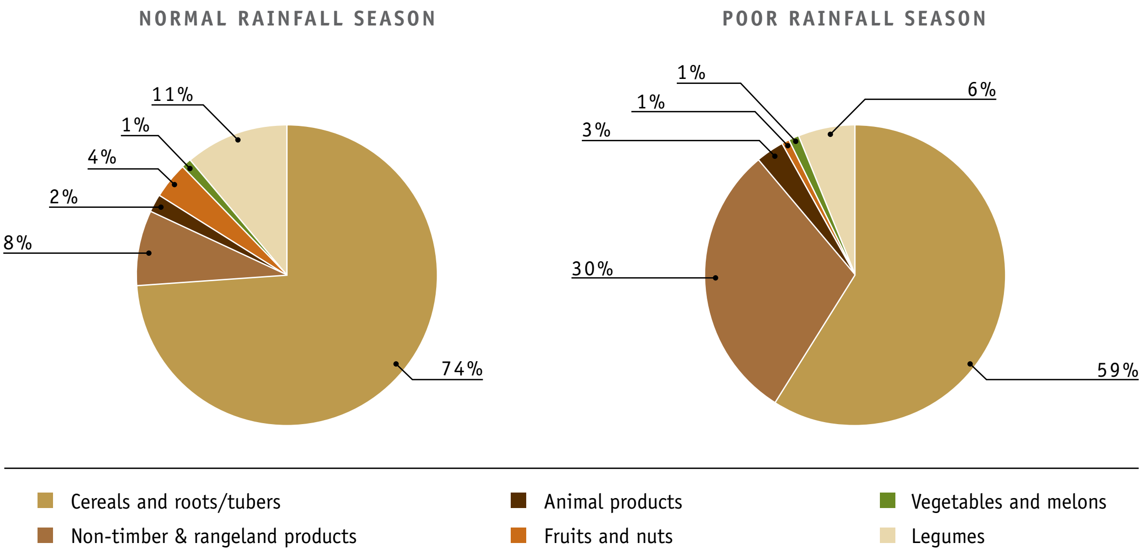
In southern Africa, as in other semi-arid to sub-humid regions in east and west Africa, farming systems are characterized by strong crop-livestock interactions. The competition for crop residues and other forms of plant biomass between livestock and soil/water management exerts significant pressure on the development of sustainable agronomic techniques. Although increased demand for staple crops has progressively threatened livestock production, emerging studies on climate change adaptation have also revealed that integrated crop-livestock systems are likely to enhance the capacity of African smallholders to adapt to climate change and variability (Chilonda *et al.*, 2007; Thornton *et al.*, 2007; Mapfumo *et al.*, 2014).

LOSS OF RESILIENCE AS THE NATURAL RESOURCE BASE DIMINISHES

It is common in most African countries that the responsibilities for agriculture and environment/natural resources are held by separate government ministries, reflecting the prevailing conception of agriculture. However, there is strong and growing evidence of intricate interdependencies between agriculture (crop/livestock), fisheries and forestry systems, particularly for smallholder communities who face increasing pressures associated with climate change and variability (IPCC, 2014; Mapfumo *et al.*, 2014). Smallholder farming communities have continued to rely on their immediate natural ecosystems to provide: subsidies to their agricultural production systems; safety nets against climate-induced failures in agricultural seasons and/or institutional support services; and supplementary food and nutrition for resource-constrained (poorer) households who often face perennial deficits. Many past studies have characterized and quantified some of the contributions of the natural ecosystems to the livelihoods of local communities (e.g. Nyathi and Campbell, 1993; Campbell, 1996; Shackleton and Shackleton, 2004). These and other studies clearly indicate the critical role of specific ecosystems and natural resource regimes in enhancing the resilience of livelihood systems and alleviating poverty in some communities (Cavendish, 2000; Shackleton and Gumbo, 2010). However, a glaring revelation from these research studies is the lack of focus on developing approaches that integrate the management of these valuable natural resources into agricultural production systems within and across different agroecologies.

Furthermore, recent studies reveal that despite concerted efforts to achieve agricultural growth in Africa, many smallholder communities are paradoxically increasing their dependence on natural ecosystems in order to adapt to current and emerging threats of climate change and variability (Woittiez *et al.*, 2013; Chagumaira *et al.*, 2015). Woittiez *et al.*, (2013) identified 27 different types of NTFPs that smallholder communities commonly depend on. They showed that poorer households derive 40 percent of their energy uptake from these resources during poor rainfall seasons. Overall, the contribution of NTFPs to household energy intake increased three times during drought years (Figure 5). Chagumaira *et al.*, (2015) provide further evidence to suggest that, in response to increased climate variability, food baskets and income sources for both wealthier and resource-constrained smallholder households are increasingly shaped by availability and access to common natural resource pools that provide different NTFPs. While wealthier households were found to harvest NTFPs mainly to complement their food needs, the resource-constrained households gathered significant quantities for both consumption and marketing to generate income (Chagumaira *et al.*, 2015). Evidently, at the local level, farming systems are inevitably moving away from the defining principles of conventional agriculture due to climate risks and other multiple stress factors, yet development policies are still premised on the conventional agriculture paradigm. These findings suggest a need to embrace agroecological approaches in the current quest for transformation of African agriculture towards more resilient production and livelihood systems.

Figure 5. **Source of energy consumption as a percentage of total intake per person per year by smallholder farming communities as influenced by rainfall variability under a changing climate in Hwedza District, Zimbabwe**



Source: adapted from Woittiez *et al.*, 2013

TOWARDS THE CREATION OF VIRTUOUS CYCLES:
FROM NUTRIENT CYCLES TO SOCIO-ECOLOGICAL PROCESSES

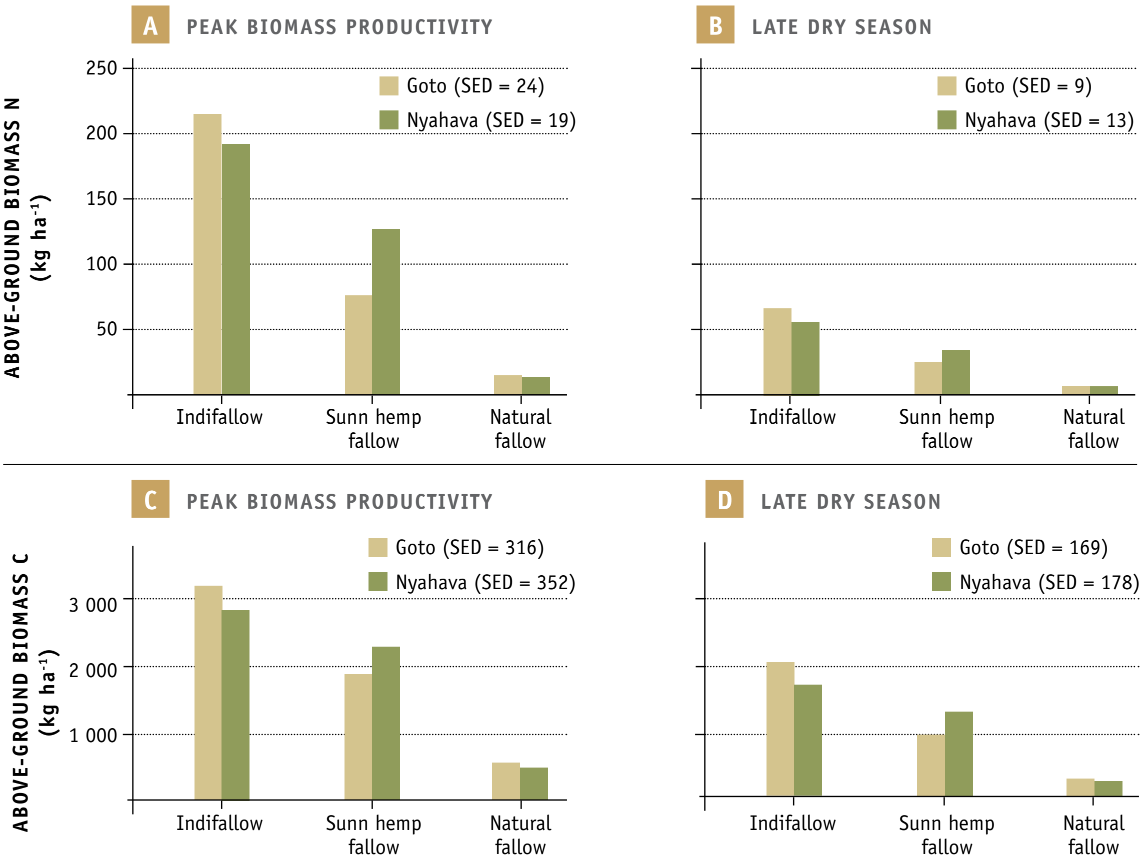
It is apparent that any transformation of African agriculture towards more productive, resilient and sustainable food systems will not only require a high level of novelty, but also systematic and integrated approaches that link ecological to socio-economic processes. To contribute towards the development of such approaches, SOFECSA first sought to break the vicious nutrient cycles that existed by focusing on mechanisms for restoring and sustaining soil productivity. Building more responsive soils to fertilization and water use is considered a key entry point to the creation of virtuous socio-ecological cycles, as opportunities emerge for communities to configure new production processes for sustainable food systems.

Harnessing ecological processes to restore soil productivity

Natural fallowing has traditionally been used as a key method of soil fertility restoration in Africa and many other parts of the world. However, increasing population pressure and diminishing agricultural land resources have rendered the method inappropriate as farmers are compelled to continuously cultivate the same pieces of land to meet the growing demand for food, feed and fibre (e.g. Garrity *et al*., 2013). Of critical concern over the past decades has been the growing evidence of croplands being abandoned by African smallholder farmers due to diminishing productivity and degradation in the context of poor access to fertilizers and scarcity of external organic nutrient inputs (Mapfumo *et al*., 2005; Tittonell *et al*., 2005; Nezomba *et al*., 2010; Manzungu and Mtali, 2012). Despite shrinking farm sizes, it is apparent that farmers are increasingly fallowing land not as a strategic land-use option to restore productivity, but as a desperate measure to reduce the risk of losing fertilizer and labour investments. Therefore, finding mechanisms to restore these croplands is critically important, as continued loss of the increasingly limited land available to farmers poses a major threat to food security.

Observations from farmers' abandoned fallow fields across three different agroecological zones in Zimbabwe revealed isolated and irregularly distributed yet healthy stands of herbaceous leguminous species (Mapfumo *et al*., 2005). An exploratory ecological study of these legume plants by Mapfumo *et al*. (2005) revealed their exceptional capacity to nodulate with indigenous nitrogen-fixing rhizobia (*Rhizobium* spp.) and to grow on sandy soils (5-20 percent clay) characterized by low levels of nitrogen and phosphorus. Farmer participatory research methods were employed to enable joint identification, seed harvesting and collection with local communities in the respective study areas. Up to 37 different species were identified across the three agroecological zones and detailed studies were undertaken on species population dynamics (Tauro *et al*., 2009; 2010) and characterization of chemical quality and nutrient release patterns of the resultant plant biomass. This enabled the design of interventions that involved the field establishment of mixed stands of predominant legume species collected from the respective agroecologies, eventually leading to a new concept of 'indifallows' (indigenous legume fallows) (Mapfumo *et al*., 2005; Nezomba *et al*., 2010). Dominant indifallow species included *Crotalaria*, *Tephrosia*, *Indigofera*, *Rothia*, *Zornia* and *Chamaecrista*. Moreover, these species were not palatable to livestock. A major success of the indifallows was their capacity to generate nitrogen-rich biomass in amounts that were at least five times greater than what was generated under natural fallow. The indifallows surpassed the performance of sunn hemp (*Crotalaria juncea*) -based green manure as the next best option available to farmers (Figure 6). The capacity of farmers to identify the legume species using local knowledge enabled them to collect seeds and contribute to the debate on how the indifallows should be established (Mapfumo *et al*., 2005). Rotational benefits to subsequent crops in rotational sequences were modest but highly significant (Nezomba *et al*., 2010). The indifallow was therefore considered a potential entry point for kick-starting the productivity of soils on farmers' nutrient-depleted fields and was used in SOFECSA initiatives. The successful performance of indifallows has implications for the development of technical options to generate biomass and enhance organic matter management in agriculture.

Figure 6. **Biomass productivity and amount of N generated under indigenous legume fallows (indifallows) in comparison with natural fallow and sunn hemp green manure in the Goto and Nyahava smallholder areas of eastern Zimbabwe**



Source: Nezomba *et al.*, 2010

Kick-starting the soils: Sequencing integrated soils fertility management options

Continuous monocropping of most soils in Africa has resulted in a downward spiral in soil fertility and crop productivity due to chronic nutrient mining. This is one of the major causes of land degradation and an underlying source of food and nutrition insecurity. SOFECSA has responded by advancing a concept of sequencing ISFM options to restore and maintain the productivity of nutrient-depleted soils. The concept is premised on the following observations:

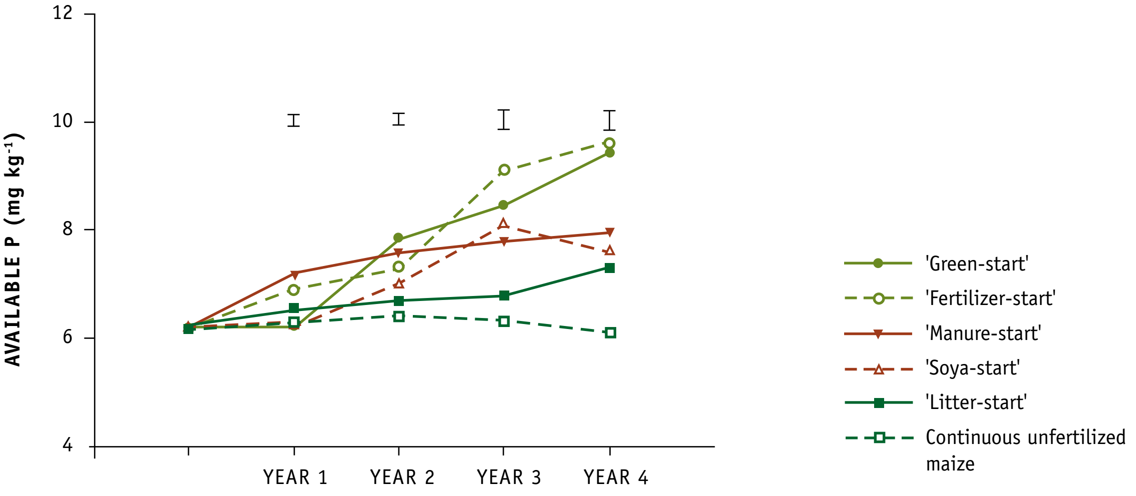
- Soils in fields abandoned by farmers due to a lack of productivity and poor response to normal fertilization are primarily constrained by deteriorating chemical and biological properties arising from diminishing nutrient stocks and SOM depletion;
- A combination of locally adaptable legume species and phosphorus fertilization will stimulate soil biological activity, which if followed by a sequence of appropriate organic-inorganic fertilization regimes, can lead to sustained productivity;

- Farmers of different resource endowments have access to different nutrient resources and will therefore depend on different ISFM sequences (entry points) to restore the fertility of their soils to levels where the use of fertilizers becomes sustainable;
- Appropriate sequencing of ISFM technology options that involve multiple nutrient sources results in incremental gains in soil nutrient stocks and SOM, leading to an improved capacity to restore productivity.

ISFM sequencing studies were conducted over four years involving organic resources, nitrogen-fixing legumes and mineral fertilizers (Nezomba *et al.*, 2015a). Organic resources that are commonly available to farmers were used, primarily cattle manure, woodland litter and crop residues, while the legumes included grain, green manure and the indigenous species. Different treatments were used to start the ISFM sequences during the first year of intervention: green manure legume (Green-start), soya bean grain legume (Soya-start), indifallow (Indifallow-start), recommended fertilizer rate (Fertilizer-start), cattle manure (Manure-start) and woodland leaf litter (Litter-start). In subsequent seasons these first season treatments were followed by different combinations of organic inputs and varying rates of fertilizer, particularly phosphorus (Nezomba *et al.*, 2015a; 2015b). The sequences exhibited incremental benefits in calorific and protein production and after four years there was a clear separation in the amount of soil phosphorus buildup under the different sequencing treatments (Figure 7). Green manure plots and those receiving the recommended mineral fertilizer rates resulted in the highest phosphorus accumulation after four seasons of cropping under the sequences. The sequences also provided benefits to maize grain yield, which were three to ten times greater than the unfertilized control (Nezomba *et al.*, 2015a).

After the soil restoration phase lasting four years through the ISFM sequences, there were positive changes in maize yield responses to different nitrogen fertilization rates and improvements in grain legume productivity. The largest maize gain yield response to nitrogen application was after the indifallow (Indifallow-start) and sunn hemp green manure (Green-

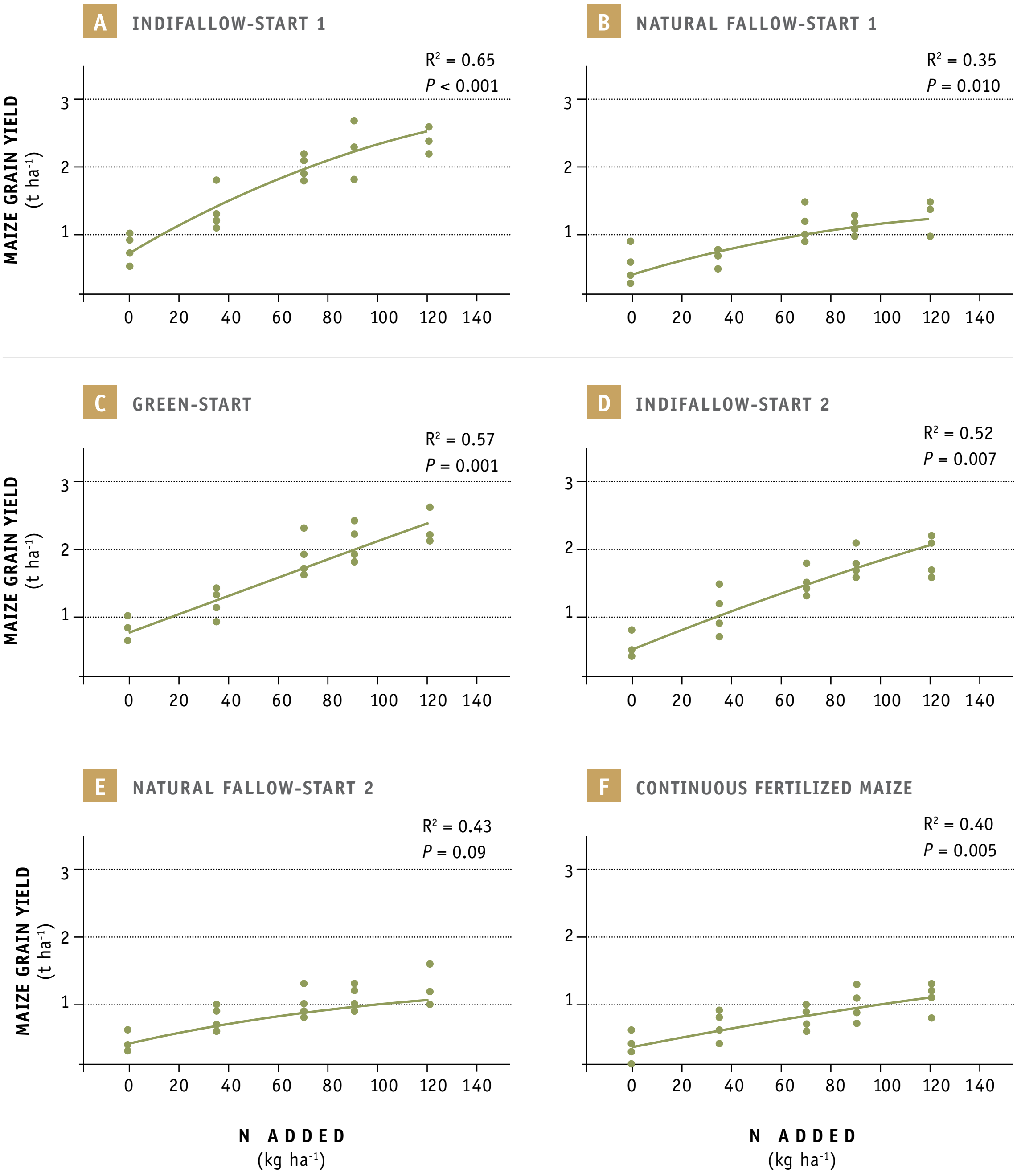
Figure 7. **Plant available P accumulated in sandy soils after four years of ISFM sequences under smallholder farming conditions in Zimbabwe**



Source: Nezomba *et al.*, 2015b

start) -based sequences (Figure 8). These sequences were clearly superior to continuous fertilized maize and natural fallows, resulting in maximum yields of more than 2 tonnes ha^{-1} compared with about 1 tonnes ha^{-1} under the latter. The poor fertilizer responses under continuous fertilized maize and natural fallows confirmed the responses that farmers commonly achieve under their current practices.

Figure 8. **Maize grain yield response to N fertilizer following four seasons of different ISFM sequences on a sandy soil in eastern Zimbabwe**



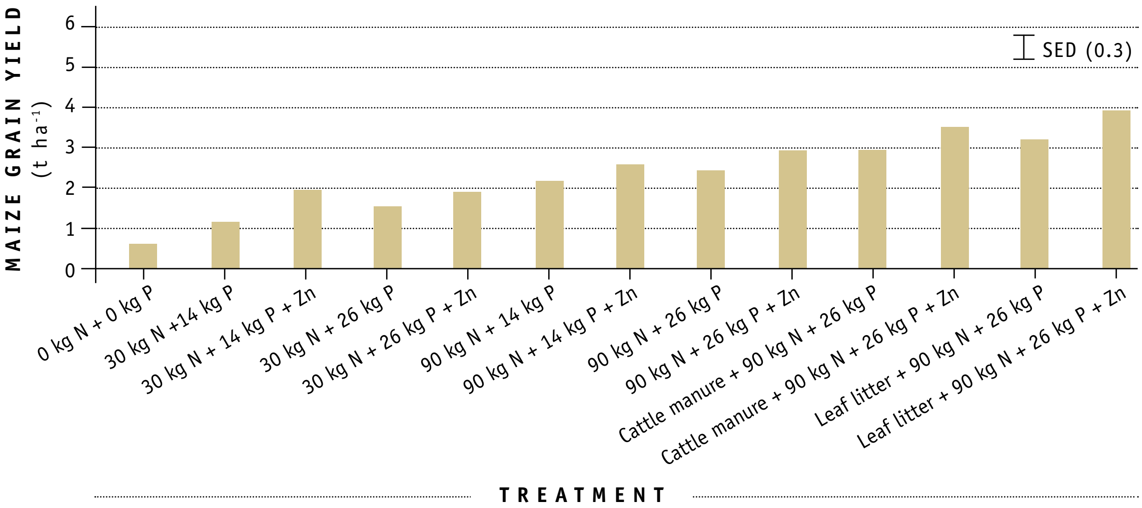
Source: Nezomba *et al.*, 2015a

Addressing multiple nutrient deficiencies

While the sequencing of ISFM options, anchored on use of indigenous legumes, evidently led to significant yield benefits for both legumes and staple maize (Nezomba *et al.*, 2015b), there were also indications of multiple nutrient deficiencies that could not be addressed without additional fertilizer formulations. Current fertilization regimes and agronomic management practices have tended to focus on a narrow range of macronutrient elements, particularly nitrogen, phosphorus and potassium, and to some extent calcium (in lime) and sulphur. However, plant nutrition studies have increasingly shown the differential impacts of nutrient mining on soil micronutrient status. Recent studies have revealed highly compromised grain quality of staple cereals in southern Africa due to micronutrient deficiencies of zinc, selenium, iron and iodine. This has considerable negative effects on human health including impaired growth and cognition mainly in children, susceptibility to diarrheal infections, pneumonia and impaired immunological function and malnutrition (Chilimba *et al.*, 2012; Manzeke *et al.*, 2012; Joy *et al.*, 2014).

It appears that micronutrient deficiencies set a silent yield barrier for crops in agricultural systems. There is increasing evidence to suggest that the other yield benefits of using organic nutrient resources arise from the multiple nutrients released upon mineralization of these resources. Livestock manure and woodland leaf litter provided typical examples in the SOFECSA case (Manzeke *et al.*, 2014). However, significant yield gains were still obtained following combined application of zinc fertilizer with manure or woodland litter and NPK fertilizer (Figure 9). This combination increased the maize grain yields by more than 35 percent and more importantly improved the grain zinc content and hence nutritional quality (Manzeke *et al.*, 2012). These findings are confirmed in a related study by Rusinamhodzi *et al.*, (2013) who found incremental maize yield responses to combinations of liming and sulphur, zinc and manganese fertilizer formulations after addition of manure and nitrogen.

Figure 9. **Added yield benefits of zinc fertilization on maize yields under smallholder farming conditions on sandy soils in Zimbabwe**



Source: Manzeke *et al.*, 2014

THE LEARNING CENTRE AS A VEHICLE FOR PROMOTING ADAPTATION AND ADOPTION:

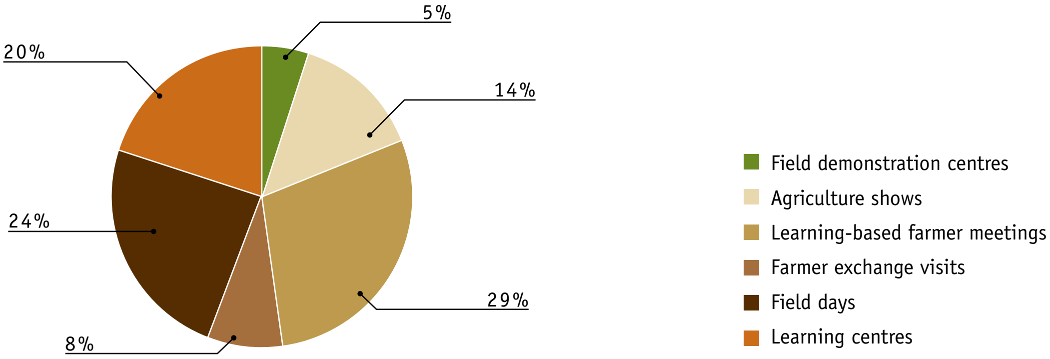
IMPLICATIONS FOR AGROECOLOGY

The scaling up of technologies and practices associated with the management and conservation of natural resources has always presented a challenge in Africa due to a general lack of adoption among beneficiary groups (e.g. Ajayi *et al.*, 2007). For example, technological packages such as ISFM, conservation agriculture and agroforestry have experienced limited adoption in Africa despite evidence of their technical soundness and potential benefits (Mekuria and Siziba, 2003; Mugwe *et al.*, 2009; Corbeels *et al.*, 2014). These and numerous other research findings have revealed inadequacies of current extension methods and approaches, which have largely been designed in the context of conventional agriculture. Against this background and experiences of limited adoption of technical packages, SOFECSA developed a field-based farmer *Learning Centre* concept. The approach was tested, particularly in the Hwedza and Makoni districts of eastern Zimbabwe and to a lesser extent in central and southern Malawi and Manica Province of Mozambique. The major focus of this emerging concept is to create an environment for co-learning and co-innovation with farmers, extension workers and diverse agro-service providers including researchers (Mapfumo *et al.*, 2013). A Learning Centre is defined as a field-based interactive platform for integrating local, conventional and emerging knowledge on superior agricultural technologies, practices or innovations requiring farm-level adaptive testing for wider promotion to address complex problems. Learning Centres include three main components: (i) a farmer learning alliance; (ii) a field for participatory evaluation and/or adaptation of prioritized technical options; and (iii) a research/technical support team. The Learning Centre concept is based on the following premises:

- The information and knowledge flows that take place between the participants of agricultural technology development, evaluation and adaptation processes (which influence adoption) are non-linear and dependent on interactive feedback processes;
- Current extension approaches offer limited opportunities for the integration of conventional scientific knowledge and indigenous/local knowledge and processes in ways that promote effective learning and innovation;
- Equipping farmers and local communities with principles and concepts relating to relevant technologies through learning-based processes will enable them to come up with context-specific solutions.

Within the study areas, implementation of the Learning Centre concept significantly changed approaches to information and knowledge sharing as well as patterns of interactions between researchers, extension agents (public and private) and farmers. The increased information and knowledge exchange, as well as the inclusive participation of different categories of farmers including women (Mapfumo *et al.*, 2013; Mashavave *et al.*, 2013), added a new dimension to farmer learning processes and defined new learning platforms at the community/local level (Figure 10).

Figure 10. **Farmers' preferences for different agricultural information and knowledge sharing platforms in Hwedza District, Zimbabwe**



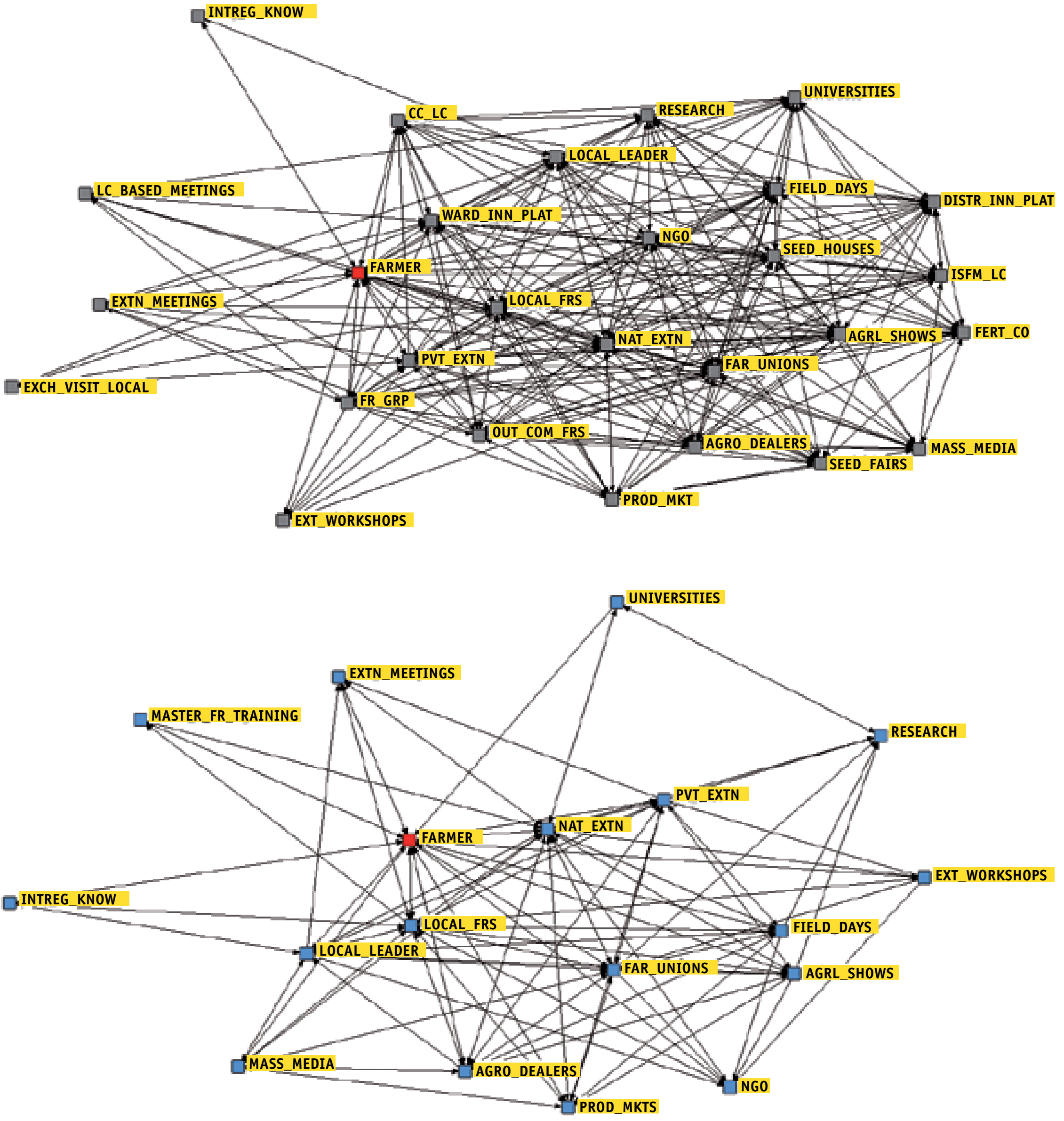
Source: Gwandu *et al.*, 2014

The open and dynamic composition of the learning alliance allowed for enhanced interactions between different stakeholders. When the farmer learning alliances were linked to innovation platforms championed by the national extension agency at district level, the intensity and extent of interactions between farmers and different stakeholders were enhanced (Figure 11). As a consequence, Learning Centres can be used as entry points for addressing socio-ecological problems as farmers gain the capacity to self-mobilize and self-organize to address local problems and articulate demand for specific services from relevant actors/stakeholders.

SOFECSA's interventions involving the implementation of Learning Centres experienced reasonable success in improving productivity and food self-sufficiency among participating farmers (Nyikahadzoi *et al.*, 2012; Mapfumo *et al.*, 2013). The successes of Learning Centres were mainly attributed to:

- Building on local knowledge and strengthening local institutions to support learning processes;
- Equipping farmers and actors with principles rather than prescriptions;
- Embracing a systems approach that attracted the participation of interdisciplinary and multi-institutional actors;
- Promoting context-specificity and best-fit solutions through targeting of agroecologies and socio-economic groups (e.g. farmer resource endowment categories);
- Incorporating the lessons learned and farmers' feedback into future principles that were given back to communities through training and further learning.

Figure 11. **Interactions between farmers and different stakeholders with (top) and without (bottom) the existence of Learning Centres coupled to district innovation platforms in Makoni, Zimbabwe**



Key: Information access and sharing pathways identified for farmers in Chinyika East, Makoni District, Zimbabwe

INFORMATION SOURCES

AGRO_DEALERS: suppliers of agricultural inputs
DIST_INN_PLAT: district innovation platform
FARMERS: farmer's own farming experience
FERT_CO: fertilizer companies
FR_GRP: local farmer groups
FR_UNIONS: farmer unions
INTREG_KNOW: intergenerational knowledge
LOCAL_FRS: farmers within the community
LOCAL_LEADER: authoritative figures in the community
MASS_MEDIA: mass media

MASTER_FR_TRAINING: master farmer training programme
NAT_EXTN: national (government) extension agents
NGO: non-governmental organizations
OUT_COM_FRS: farmers from outside the community
PROD_MKT: players in produce markets
PVT_EXTENSION: private extension agents
RESEARCH: research organizations
SEED_HOUSES: seed companies
UNIVERSITIES: institutions of higher learning
WARD_INN_PLAT: ward innovation platform

PLATFORMS FOR INFORMATION SHARING

AGRL_SHOWS: agricultural shows
CC_LC: climate change Learning Centres
EXCH_VISIT_LOCAL: exchange visits with local farmers
EXT_WORKSHOPS: external farmer workshops
EXTN_MEETINGS: extension facilitated farmer meetings
FIELD_DAY: field days
ISFM_LC: integrated soil fertility management Learning Centres
LC_BASED MEETINGS: field-based Learning Centre meetings
SEED_FAIRS: seed fairs

Source: Mashavave *et al.*, 2013

CONCLUSIONS

The cases discussed in this chapter provide evidence that there is scope for turning the current vicious nutrient cycles that affect African smallholder farmers into virtuous cycles that trigger positive livelihood outcomes. It is clear that smallholder farmers in Africa are faced with multi-stress factors underpinned by a diminishing capacity to achieve sustainable food security using current agricultural production models and associated food systems. Poor and declining soil fertility is a major problem driving not only land degradation and food insecurity, but also changes in land-use patterns and natural resources management by the predominantly smallholder communities in Africa.

Novel interventions are necessary to foster resilience in African agricultural and livelihood systems. A change of paradigm is urgently needed, towards more holistic agroecological approaches in order to achieve agricultural transformation and strengthen sustainable livelihoods and food and nutrition security in Africa. Such a transition will require the collaboration of scientists from different disciplines, alongside public and private development actors and policy-makers.

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04

PEOPLE MANAGING LANDSCAPES: AGROECOLOGY AND SOCIAL PROCESSES

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Abstract

This chapter is based on an experience developed in the Zona da Mata of Minas Gerais, Brazil, within the Atlantic Rainforest biome. The Atlantic Rainforest is considered a hotspot of biodiversity. Today, the forest occupies about 7.5 percent of the original biome and it is critical for biodiversity, containing numerous endemic species. Since 1988, the

Centre for Alternative Technologies of the Zona da Mata (CTA), an NGO and group of professors and students of the Federal University of Viçosa have been working in this region in partnership with agricultural families, following agroecological principles. As understood in the Zona da Mata, agroecology is a science, but the scientific knowledge is a co-production among farmers and scientists. The farmers are not only a source of knowledge, but also autonomous and creative agents of transformation. Agroecology is also a movement and a practice. During the 1980s, a strong movement of family farmers developed, which led to the creation of unions and other organizations to represent their interests. CTA emerged in this context; its social basis consists of local family farmers unions within the region. CTA participates in the Brazilian agroecological network called National Articulation of Agroecology. For the transition from conventional to agroecological agriculture, appropriate public policies are needed, prioritizing investments in sustainable production. Therefore, the Brazilian agroecological policy is also briefly discussed. The adoption of agroecological principles in the Zona da Mata is connected with creative ways of dealing with land scarcity and land degradation. To deal with land degradation and to diversify production, experimentation with agroforestry coffee systems has taken place using participatory methodologies. These systems have been important for improving food for the family, for domestic and wild animals, and increasing income. The trees used in the systems also provide ecological services, such as the improvement of soil quality, increased carbon sequestration, improvements in water quantity and quality, attraction of pollinators and natural enemies, and providing shade to the workers. Presently, a project called 'knowledge exchange' involving family farmers, scientists, students and technicians is being developed.

INTRODUCTION

The Atlantic Rainforest biome is an area of dense and open evergreen forest that stretches along the Brazilian coast and extends 300 km inland. The Atlantic Rainforest is among the top five richest and most threatened reservoirs of plant and animal life on Earth, so-called biodiversity hotspots (Myers *et al.*, 2000). In past eras, the Atlantic Rainforest covered around one million km^2, corresponding to almost 12 percent of the area of the country (Dean, 1998). Due to its relative accessibility, deforestation started just after European colonization and by the nineteenth century, most of the forest had been cut. Today, the Brazilian Atlantic Rainforest occupies about 7.5 percent of the original biome and has become one of the most notorious examples of radical destruction of tropical forests (Myers *et al.*, 2000). The remaining forest is critical for biodiversity conservation, because it contains numerous endemic species, including

73 species of mammals (of which 21 species and subspecies are primates), 160 species of birds and 165 species of amphibians (Moffat, 2002). Thus, conserving the remaining forest cover is essential, but reversing environmental degradation of the region by sustainable management is also paramount.

The region of the Zona da Mata (about 36 000 km^2) is situated in the Atlantic Rainforest in the southeast of the state of Minas Gerais (Figure 1). Non-native exploitation of the region dates back to the mid-19th century with the expansion of coffee (*Coffea arabica* L.) production from the east, and the settling of migrants from the declining neighbouring gold-mining area (Valverde, 1958). It only took a few decades to cause great ecosystem damage. Coffee cropping replaced the Atlantic Rainforest, breaking the nutrient cycling of the forest ecosystem and leading to a drastic reduction of soil fertility due to crop harvesting. Moreover, coffee was (and is) cultivated on hills, where soil erosion was accelerated, leading to land degradation. This resulted in coffee farms occupying new and more fertile areas, causing further deforestation, while some of the old coffee fields were subsequently used as pasture or for production of staple food (Valverde, 1958).

Today, farmers mainly cultivate pasture and full-sun coffee, often intercropped with corn and/or beans. Coffee is the main cash crop. Other significant crops are sugar cane, cassava and beans. Since the 1960s, governmental policies have been promoting Green Revolution technologies, which have only been partially adopted due to the environmental and socio-economic constraints of smallholder production in the region (Gomes, 1996). The introduction of Green Revolution elements into the peasant economy has contributed to significant environmental deterioration (biodiversity loss, agrochemical pollution, erosion due to deforestation, degradation of water sources, etc.), as well as to the weakening of family farming as an economic enterprise (indebtedness, dependency on single crops, competition with large commercial enterprises, etc.). Using multivariate analysis, Fernandes *et al.* (2005) showed that approximately 80 percent of the municipalities in the region had a degradation index higher than 40 percent, with negative effects on the economy of the region.

In general, the agro-ecosystems in the Zona da Mata have experienced decreasing productivity due to the increasing intensity of soil use, involving practices that are inadequately adapted to the environment, such as coffee crops grown on steep slopes without soil conservation measures. In a Participatory Rural Appraisal, carried out in 1993 in the region, the family farmers explicitly identified soil degradation as the cause of decreases in the productivity of their agro-ecosystems. According to the farmers, the "land was weak!" (Cardoso *et al.*, 2001). After the establishment of agroforestry systems, Franco *et al.* (2002) showed that agroforestry coffee systems lost substantially less soil on average compared with coffee grown in monocultures (217.3 kg of soil ha^{-1} $year^{-1}$ vs 2 611.9 kg ha^{-1} $year^{-1}$).

The ecological and socio-economic problems in the Zona da Mata are not simply caused by a lack of knowledge on the part of the land users. As in other parts of the world, these problems are interrelated and derived from the historical conditions of agriculture. These ecological and socio-economic problems require urgent and integrated solutions.

In spite of the problems faced, smallholder production has maintained its vital importance within the region, mainly through the production of food crops for domestic consumption.

During the 1980s, a strong movement of small producers and farm labourers developed, leading to the creation of new unions that represented their interests (rural workers unions) and the organization of smallholders and agricultural wage earners at various levels and in different entities. The CTA (www.ctazm.org.br), an NGO whose social basis consists of local smallholder and farm labourers unions from within the region, emerged within this context. CTA is active in 21 municipalities, corresponding to the area of influence of 14 local unions.

Figure 1. **Zona da Mata region in the State of Minas Gerais, Atlantic Rainforest biome, Brazil**

🟩 Zona da Mata ⬛ Atlantic Rainforest biome ☐ Brazil

Source: adapted from MMA, 2008

AGROECOLOGY AS A SCIENCE, MOVEMENT AND PRACTICE

The experience of Zona da Mata of Minas Gerais is not isolated; it is connected to a network of agroecology. Agroecology is considered as a science with principles, concepts and methodologies that allow the study, design, management and evaluation of agro-ecosystems. Agroecology is multidisciplinary and its objective is to develop different styles of agriculture within an ecological framework and to elaborate strategies for sustainable rural development (Altieri, 1995).

On the scientific side, the Brazilian Association of Agroecology (ABA) was created in 2004 (www.aba-agroecologia.org.br) and has since organized eight Agroecological Brazilian Conferences. In 2013, around 4 000 people attended the conference and more than 1 000 abstracts were presented. ABA also publishes the Brazilian Agroecological Journal. In 2006,

agroecology was officially recognized as a science by the Brazilian Agricultural Research Corporation, and the referential benchmark for agroecology was published (www.embrapa.br/publicacoes). Recently, technical undergraduate and graduate courses on agroecology have been established at several universities, theses have been developed and papers published.

In agroecology, as understood by the group in Zona da Mata, scientific knowledge is co-generated by scientists and farmers. The farmers are not only a source of knowledge but also autonomous and creative agents of transformation. The personal perception, knowledge, feelings and skills of the farmers (the managers) are more important than any particular farming system (Oettlé and Koelle, 2003). In this way, farmers can be inspired to experiment, test, learn and think for themselves (Bolliger *et al.*, 2005).

However, for CTA, agroecology is more than a science. As a movement and practice, agroecology has its roots in the alternative agriculture movement. In Brazil, agroecology started as a form of alternative agriculture in the late-1970s and 1980s. Alternative agriculture was a response to the environmental and social problems created by technologies introduced by the Green Revolution, such as the use of pesticides and fertilizers. The main actors of alternative agriculture were agronomists (linked to the Federation of the Agronomist Associations and the Federation of the Students of Agronomy, which are still very active), but the movement rapidly gained adepts in other disciplines. The agronomist organizations promoted several alternative agriculture meetings. The last meeting, held in 1989[1], was attended by around 4 000 people. Other important actors in the alternative agriculture movement included NGOs and farmers organizations, especially the Grassroots Ecclesial Communities (CEBs)[2] and Pastoral Land Commission (CPT), which were linked to liberation theology and connected to the Catholic Church.

Around this time, re-democratization replaced the dictatorship in Brazil. In the conjuncture of political re-democratization during the 1980s, a movement for more independent unions, known as 'new unionism', started. During the dictatorship, most of the rural workers unions were subservient to the state and the patronage structure around social security services. Several counties had only landowners and patron unions. The 'new unionism' and other movements of rural workers and farmers in many regions (including Zona da Mata) were profoundly influenced by the experience of the CEBs. In the 1970s and 1980s, these community groups became important new political actors that operated beyond traditional patron-client relationships. Local Catholic activists and clergy were able to mobilize significant numbers of people through the CEBs. Almost all of the leaders of the new rural workers unions created in the mid-1980s were very active in the CEBs. The CEBs' proposal to create groups of reflection and organize farmers into politically oriented readings of the biblical texts played an important part in the political mobilization of farmers and rural workers. Critical capacities of deliberation, reflection and organized action were acquired by the peasants in these CEB groups (Comerford, 2003).

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[1] After 1989, the Alternative Agriculture meetings were substituted by the National Meeting of Agroecology and the Agroecological Brazilian Conferences.

[2] See: www.dhnet.org.br/direitos/militantes/freibetto/livro_betto_o_que_e_cebs.pdf

The religious idiom also gave the farmers an interpretative framework and a moral vocabulary to express their grievances and sense of injustice. At the same time, the CEBs accentuated the solidarity between suffering people and the need for action within the world to revert their situation (Comerford, 2003). The experience of the CEBs stimulated the learning of organizational skills and political capacities among rural workers and small farmers in several regions of Brazil, including the Zona da Mata. The CEBs also helped to make agroecological views meaningful to farmers. Both CEBs and the CPT were very active and frequently encountered new allies and proposals, including alternatives to conventional Green Revolution agriculture. However, alternative agricultural proposals had no appeal for most of the 'old' rural workers unions, who had been subservient to the corporative and patronage structure of the state for many years. In the Zona da Mata, CTA engaged actively with rural workers and smallholders in the creation of the new rural workers unions, making commitments and alignments with the social movements. At several moments, CTA was an important mediator between political and bureaucratic actors and the workers movements. In this way, a strong web of relationships was established between some of the new rural workers unions and the staff of CTA. Most of the new unions were aligned with the Labour Party and the Unified Central of Labourers, which represented the 'new unionism'.

Other NGOs, similar to CTA, were founded in the south, southeast and northeast of Brazil. These NGOs formed the Rede PTA (Project of Alternative Technologies), a network of NGOs that searches for alternatives to the Green Revolution model of agriculture. From the start, the PTA network attempted to establish close contacts with the rural workers unions. Thus, alternative agriculture has been intertwined with the history of rural workers unions and farmers associations in many regions of Brazil, including the Zona da Mata. The double link with national/transnational networks of NGOs and rural workers and farmers organizations was strategic for the development of the agroecological projects. Networks are crucial vectors for learning. They can range from informal networks of neighbours and family to national and international networks, and have been identified by farmers as the most important source of information and stimulus for innovation and learning (Oettlé and Koelle, 2003).

The NGOs sought to give technical advice to family farmers, in close cooperation with the ecological and alternative agriculture movements. The NGOs translated the theoretical proposals of the PTA network for 'alternative technologies' into concrete actions and practices, in close cooperation with the rural workers unions or other organizations. Important sources of project funding and institutional mediation also emerged from this partnership. The partnership between the NGOs and farmers organizations enabled various experiments with alternative practices. Since the late-1980s, they have worked together in experimental areas and to demonstration alternative techniques of ecological agricultural practices, which has resulted in the presence of several agroecological farms throughout Brazil.

The partnership was a process of mutual learning from both sides. At first NGOs were often confronted with scepticism or indifference on the part of small farmers towards the generality of prescriptions for a more ecologically oriented agriculture. In response, the NGOs made an effort to translate the general guidelines of the PTA programme into more concrete actions.

Difficulties in the implementation of the programmes of experimentation were focal points for reorientation and the incorporation of the suggestions and criticisms of the farmers. Using participatory methodologies, the technicians made an effort to identify the demands of the farmers and attempted to address them. In the process, CTA broadened its areas of intervention to include demands related to areas of local development, health, education, environmental conservation, commercialization, land acquisition, etc. In parallel, farmers reframed their own farming experiences and became gradually more active in their experimentation with agroecological practices.

We argue that agroecology is also a practice, connected with a *lifestyle* in which the farmers have to be aware of all aspects of their agro-ecosystems, including production and technology, but also the environment, health, education and forms of sociability. Lifestyle can also be seen as a farming style – a complex but integrated set of notions, norms, knowledge elements, experiences, etc., held by a group of farmers in a specific region, which describes the ways that farming practices should be carried out (Oettlé and Koelle, 2003). Through their practices and strategies of management, farmers generate not only material income, but also social and political capabilities. For example, agroecological farmers receive many visits to their farmsteads and participate in national meetings, and regional and national committees. Careful analysis of how farmers compose their livelihood strategies with sustainable practices can reveal many lessons for policy.

Since the re-democratization, farmers of several regions developed organizational capacities, created their own institutions, and established strong ties within the community, systems of rules, and links with strategic external actors. Their organizational initiatives included participation in local and regional farmers associations, women's associations and municipal forums of participation, as well as the creation of credit cooperatives. In several municipalities family farming schools were founded. In these processes, the actors discovered that agroecological practices were embedded in other interdependent dimensions of livelihood.

In the 1990s, the PTA network connected with the wider Latin American network, and the name 'alternative agriculture' changed to 'agroecology'. At the end of 1990s, the PTA was superseded by the ANA (National Articulation of Agroecology). The ANA differs from the PTA – it is not only a network of NGOs, but also of the social movements and scientists involved (www.agroecologia.org.br). Consequently, agroecological practices in Brazil are embedded in networks of relations and organizational forms which substantially reinforces the process of co-production, enlarges the resource base (material and immaterial), supports the autonomy of the farmers, and can open new livelihood options. The PTA (in the past) and ANA (currently) strive to promote equal partnerships between farmers, researchers and environmentalists. The ANA organizes the National Meeting of Agroecology, the first of which was held in 2002 and the third in 2014. These meetings were especially attended by agroecological farmers (around 50 percent women).

BRAZIL'S NATIONAL PLAN FOR AGROECOLOGY AND ORGANIC PRODUCTION (PLANAPO)

Through its experiences from around Brazil, the ANA was invited to provide an input to Brazil's national policy for agroecology. For this process, the environmental ministry supported five regional meetings of the ANA (corresponding to Brazil's main biomes) and a national meeting in 2011. More than 300 people participated in the six meetings. The participants were representative of the different social movements (e.g. landless, unions, women, ABA, ANA). A document was produced as a basis for negotiations with the government. A national seminar was then organized to deliver the document and facilitate discussions with the government. Based on this, the government elaborated a first draft of their policy and another national seminar was organized to discuss this draft. In 2012, the Marcha das Margaridas (The Peasant Women's demonstration in Brasília) asked President Dilma Rousseff to launch the national policy for agroecology. She agreed and the policy was launched in August 2012.

With the creation of the policy, the way was paved, but the process did not stop. The creation of the law alone provides no guarantee of actions or for the money needed. The policy was followed by a National Plan for Agroecology and Organic Production (PLANAPO). Two committees were created to formulate the plan, one formed by government staff from four ministries and one formed by civil society. The civil society committee consisted of 26 participants from 23 organizations. The role of this committee was to evaluate the plan and provide inputs.

PLANAPO was launched in October 2013. This was the first time that the social movements have gathered to formulate an agroecological policy, which can already be considered as a positive result of the policy. Another significant point was the recognition and support of the use of landrace seeds in the policy.

Although present in the ANA document, the guidelines and principles related to land concentration and water control were excluded from the policy. In Brazil, around 84 percent of agricultural holdings are in the hands of family farmers, but they occupy only 24 percent of the agricultural area. Thus, family farmers have to deal with land scarcity (IBGE, 2006). The ownership of land is a particularly important issue for farmers, because it implies autonomy and the ability to manage their land independently, which is strongly intertwined with the philosophy of farming (Oettlé and Koelle, 2003). In agroecology, it is difficult to obtain autonomy without ownership of the land.

Although dealing with land scarcity, family agriculture produces 70 percent of the Brazilian food on this 24 percent of land (IBGE, 2006). This means that Brazil's food sovereignty and security rest in the hands of family farmers. Soya beans, produced mainly for export, occupy around 35 percent of agricultural land (excluding pasture) and use 40 percent of all pesticides. Brazil now has the highest usage of pesticides, on average using five litres of pesticide per person per year. Among small farmers (0-10 ha), 27 percent use pesticides, compared with 36 percent of medium farmers (10-100 ha) and 80 percent of big farmers (larger than 100 ha) (Carneiro *et al.*, 2012).

CASE STUDY: AGROFORESTRY SYSTEMS

The adoption of agroecological practices has been connected with creative ways of dealing with land scarcity and land degradation. Since it started in 1988, soil conservation has been one of CTA's main activities, mainly based on the use of green manure. A key moment during this soil conservation work was the Participatory Rural Appraisal (PRA) carried out in 1993-94 by the Rural Workers Union (STR), CTA and the Federal University of Viçosa, to investigate and diagnose problems in agriculture. During the PRA, farmers were involved in a process of discussion, evaluation and planning of their agro-ecosystems. The diagnosis was characterized by the intense participation of farmers and many other local actors. An agenda of interventions for local development emerged from the discussions and the legitimacy of CTA and STR as representatives of broad local interests were consolidated.

During the diagnostic process, farmers and other local actors identified a wide spectrum of interdependent problems. In particular, concerns over declining productivity due to soil degradation, health problems emerging from the use of chemical pesticides and the insufficient land entitlements of smallholders and sharecroppers were diagnosed as critical problems for family agriculture. Soil degradation was not a novel problem in itself, but a well-known difficulty of the region. However, the PRA process allowed farmers to discuss and describe it to the researchers and NGO staff, instead of the other way around, as is more common.

The farmers prioritized land-use problems and selected a committee called 'terra forte' (strong land), composed of farmers and staff from the NGOs and the Soil Department of the Federal University of Viçosa, to present land conservation proposals designed to overcome soil degradation. The committee suggested several practices that were common to the farmers and were raised during the diagnostics: i) sugar cane planted in a line between coffee lines; ii) green manure; iii) use of lime as a source of calcium and magnesium; and iv) management of spontaneous vegetation. The use of agroforestry systems was a further practice that was suggested, which was not previously known to the farmers. All propositions emphasized the importance of the local knowledge of the farmers, the exchange of experiences and their role in the process of local development. As a result, a participatory experimentation with agroforestry systems was initiated.

Agroforestry as a possible solution

In 1994, some agroforestry plots were established to reclaim and conserve soil in the Zona da Mata. From 1994 to 1997, 39 small-scale experiments were established, involving 33 smallholder farmers in 25 communities from 11 municipalities of the Zona da Mata. Thirty-seven of the systems focused on coffee and two were based on pastures. Coffee, the main cash crop in the region, has favourable characteristics for agroforestry. It occurs naturally in semi-deciduous forests in Ethiopia, its area of origin. The microclimatic conditions of these forests are reproduced in agroforestry systems. The period of flowering, when more light is required, coincides with the dry season and many tree species in the Atlantic Rainforest biome lose their leaves during this period, whereas other trees can be pruned, avoiding light competition with coffee (Cardoso *et al.*, 2001).

From 2003 to 2005, the experience with agroforestry systems was investigated and documented using a participatory approach involving 18 farmers. The method followed several steps: a review of the relevant literature, including reports of CTA, theses and scientific articles; visits and interviews with farmers; and meetings with farmers and staff of CTA and the university. When appropriate, PRA tools such as maps and diagrams were used (de Souza *et al.*, 2012a).

During the experiments, several tree species were included or excluded from the systems. The main criteria for inclusion/exclusion was the species' compatibility with coffee. In particular, tree species that would not compete with coffee plants for nutrients, water and light were sought. The main indicators for compatibility were health aspects of the coffee plants and the deep roots of the trees. Besides these, other important criteria included: i) biomass production (indicated by the amount of residual material produced due to the natural fall of leaves or due to pruning); ii) the labour necessary to manage the trees (facilities to prune and to obtain seedlings, the architecture of the branches and the deciduousness of the trees); and iii) production diversification, indicated by trees supplying food for humans, as well as domestic and wild animals, and the production of wood for fire or constructions (de Souza *et al.*, 2010).

Eighty-five different tree species were identified as being used in the agroforestry systems, with an average of 12 tree species per system (excluding coffee). The main species used in the systems were native. To the best of our knowledge, some had never been reported to be used in agroforestry systems. To avoid difficulties in obtaining seedlings or seeds, the farmers preferred spontaneous species such as *Aegiphila sellowiana*. Using this approach, it is not necessary for farmers to plant trees, but rather to manage the plants that appear in the field (de Souza *et al.*, 2010).

Based on the amount of coffee harvested and the production costs, the agroforestry systems resulted in a lower cost–benefit ratio than full-sun coffee systems. However, the diversification through agroforestry systems also allowed more products to be harvested, such as avocado (*Persea americana*) and banana. These products were important for the food security and sovereignty of the farmers and for commercialization (de Souza *et al.*, 2010).

Agroforestry systems: specific research

Following the documentation of existing agroforestry coffee systems, various aspects of the systems were further investigated. Here, we present some of the results. In a floristic study, we found 28 species of Leguminosae trees in seven agroforestry systems (all with an area smaller than 1 ha). Except for one species (*Leucaena leucocephala*), all were native to the Atlantic Rainforest. Two forest fragments neighbouring the seven agroforestry systems contained fewer Leguminosae species than the agroforestry systems. Eleven of the 20 species found in the fragments also occurred in the agroforestry systems, including *Senna macranthera, Inga* spp. and *Dalbergia nigra*. *Senna macranthera* and *Inga* spp. are among the main species used in the agroforestry systems, while *D. nigra* is an endangered species from the Atlantic Rainforest that

was found in two agroforestry systems. The results of the floristic study show how agroforestry systems mimic the forest fragments in terms of species composition, making them important for the conservation of regional biodiversity (de Souza *et al.*, 2010; Fernandes *et al.*, 2014).

Of the legume species identified in the agroforestry systems, 17 are known to fix nitrogen and 16 are native, mainly from the genera *Machaerium, Erythrina* and *Inga*. According to the literature, *S. macranthera* has no known association with nitrogen-fixing bacteria. However, in a study of three legume species, Duarte *et al*. (2013) found higher nutrient releases from leaves of *E. verna* and *S. macranthera* than from leaves of *I. subnuda*, while there were only small differences in biological nitrogen fixation (BNF) among the legumes. Therefore, we argue that it is important to assess the capacity for BNF in Brazilian species of *Senna*. When considering the annual litter produced by these trees, their contribution to the nitrogen cycle (even at low percentages of BNF) can be substantial, especially for *S. macranthera* and *I. subnuda* (Duarte *et al.*, 2013). Considering their nitrogen mass fractions, each *S. macranthera* and *I. subnuda* tree would contribute approximately 60 and 140 g N per year (respectively) due to BNF (Duarte, 2007). Family farmers typically apply around 40 g N per coffee plant per year, using a NPK formulation of 20-05-20. Hence, the trees in agroforestry systems have the potential to substantially decrease the costs of fertilizer for family farmers.

Another characteristic of *Inga* trees is that they possess extrafloral nectaries, which provide alternative food to natural enemies of coffee pests. We investigated whether extrafloral nectaries of *Inga* trees associated with coffee could enhance pest control in coffee agroforestry systems. We collected 287 visitors of 79 morphospecies feeding on extrafloral nectaries of *Inga* trees. The arthropods collected belonged to the classes Arachnida and Insecta. Within the Insecta, we identified seven orders, which included natural enemies such as parasitoids, ants and other generalist predators. Sixteen of the recorded predators had already been reported as predators of either coffee leaf miners or coffee berry borers. The thrips, *Trybomia* spp. (Thysanoptera: Phlaeothripidae), that were found visiting extrafloral nectaries of *Inga* trees were observed inside coffee fruit that had been infiltrated by pests and feeding on coffee berry borers – a phenomenon that had not previously been reported. A correlative investigation suggested that the provision of alternative food for natural enemies by *Inga* trees leads to increased natural control. This could be caused by natural enemies aggregating around trees that provide nectar and by a numerical response of natural enemy populations to the increased availability of food (Rezende *et al.*, 2014). These results were confirmed by a replicated field experiment (Rezende, 2014).

Nine species of bees were found in the agroforestry systems: *Apis mellifera* (the only exotic species), *Trigona spinipes, Schwarziana quadripunctata*, *Trigona hyalinata*, *Bombus atratus*, *Frieseomelitta varia*, *Augochloropsis patens*, *Tetragonisca angustula* and *Partamona cupira*. It was observed that pollinators were responsible for an average increase in coffee production of 5 percent (Ferreira, 2008).

The improved soil cover in agroforestry systems resulted in decreases in soil loss due to erosion (Franco *et al.*, 2002) and increased production of water by natural sources on farm holdings. In one example, the family reported that the water produced on their property increased after introducing agroforestry systems; the amount of water is now more than sufficient for seven families where it had not been enough for two families in the past (Ferrari *et al.*, 2011). On this farm, the agroforestry pasture lost at least 30 times less soil and six times less water than the neighbouring full-sun pasture. Overall, the loss of soil was at least 10 times less, and the loss of water 30 percent less in agroforestry coffee systems (Carneiro, 2013). The temperature inside the agroforestry systems was reduced by up to 5 percent (de Souza *et al.*, 2012b) compared with full-sun coffee systems and the presence of trees also improved carbon sequestration (Duarte, 2007).

PEASANT-TO-PEASANT

Together with family farmers and their organizations, CTA and partners strive to study and to scale up the successes of agroecological experiences in the region. To that end, we follow the 'peasant-to-peasant' methodology (Machín Sosa *et al.*, 2012) with some adaptations; we promote meetings with the farmers on their farmsteads in order to observe and analyse their ecosystems. Besides the family farmers, students, researchers, agronomists and professors attend these meetings. Once per year, we have a regional meeting with farmers at the University. During these meetings, attended by over 200 farmers, everybody learns, farmers' needs are articulated and research questions are formulated and answered.

Despite these efforts, agroecological experiences, such as those with agroforestry systems, are not being mainstreamed in the region. This could easily occur with the right political incentives and technical advice. With agroforestry systems, the permeability of the agricultural matrix would increase dramatically, resulting in a landscape structure that is more compatible with the conservation of biodiversity in the Atlantic Rainforest (Vandermeer and Perfecto, 2007).

CONCLUSIONS

The agroecological experience in Brazil should be understood in the context of peasants' household strategies of resource access, their particular forms of organization and the interventions of NGOs. Our hypothesis is that the successful expansion of agroecological practices and innovative forms of organization are linked to solidarity networks among farmers – based on kinship, friendship and religious movements – and networks with NGOs and other institutional and political actors.

The adoption of agroecology by farmers increases when they are better integrated with farmer organizations. Another important factor is the 'co-production' of knowledge promoted by agroecology, for which an equal partnership between farmers, researchers and environmentalists is essential.

Social learning, connecting scientific and local knowledge was important for the development of agroforestry systems in the region. The introduction of agroforestry systems increased agrobiodiversity and enhanced important ecosystem services, including soil conservation and quality, which is the basis for the development of healthy agro-ecosystems.

ACKNOWLEDGEMENTS

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05

AGROECOLOGICAL APPROACHES TO BREEDING:
CROP, MIXTURE AND SYSTEMS DESIGN FOR IMPROVED FITNESS, SUSTAINABLE INTENSIFICATION, ECOSYSTEM SERVICES, AND FOOD AND NUTRITION SECURITY

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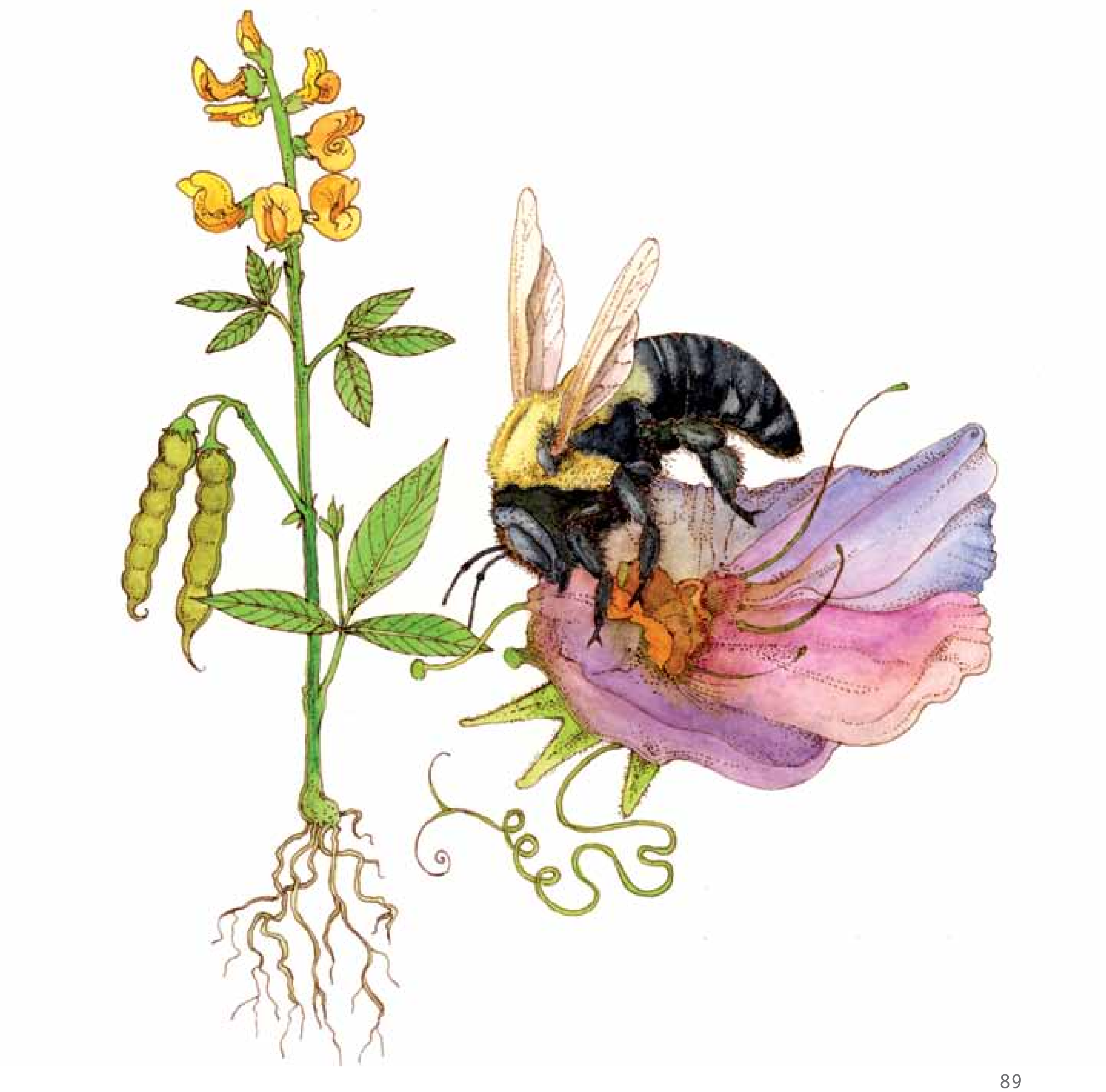

05

AGROECOLOGICAL APPROACHES TO BREEDING: CROP, MIXTURE AND SYSTEMS DESIGN FOR IMPROVED FITNESS, SUSTAINABLE INTENSIFICATION, ECOSYSTEM SERVICES, AND FOOD AND NUTRITION SECURITY

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Abstract

Agroecological approaches are designed to attain sustainable food production systems, with enhanced ecosystem function and resource efficiency, drawing from science, practice and social engagement. In addition to good management, the choice of appropriate crop and cultivar for these agroecological targets is essential. Crop and genotype selection must first focus upon agroecological fitness, which requires a close understanding of the desired crop and plant behaviour in order to achieve the productivity, sustainability and ecosystem goals. An important issue is crop design, specifically the traits and trait combinations that confer resource efficiency and ecosystem function, as well as yield and nutritional quality. The dynamics of crop response should also be considered, including patterns of adaptation to different soil constraints or management regimes, and how these patterns may vary with seasonal conditions and climate change. The necessary crop design will differ depending upon these ecosystem and management considerations. These principles can then be adapted to alternative systems, including intercropping, relay sowing and mixtures, based upon the concepts of competition and commensalism. The products that are generated must be considered, whether grain, forage, livestock or all of these, and the associated system evaluated rather than individual efficiencies. Issues for selection in mixed systems are examined with reference to the concepts of co-evolution and joint selection, drawing from diverse examples, including underused and perennial crop forage and tree species. The identification of successful systems will require an improved agroecological understanding as a basis for improved crop, mixture and systems design.

INTRODUCTION

In classic plant breeding (Allard, 1960), plant improvement requires the evaluation of diverse genetic materials for improved adaptation to particular sets of conditions. A diverse set of plants is assembled for evaluation, or additional variability is generated by crossing contrasting lines that possess traits which are desired in combination in the new phenotype. It is essential that the evaluation is conducted in conditions that are representative of the target environment, including its relevant cultural practices (Wade *et al.*, 1996). Improved performance and stability are generally accomplished by first adjusting the growth cycle to better suit the available growing season (Muchow and Bellamy, 1991). Attention is also paid to major biotic and abiotic stresses, so the effective phenotype is stable across the range of conditions that are likely to be encountered (Cooper and Hammer, 1996). The sampling or creation of genetic diversity, followed by its evaluation and selection, and the subsequent release of improved phenotypes, is a robust model with wide application. This chapter explores how these principles can be adapted to new plants and more complex systems, such as relay crops, intercrops and mixtures, including pastures and dual-purpose crops for grazing by livestock. The intention is to select adapted phenotypes for agroecological systems that are characterised by the need for sustained or increased yields, improved ecosystem services, more secure farmer livelihoods and better food and nutrition security.

AGROECOLOGICAL PRINCIPLES FOR MONOCULTURE SYSTEMS

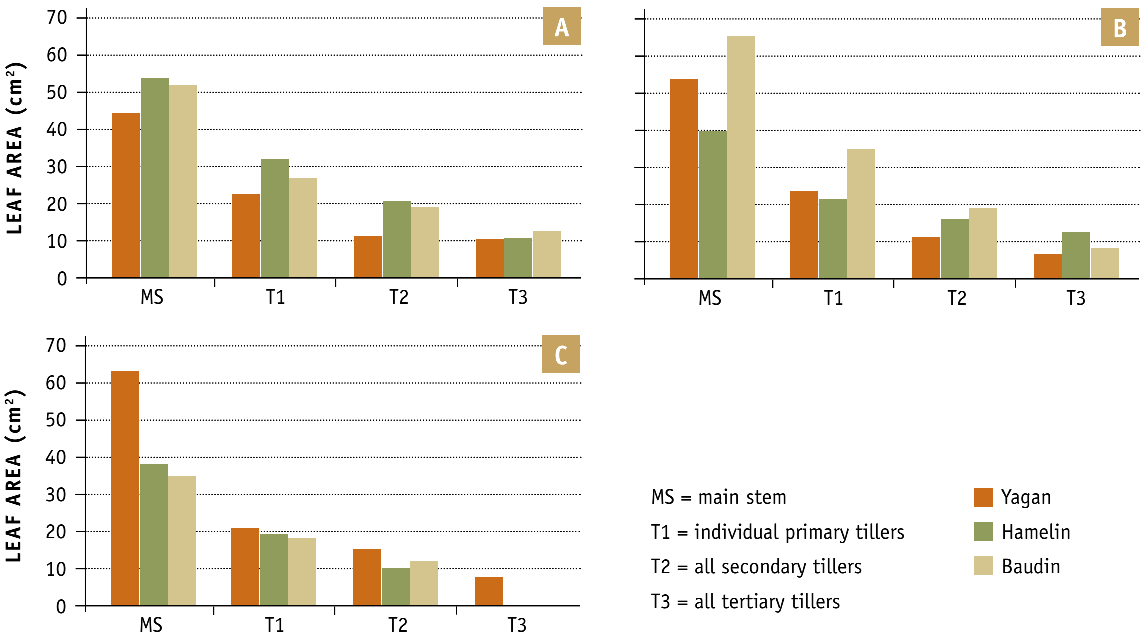
In all systems resources are finite, so the principle of crop and system design is to capture resources when they are available in order to minimize losses and retain the capacity for continued system function. To do so requires an understanding of the system dynamics, and the tailoring of demand to supply. Therefore, a key issue is the competition for resources and its appropriate phenotypic expression. This is first considered for a pure crop stand (e.g. wheat or barley monoculture), and then the competition model can be adapted to more complex systems.

It is important to recognize that different growing conditions occur early in a breeding programme, where plants are carefully spaced, allowing for the full expression of traits. In comparison, in the actual conditions of a pure crop stand, plant competition and interaction are important factors in plant success. In fact, a different plant type is more successful in spaced nurseries relative to mature swards. This is illustrated by Figure 1, in which three contrasting barley lines are grown in pots as sole plants, or surrounded by two or four close neighbours (i.e. one, three or five plants per pot) (O'Callaghan, 2006). As a spaced single plant, the cultivar Hamelin is able to tiller out better, but when surrounded by four neighbours, the cultivar Yagan is better (Figure 1). Over time these differences become more pronounced (Figure 2), demonstrating differing behaviours, adaptations and competitive abilities.

In pure stands the intent is to minimize interplant competition, so like plants can prosper with their neighbours (Donald, 1951). While the more restricted tillering cultivar may be preferred in that situation, a freely tillering cultivar may be better when weeds are present (Donald, 1968). This is well shown in rice by the cultivar Mahsuri from Malaysia, which is highly competitive due to its large projected leaf area, including a larger than usual flag leaf. Thus, the conditions under which a crop is intended to grow should be a consideration in the breeding programme, such as whether it is for monocropped stands, or to be grown in polyculture.

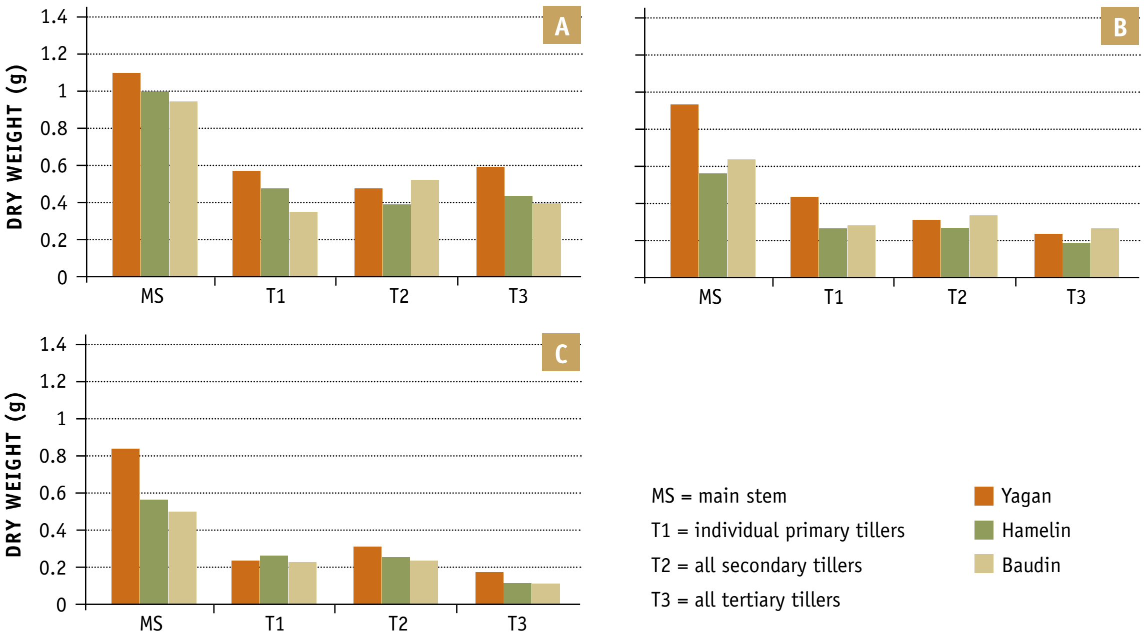
In considering the improvement of individual crops, it is important to discriminate between the level of investment likely for a major crop, and how it would be possible to make improvements in a new crop or species. For a new crop, the essential principle is to truncate the investment process by foregoing a large formal breeding programme. Initial investment should be used to assemble a diverse set of lines for evaluation, and looking for lines that are better able to perform under the conditions of the test. An example is provided by rice in Cambodia, from which germplasm was lost under the Khmer Rouge regime. Cambodian lines were reintroduced from the world collection, evaluated in the field, and either the reintroduced line or an off-type

Figure 1. **Size of leaf area at 39 days for Yagan, Hamelin and Baudin barley grown in a controlled environment room with (A) one, (B) three and (C) five plants per pot**



Source: adapted from O'Callaghan, 2006

Figure 2. **Tiller dry weight at 62 days for Yagan, Hamelin and Baudin barley grown in a controlled environment room with (A) one, (B) three and (C) five plants per pot**



Source: adapted from O'Callaghan, 2006 (mixture or mutant) was selected and released. Quick gains were possible using this approach, before a full breeding programme including crosses was later developed. Such an approach could be used for potentially promising new crops, such as teff, *Setaria*, other short duration grasses, wild sunflowers, *Lepidium campestre* as an oilseed, bambatse groundnut as a pulse, and many shrub and tree species.

These principles of architectural design from monocultures can be adapted to more complex systems, such as relay crops, intercrops and mixtures, including pastures and dual-purpose crops for grazing by livestock. In doing so, component species can be drawn from annual or perennial species. Recently, efforts have been directed towards developing a suite of perennial crops, which are expected to offer further desirable system alternatives (Wade, 2014), including mixture compatibility, grain and graze opportunities, and system sustainability. In the next section, concepts of architectural design are considered using a variety of examples from Batello *et al*. (2014), the *Proceedings of the FAO Expert Workshop on Perennial Crops for Food Security*. The implications for breeding targets, selection procedures and proof of concept are then discussed.

AGROECOLOGICAL PRINCIPLES FOR MIXED SYSTEMS

The advantage of a mixture is that the component species can act at different times or in different zones in order to enhance the effectiveness of resource capture, thereby reducing losses. Furthermore, companion species can be chosen with special attributes to assist effective resource capture, and to ensure delivery of appropriate products for farmers, grazing animals and consumers. For example, on soils of low phosphorus availability, species can be chosen whose roots exude organic acids to mobilize phosphorus. Nitrogen benefits can accrue from the use of legumes for symbiotic nitrogen fixation, or other species with desirable root associations consistent with the enhancement of non-symbiotic nitrogen fixation. Plants such as grasses with deep and extensive root systems can mop-up available nitrate, especially nitrate leached to deeper soil layers. Nutrient acquisition can also be aided by mycorrhizal associations, or by combinations of species which grow in different seasons. An issue that must be considered is the desirability of targeting mutual advantage favouring commensalism over competition. As indicated briefly above, this commensalism can accrue by partners drawing resources from different zones or at different times. Alternatively, there may be biotic benefits via the suppression of pests or encouragement of their parasites and pathogens. The emphasis here is on the selection of compatible plants for mixtures and their associated system benefits. Before doing so, it is worth pursuing examples of these relationships in contrasting systems.

Case studies of types of mixed systems

Undisturbed natural systems provide the reference point for long-term system sustainability, in which continuous cover is maintained. In disturbed systems, that scenario is most closely resembled in permanent pasture systems. These systems generally lack formal population structure, with random combinations of perennial and annual species grown in mixed swards, whose composition varies with resource availability and grazing intensity, as determined by management. Grass–legume pastures are commonly used to combine the nitrogen-fixing benefits of the legume with the nitrogen-responsive attributes of the grass, so that the grazing animal can access improved biomass of higher overall nutritive value (e.g. *Phalaris aquatica–Trifolium* spp.; see Figure 3A). Plants included in the pasture can be selected for particular desirable attributes, such as for thrip resistance in the case of gland clover (*Trifolium glanduliferum*), which is illustrated in Figure 3B (Hayes *et al.*, 2014). These pasture systems provide a ground cover and nutrient cycling reference for other disturbed systems.

Figure 3. **Mixed perennial grass–legume pasture**

(**A**) A mixed forage pasture sward containing a perennial grass (*Phalaris aquatica*) and hard-seeded self-regenerating annual legume species (*Trifolium subterraneum*, *T. michelianum* and *T. glanduliferum*)

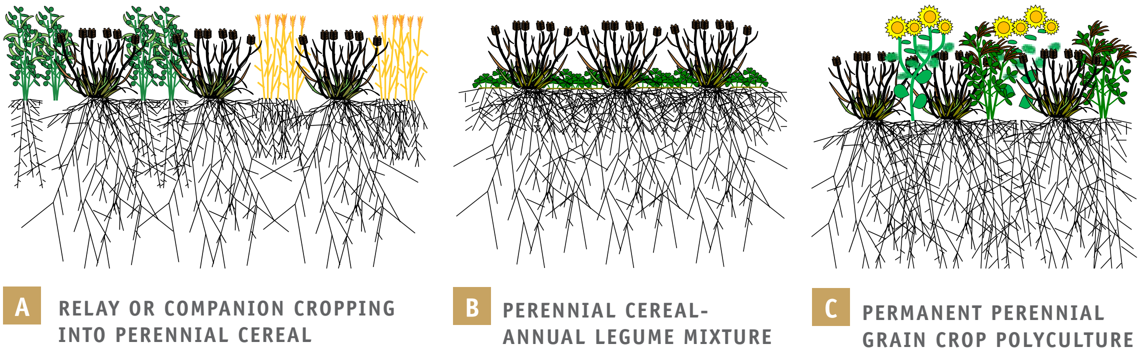
(**B**) Gland clover (*Trifolium glanduliferum*), a self-regenerating annual forage legume released commercially in Australia for its superior insect pest resistance

Source: Hayes *et al.*, 2014

Crop-based systems generally involve structured populations. Here, structure refers to a formal and predictable layout. For example, in a structured population, each species in sown in rows facilitating mechanization, in contrast to random allocation in a polyculture. Structure implies segregation for ease of harvest, but the critical issues are ease of mechanical sowing, inter-row cultivation and harvest.

The extreme case of a structured population is sole-crop monoculture, with the crop sown formally in rows, but preferably at least into stubble from previous cover. This simple system can readily be made more complex by intercropping or relay cropping with other species (Figure 4A), while still retaining structure for ease of management (Bell, 2014). If the annual crop were replaced with a perennial crop such as perennial wheat, the cropping system automatically features at least partial continuous ground cover, which can be further improved by companion or relay sowings of other species such as legumes (Figure 4B). The concept can even be extended to permanent perennial grain crop polyculture (Figure 4C), although the lack of structure may make this complexity more suitable for smallholders, where mechanical harvest is not an issue, and grain can more readily be segregated for marketing.

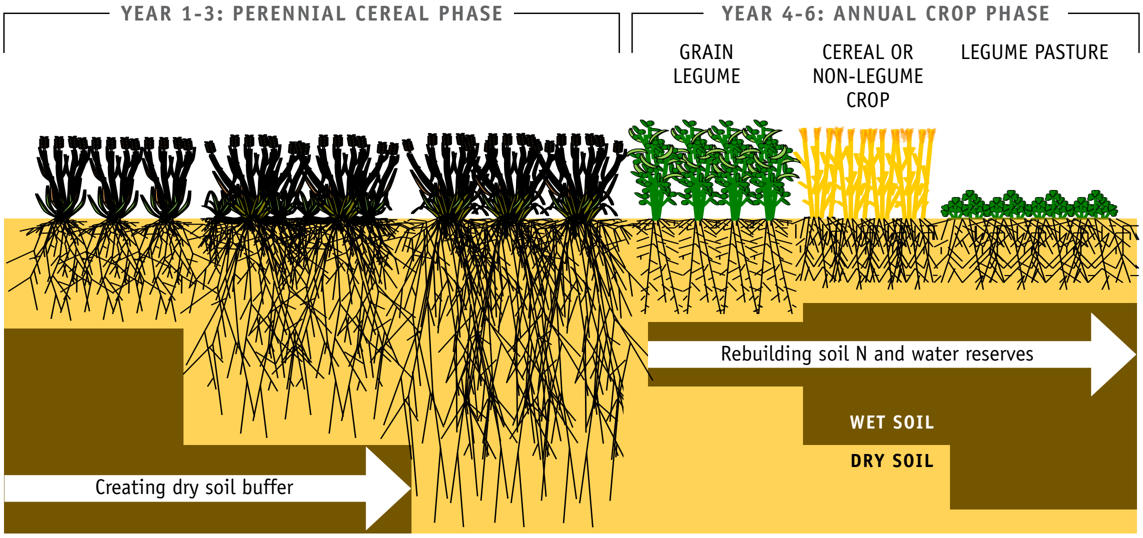
Figure 4. **Depictions of alternative farming systems involving permanent perennial cereals**



Source: adapted from Bell, 2014

Generally, some structure can be advantageous, especially in terms of securing effective combinations of productivity and sustainability. An example of phase cropping from southern Australia is presented in Figure 5, showing a diagrammatic representation of resource availability associated with the phase rotation (Bell, 2014). In this example, successive years of the perennial grain utilize soil water and nutrients that are accumulated under a previous pasture phase. That cycle is then replaced, initially by shallow-rooted legumes to restore nitrogen fertility as rainfall recharges the profile. Some water moves past the shallow roots of the annual legume, creating future reserves. Perennial legumes or legume pastures then restore the nutrient and soil water balance before the cycle is repeated. The perennial cereal phase is important in order to capture soil water resources from depth, together with any leached nitrate, in order to avoid the loss of resources past the root zone. This is one structured cropping example of closing the system to ensure balance in resource dynamics and system sustainability.

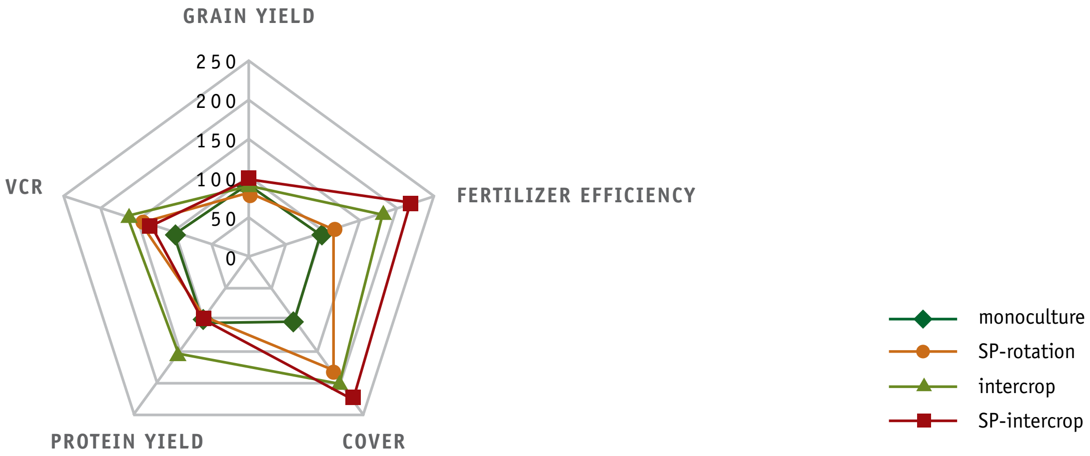
Figure 5. **Phase perennial crop–annual crop/pasture rotation**



Source: Bell, 2014

Another example involving structured cropping is the doubled-up legume system being adopted in Malawi in southern Africa. Semi-perennial pigeon peas provide intercropping opportunities for farmers. Because of their slow growth rates in the first year, they do not compete aggressively with faster growing legumes such as groundnuts (Snapp, 2014). As pigeon peas regrow in the second season, they can compete with more aggressive crops such as maize. Using this rotation, soil fertility is improved for the maize crop, while human nutrition is improved by including groundnuts and pigeon peas. Importantly, shrubby pigeon pea intercrops and rotations decrease fertilizer requirements (Figure 6), improve fertilizer-use efficiency, raise protein yields, increase carbon and nitrogen assimilation and phosphorus availability, provide greater soil cover and increase value–cost ratios (Snapp, 2014). Such ecological trade-offs are important. For example, by adding pennycress as ground cover within a maize–soybean rotation on cropped land in Minnesota (Figure 7), sediment loss to the Missouri River, and ultimately, the Gulf of Mexico, was greatly reduced (Runck *et al.*, 2014). Selection of plants with desirable traits for such complex systems should further improve system performance and sustainability.

Figure 6. **Shrubby pigeon pea intercrops (SP-intercrop) and shrubby pigeon pea rotations (SP-rotation) improve value–cost ratio (VCR), fertilizer efficiency, protein yields and provide greater cover compared with monoculture maize**

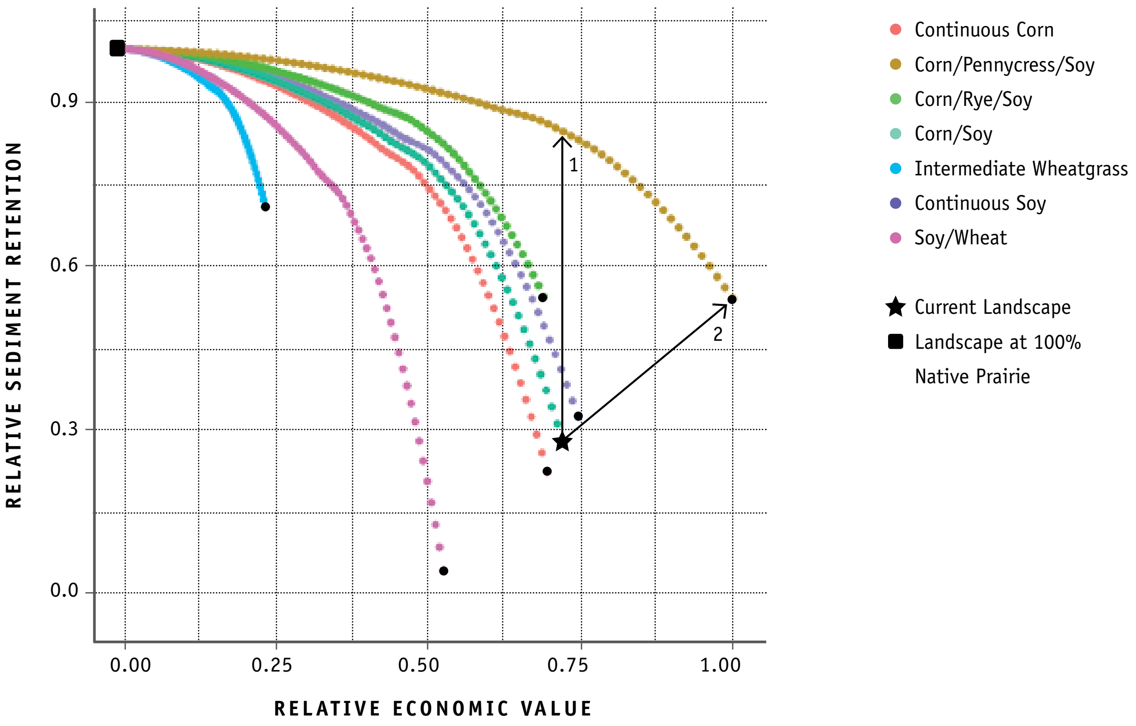


Source: Snapp, 2014

Trees can also contribute positively to the complexity and stability of the landscape and the production system. *Faidherbia albida* is a leguminous fodder tree native to Africa that is dormant in the wet season, but active in the dry season. A maize crop as understory can be grown in the wet season with nitrogen benefits through leaf drop from the tree, after which the tree produces standing dry season fodder reserves for livestock (Dixon and Garrity, 2014). This system is compatible with other crops or mixtures being grown under the trees in the wet season, and with livestock supplements such as water, salt, and molasses-urea being

Figure 7. **Ecological trade-offs for seven different crop rotations in Watonwan County, Minnesota**

ECOLOGICAL TRADE-OFF OF TRANSITION FROM PRAIRIE ECOSYSTEM TO AGRO-ECOSYSTEM



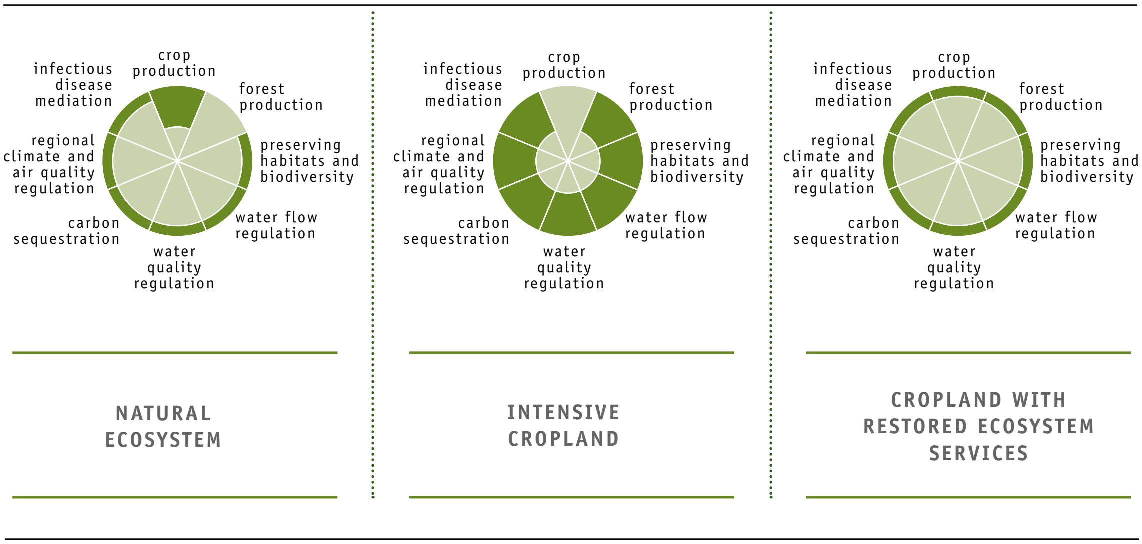
Curves indicate the trade-off between relative sediment loss and relative economic value of each rotation. The black dot at the end of a curve represents the maximum potential loss, and the star represents the position of the current landscape. The square represents a landscape that is entirely native prairie. Black arrow one shows the sediment retention service gain that could be made without losing any economic output at the county level by switching to a CPS rotation. Black arrow two shows the potential economic and ecosystem service gains that would be possible by shifting 100 percent of cropped land from the existing rotation to 100 percent CPS rotation.

Source: Runck *et al.*, 2014

provided during the dry season. *Faidherbia* is native to sub-Saharan Africa, and is now being promoted and adopted widely in Africa and elsewhere because of its desirable attributes. Another example is the three-layered system with coconuts (tall), oil palm (intermediate) and annual crops (short). The resilient or drought-tolerant perennials shelter the more sensitive crops in the understory, a principle used to sustain agriculture in oases even in desert regions such as Morocco. As systems become more complex, they approach the perennial polyculture. The return to greater system complexity restores ecosystem services (Figure 8), analogous to the original system (Reganold, 2014).

Participatory agroforestry can break the land degradation–social deprivation cycle in shifting agriculture, using improved two-year legume fallows, participatory selection, and value adding of forest products (Leakey, 2014). These examples demonstrate the benefits of ecosystem complexity for sustained performance, while retaining biodiversity, assuring nutrient cycling, and improving farmer and consumer livelihoods and nutrition.

Figure 8. **Ecosystem services under three land-use regimes**



Source: Reganold *et al.*, 2014

Issues for selection in mixed systems

In selecting for performance in mixed systems, the same principles that are used in monocrop systems still apply, and mixtures can over-yield relative to conventional monoculture. It is essential to evaluate the performance of the mixture in the conditions under which it is intended to be grown. So if the system is rainfed on soils of low fertility with material cut for hay or grazed early in the cycle or after harvest, then evaluation should be conducted under the same conditions. It is important to consider the performance of the system, rather than that of the individual components. In other words, in a dual-purpose perennial wheat crop with an undersown legume for grain and graze, the measure of success may be livestock performance rather than the grain yield of either crop. Furthermore, the characteristics for superior performance in mixtures may differ from those for a pure stand. Consequently, agroecological systems lend themselves to participatory selection *in situ*, so there is an opportunity for smallholders to favour their own preferences in selection. A prerequisite for this would be that smallholders have access to a wide variety of genetic variation, from which they can make selections. This seems to run against the prevailing paradigm on patenting and certification of seed as opposed to promoting seed saving by farmers.

The discussion presented above is founded upon the broader underpinning scientific principles (Allard, 1960), which also apply in participatory selection. It is important to understand the characteristics of the target population of environments (and their management regimes), and choose representative sites and conditions for evaluation of the diverse materials assembled, under conditions that are representative of how they will be used (Wade *et al.*, 1996). Promising materials can then be further tested in individual villages or farms for local preferences. It is important to recognize constraints to selection progress, such as genotype by environment interaction, and to keep these constraints in mind while making selections (Wade *et al.*, 1999).

For stability of performance, for example, the plants and mixtures may need to be selected for resilience under drought. In this case, it is essential to make selections when the relevant stress is encountered. If selections are made under all conditions and not just the target conditions, successive rounds of selection can result in a loss of genetic gains. There is a more complex model, involving selection for potential performance and performance under stress, but that requires a more formal programme to ensure materials with both desired attributes are retained. It may still be accomplished under participatory selection, but is likely to require larger populations, keeping of records, and selection based on performance in both seasons together rather than one after the other. Efforts to do this properly should bring rewards, but requires more work.

The above comments should apply when materials are already reasonably adapted, so further iterative gains can be made by participatory selection *in situ*. However, challenges could arise, requiring a more formal breeding programme or a larger research investment for success. For example, the advent of a serious disease such as a root or crown rot may require specialist attention, including molecular approaches. Likewise, for sustained progress in improved nutrition quality, it may be essential to measure micronutrient content or concentrations of chemicals which inhibit digestibility of forage. If abiotic stress tolerance was not present in the available materials, pre-breeding may be required to recruit suitable plants for evaluation in mixed systems, in order to secure plants possessing the essential suite of abiotic or biotic tolerances that can perform as required.

Species that are pre-adapted to grazing have evolved with their grazer. Plants developed adaptations to allow them to be grazed, e.g. protected growing points low in the canopy in grasses, while animals adapted mouthparts and digestive flora suited to dealing with various plant constituents, as well as the capacity to forage widely, become fertile and produce surviving young, even in harsh conditions. Thus, for mixed systems including livestock, the principles of co-evolution and joint selection also apply. It may be possible to select plants that are better performing in mixtures under grazing, and livestock better able to perform with the materials on offer. Co-evolution in natural systems can be used as a model for selection in managed systems.

DISCUSSION

In designing mixtures, it is possible to consider combining cultivars of a species as well as mixtures of different species. Cultivar mixtures have been advocated for stability of performance, especially under disease pressure, and in particular to reduce selection pressure on the pathogen so new sources of plant resistance are not required. In monoculture systems, variety mixtures or multilines are normally chosen for phenotypic consistency, so they flower and mature together for ease of harvest. However, when applying the new agroecological principles of polyculture, different traits may be required.

Under conditions of subsistence agriculture, where a range of flowering times could improve system stability, farmers can harvest materials as they mature. Again, the consequences of the mixtures on system performance should be considered. For example, a range of flowering times in a vigorous cereal or forage grass may compete more effectively with a legume component than a single phenotype.

In extreme cases, polyculture systems may have undesirable characteristics. Combined harvest of the mixture and sale as muesli may be appealing, but variability in content and feed value may make marketing more difficult. Usually markets require consistency in product with suitable labelling. Agroecological markets will need to be built that respond to and valorise the complexity of diverse farming systems.

Plants for a mixture could be chosen simply by trying lots of species or cultivars in combined plantings and evaluating them in the target environments, but additional benefits may accrue with a targeted strategy. By considering the characteristics of the target environment, the management system to be imposed and the desired products, species or cultivars may be selected for evaluation based on the required characteristics relative to system constraints. For example, if phosphorus is sparingly available on target soils, consideration should be given to including species in the mixture with enhanced capacity to mobilize phosphorus (e.g. legumes whose root systems release organic acids). If the soil is hard, choose one species with hardpan penetration ability. If leaching is a problem, choose a crop with extensive roots to mop-up nitrate and water from depth. For soil erosion, permanent ground cover is needed, so inclusion of perennial species is favoured. For root and crown rots, rotate brassicas such as mustard and canola for release of glucosinilates. For effective pollination of sensitive species, include plants with nectaries to encourage bees, and likewise, companion species for integrated pest management. Plants with mycorrhizal associations may further assist resource capture.

The appropriate manipulation of the mixture is important to enhance resource capture by encouraging the release and uptake of limiting elements, and including compatible plant types to ensure activity throughout the growing season, so resources are not lost to contaminate the environment. Likewise, the mixture should be tailored to ensure the delivery of products with desired nutritional and other qualities for humans and livestock as needed. In choosing plants for the mixture, performance in pure stands provides some reference indication of performance capacity, particularly in terms of phenotypic stability, disease resistance and nutritional value. By considering desirable traits needed in the target environment and management system, suitable plants can be included and evaluated for performance in mixtures in those situations, and the best system (not individual) performers can be identified.

While it is desirable to conduct local fine tuning for particular situations or farmer or consumer preferences, it should also be possible to identify broader requirements associated with target systems, regions or major soil groups, so materials passed for local evaluation are already known to be promising in the expected conditions. Participatory selection in the farm or village can then provide the best local outcomes as they are desired, including issues of cultural sensitivity, social justice and economic viability within the local system.

For participatory selection to be effective, sufficient diversity must be available to permit selection advance, under conditions that are consistent with the expression of the desirable traits. This process needs to be examined rigorously by monitoring progress in farmer selection, quantifying the genetic advance, and by tracking which genes are responsible and whether they are expressed universally or under particular conditions. Such knowledge should assist sustained genetic advance in participatory selection.

CONCLUSIONS

This chapter has outlined how genetic improvements could be secured in mixed farming systems, in which combinations of species are included for agroecological stability. The principles of crop improvement are used as a basis for identifying how progress can be made in mixtures. Selection should be strictly conducted under conditions representative of the target. Plants for evaluation can be considered according to how the traits they possess can be of advantage, and success must be measured for the system rather than the individual. There is a role for participatory selection to ensure local adaptations meet farmer and consumer preferences. At the same time, more complex challenges may require a more formal breeding programme, to ensure suitable plants for agroecological evaluation in mixtures are available. Ultimately, it is the *in situ* performance of mixtures that counts here.

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06

SOIL HEALTH AND AGRICULTURAL SUSTAINABILITY: THE ROLE OF SOIL BIOTA

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Abstract

Soil health is a measure of the state of natural capital that reflects the capacity of soil, relative to its potential, to respond to agricultural management by maintaining both the agricultural production and the provision of other ecosystem services. Human–environment interactions are dominated by agriculture, which consumes more natural resources than any other human

activity. This has raised concerns about natural resource management trajectories as related to planetary boundaries and land degradation tipping points. The adaptation of ecological concepts and principles to the design and management of agro-ecosystems, through agroecology, is a key strategy that can contribute to addressing these sustainability concerns. The soil resource is central to agriculture and therefore sustainable agriculture is inherently dependent on soil health. Many ecosystem processes have the soil as their regulatory centre and soil biota play a key role in a wide range of ecosystem services that underpin the sustainability of agro-ecosystems. Recognizing the great biological diversity in the soil and the complexity of ecological interactions, this chapter focuses on management of soil biota strongly linked to functions that underpin soil-based ecosystem services. Desired features of agro-ecosystems that promote soil biological activity, which in turn promote ecosystem functioning, are discussed and illustrated using agroforestry as a case study. Farmers represent the largest group of natural resource managers on the planet and have a critical role to play in the agroecological transition towards sustainable land management. Farmers and other land managers need to be active players in the conservation and enhancement of soil health and soil-based ecosystem services. The participatory development of soil health indicators and monitoring systems, integrating local and scientific knowledge, is proposed as a key component of a new approach, supporting farmers to adapt to agricultural intensification and attendant land-use and environmental change. Such changes will move research on soil health towards becoming more proactive in supporting the development of sustainable land management.

INTRODUCTION

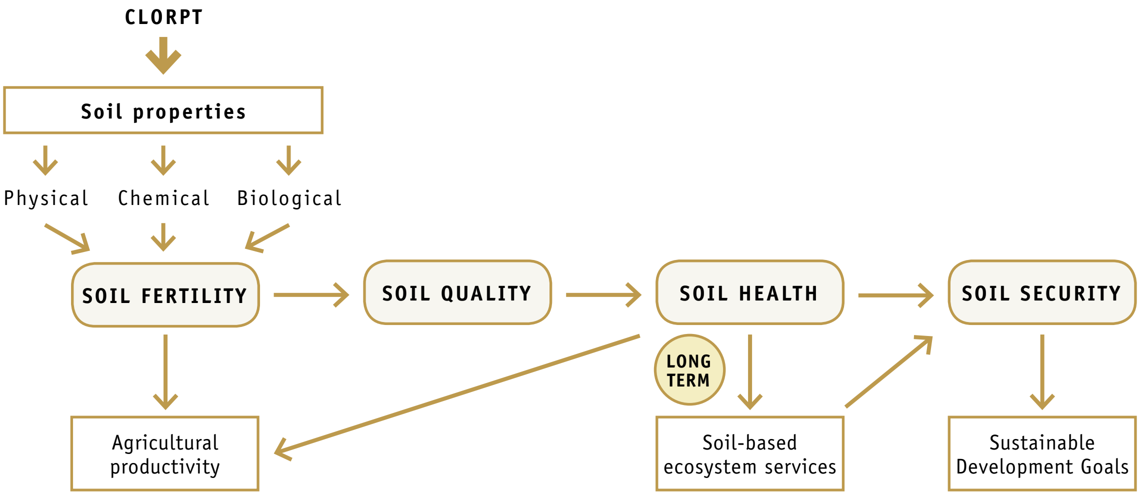
There is growing concern over the increasing impact of human activities on the climate and other aspects of the global environment and how these changes will affect the livelihoods of millions of people. Basic services supplied by natural and managed ecosystems, such as food, water, clean air and an environment conducive to human health are being increasingly threatened by global change (MEA, 2005). Research in the last decade has confirmed the existence of tipping points beyond which ecosystem service provision would be irretrievably lost, and efforts have been made to quantitatively define 'planetary boundaries' beyond which these tipping points will manifest (Rockström *et al.*, 2009). The global research platform Future Earth (www.futureearth.org) has been established as a result of the growing consensus that a framework for global stewardship is urgently needed to develop sustainable strategies for the planet in the face of global change. A first step towards such a strategy is to compile a knowledge base capable of informing its development.

Agriculture represents the predominant form of human–environment interaction by employing more people and consuming more natural resources than any other human activity (FAO, 2007). Croplands and pastures already occupy about 35 percent of the ice-free land surface, without counting forests under management and logging (Foley *et al.*, 2005). Agricultural intensification, particularly over the last 50 years, has been responsible for net gains in human well-being and economic development but often at the cost of degradation of natural resources (MEA, 2005). The adaptation of ecological concepts and principles to the design and management of agro-ecosystems through the applied science of agroecology has emerged as a key strategy to address these sustainability concerns (Altieri, 1987; Altieri and Nichols, 2005).

The soil resource is central to agriculture and therefore sustainable agriculture is inherently dependent on soil health. The soil is the critical and dynamic regulatory centre for the majority of ecosystem processes in both natural and managed ecosystems (Barrios, 2007), as well as constituting the primary stock of nutrients and carbon to sustain agricultural productivity. Consequently, soil is a key component of natural capital. Soil fertility, soil quality and soil health have often been used interchangeably in the literature. While they refer to similar concepts they sit along a trajectory of evolving conceptual approaches in soil science (Figure 1).

The seminal work of Hans Jenny (1941) highlighted the linkages between factors of soil formation (CLORPT: climate, organisms, relief, parent material and time) and soil properties, with greatest emphasis given to soil physical and chemical properties as those largely responsible for soil fertility and consequently agricultural productivity. These concepts guided what we refer to here as the 'soil fertility' paradigm, where limiting factors to crop growth could be addressed through external inputs such as fertilizers and pesticides. However, it was increasingly noted that crop yields declined after several years of intense soil use, despite the continuous or increasing application of agricultural inputs.

Figure 1. **Conceptual linkages among soil fertility, soil quality, soil health and soil security**



In the late-1980s and early-1990s soil scientists were concerned that concepts, indicators and thresholds of quality had been developed for air and water but not for the soil, which was lagging behind. Efforts by John Doran and other colleagues resulted in the definition of the concept of soil quality. This new 'soil quality' paradigm emphasized the importance of considering the soil as a living system, with a wider role including not only biological productivity but also environmental quality (e.g. impacts on air and water quality) and effects on plant and animal health (Doran and Parkin, 1994).

A third 'soil health' paradigm is now emerging together with the concept of soil security, which is an overarching concept of soil motivated by sustainable development. Soil health refers to the biological component of soil fertility and soil quality and their long-term contributions to agricultural sustainability (Doran and Zeiss, 2000). More recent conceptualizations take an integrated approach that recognizes synergies among physical, chemical and biological components of the soil. They highlight that a critical feature of soil biota is that it adapts to environmental change through natural selection while the physical and chemical components do not, hence it plays a central role in sustainable productivity and the provision of other ecosystem services. Therefore, we consider here that:

> *a healthy agricultural soil is one that is capable of supporting the production of food and fibre, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity (Kibblewhite et al., 2008)*.

Maintaining soil stocks of nutrients and carbon, for example by returning sufficient amounts and quality of organic inputs, is essential for sustainable and resilient production systems. However, soil stocks are linked to ecosystem functions via the soil biota, which has received less attention than maintaining the stocks themselves. The concept of soil security, on the other hand, is broader, multidimensional and more integrative than soil quality or soil health and equivalent in nature to the concepts of food security, water security and energy security (McBratney *et al.*, 2014). It is concerned with global environmental sustainability issues such as the maintenance and improvement of the global soil resource to produce food, fibre and fresh water, contribute to energy and climate sustainability, and to maintain biodiversity and the overall protection of the ecosystem (Koch *et al.*, 2013).

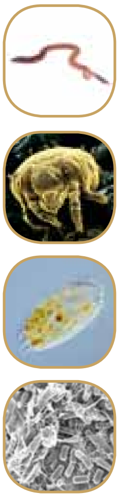
In this chapter, we first identify key ecosystem functions driven by soil biota that underpin the provision of soil-based ecosystem services, and then explore the linkages between agroecological management, local knowledge and soil health, before concluding with a set of future challenges and opportunities.

SOIL BIOTA AND SOIL-BASED ECOSYSTEM SERVICES

The soil is one of the most diverse habitats on earth and houses an enormous biodiversity. One gram of soil may contain up to one billion bacterial cells, tens of thousands of taxa, up to 200 m of fungal hyphae, and a wide range of mites, nematodes and arthropods (Wagg *et al.*, 2014). In Table 1, it can be seen that while 90 percent of plant biodiversity is known, much less is known about below-ground biodiversity, while the smaller the organisms are, the less we know about them. This huge diversity has been largely ignored because of the opaque nature of soil and the methodological difficulties involved in the study of most soil biota (Wall *et al.*, 2010). Advances in genomics are providing new opportunities to explore the previously hidden realm of soil biodiversity (Wu *et al.*, 2011; Fierer *et al.*, 2013).

Table 1. **Estimated number of plant and soil organisms organized by size**

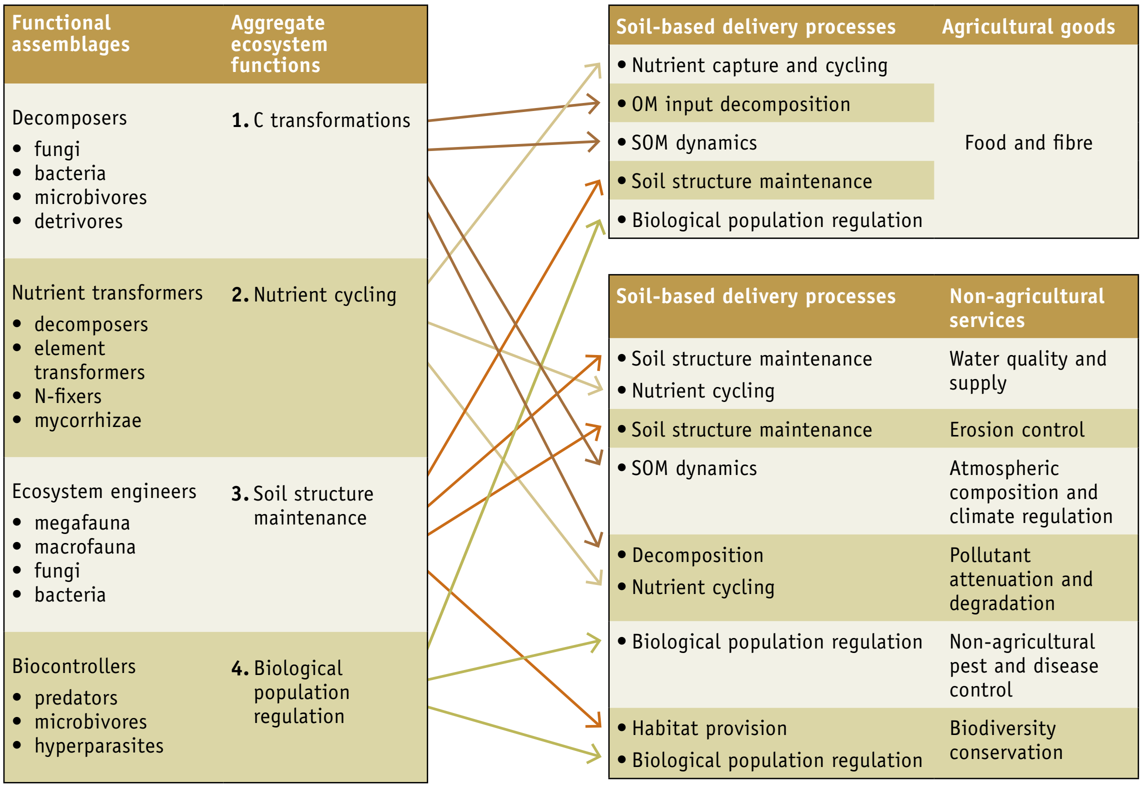
SIZE	GROUP	KNOWN SPECIES	ESTIMATED TOTAL SPECIES	% KNOWN
	Vascular plants	270 000	300 000	90
	Macrofauna			
	Ants	8 800	15 000	58.7
	Termites	1 600	3 000	53.3
	Earthworms	3 600	7 000	51.4
	Mesofauna			
	Mites	20 000 - 30 000	900 000	2.2 -3.3
	Collembola	6 500	24 000	27.1
	Microfauna			
	Protozoa	1 500	200 000	7.5
	Nematodes	5 000	400 000	1.3
	Microflora			
	Bacteria	13 000	1 000 000	1
	Fungi	18 000 - 35 000	1 500 000	1 - 2



Source: adapted from Barrios, 2007; updated using data from Bardgett & van der Putten, 2014

At present, groups of soil biota have to be selectively studied because there is no single method to study soil biodiversity and it is not possible to study all groups simultaneously. The complexity of interactions between soil biodiversity and functional attributes associated with soil fertility requires a focused approach targeting sets of soil organisms that play major roles (Giller *et al.*, 2005). Efforts in this direction by Kibblewhite *et al.* (2008) show that soil organisms can be grouped into four functional assemblages: (i) decomposers; (ii) nutrient transformers; (iii) ecosystem engineers; and (iv) biocontrollers, each composed of several functional groups (Figure 2).

Figure 2. **Conceptual framework of linkages between soil biota, biologically mediated soil processes and the provision of soil-based ecosystem goods and services**



Source: adapted from Kibblewhite *et al.*, 2008 in Barrios *et al.*, 2012b

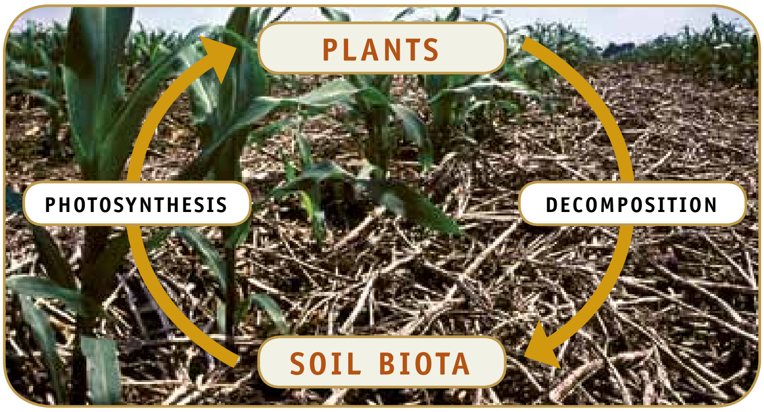
These functional assemblages contribute to four aggregated ecosystem functions: carbon transformations, nutrient cycling, soil structure maintenance, and population regulation, which through a variety of soil-based delivery processes, generate and sustain soil health (Barrios *et al.*, 2012b).

While the enhancement of agricultural production has been the focus of attention for many decades, concerns about increasing agricultural sustainability have progressively shifted attention towards ecosystem services; particularly those responsible for life support (i.e. carbon transformations and nutrient cycling) and regulation of ecosystem processes (i.e. soil structure maintenance and biological population regulation) (Swift *et al.*, 2004; Barrios, 2007). This section highlights plant–soil biota interactions in agro-ecosystems that contribute to the provision of the soil-based ecosystem services of life support and regulation.

Carbon transformations

Carbon transformations are a fundamental component of the functioning of agricultural landscapes (Banwart *et al.*, 2014). Organic materials are broken down into simpler molecules during decomposition, which is one of the most important ecosystem services performed by soil organisms, representing the catabolic complement of photosynthesis (Figure 3). Decomposition of organic materials involves different steps that include: (i) physical fragmentation, where feeding on detritus by small invertebrates generates smaller fragments but greater surface area that facilitates colonization by microbes; (ii) chemical degradation, occurring as a result of the action of enzymes produced largely by bacteria and fungi; and (iii) leaching of organic substrates, where organic and inorganic soluble compounds leach from detritus.

Figure 3. **Decomposition is central to soil function in agro-ecosystems and explicit attention to organic matter management is increasingly becoming a dominant feature in agriculture**



Nutrient cycling

Nutrient cycling is a critical ecosystem function that is essential to life on earth. Beneficial impacts of soil biota on crop yield, as a result of increases in plant available nutrients, are well understood. In particular, biological nitrogen fixation (BNF) by soil bacteria such as *Rhizobium* (Giller, 2001) and enhanced phosphorus uptake through arbuscular mycorrhizal fungi (AMF) (Smith and Read, 2008) are well documented.

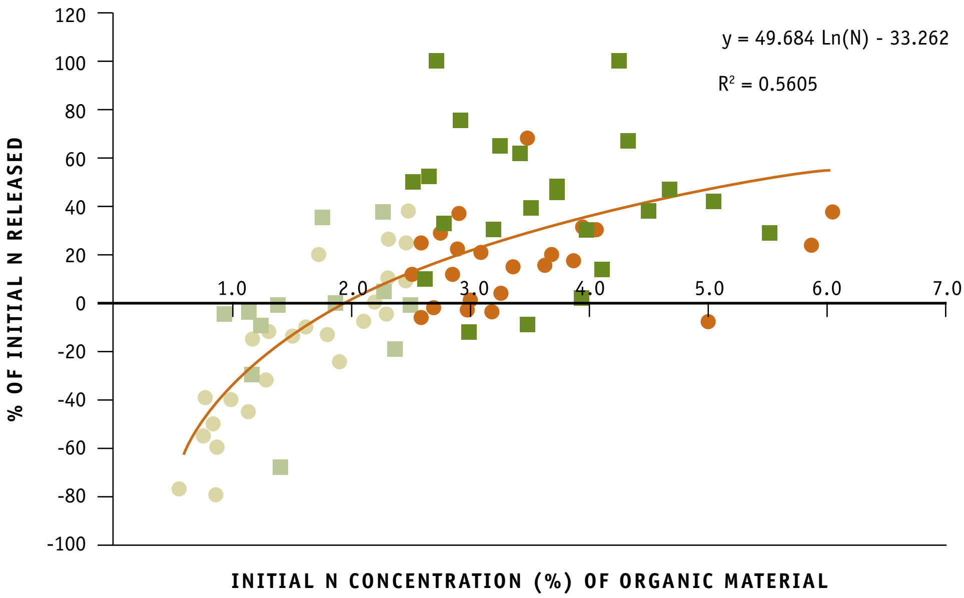
Decomposition and nutrient cycling are intimately linked. Nitrogen-fixing bacteria bring atmospheric nitrogen to leguminous plant tissues. The legume benefits, but eventually the legume tissue decomposes in the soil and as a result of the action of a number of soil organisms, plant available nitrogen is released that may be taken up by other plants (Figure 4).

Organic resource quality can play a key role in order to predictably manage organic matter additions in agriculture (Cobo *et al.*, 2002). An Organic Resource Database (ORD) was developed showing that different organic materials have contrasting decomposition and nutrient release patterns that can be predicted by their initial concentrations of nitrogen, lignin and polyphenols (Palm *et al.*, 2001).

Incubation studies in the laboratory are used to determine the intrinsic capacity of organic materials added to soil to release nutrients under optimal conditions of moisture and temperature, and thus are a measure of the potential supply of nutrients to crops. Organic materials from the ORD were incubated and the results synthesized in Figure 5.

Figure 4. **Biological nitrogen fixation (BNF) constitutes a central contribution of nutrient cycling to agro-ecosystems**

Figure 5. **Nitrogen released or immobilized from organic materials as modified by high lignin or polyphenol concentrations**



L= % Lignin

PP= % Polyphenols

● >2.5%N, >15%L, >4%PP

● <2.5%N, >15%L, >4%PP

■ >2.5%N, <15%L, <4%PP

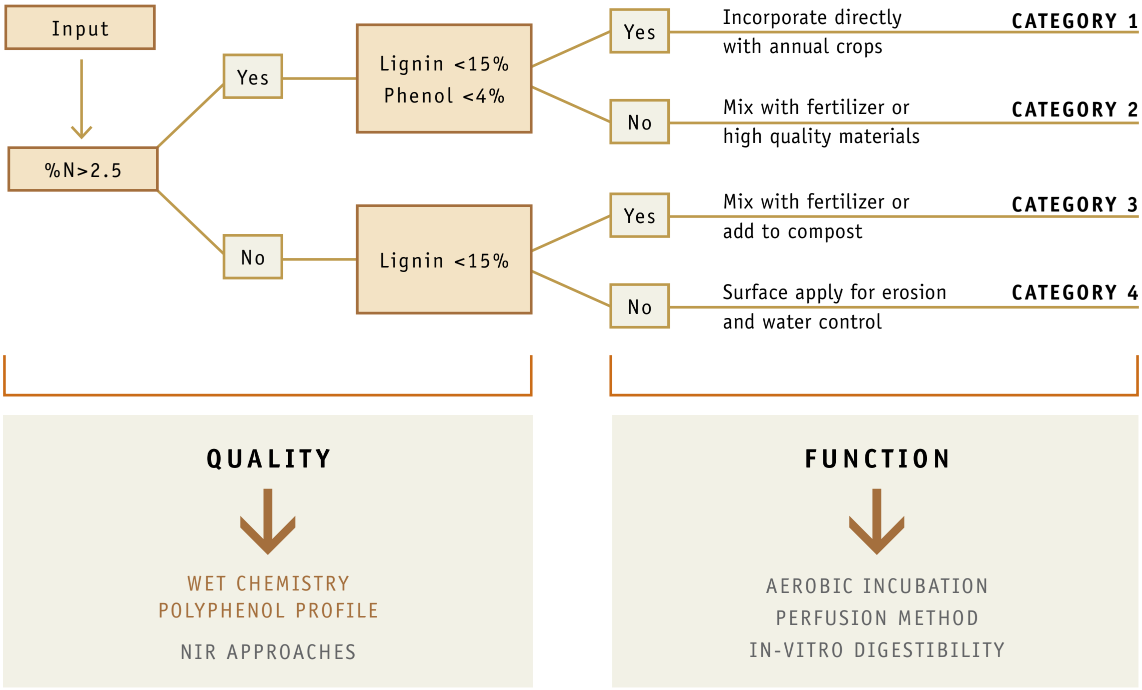
■ <2.5%N, <15%L, <4%PP

Source: adapted from Palm *et al.*, 2001

The results showed that while the initial nitrogen concentration of organic materials is the overall best predictor of nitrogen release, the lignin and polyphenol concentrations as modifiers of such release contributed to a better fit to the data. Palm *et al*. (2001) developed a decision support tool for organic matter management based on plant tissue quality (Figure 6), that was later validated using functional assays and a wider set of organic materials (Vanlauwe *et al*., 2005).

This provides an excellent example of how fundamental research can support on-farm decision making. Furthermore, the study of nutrient stocks held in organic materials provided by the ORD, together with knowledge of the flow of specific organic materials, represents the key information needed to guide more efficient nutrient management in agricultural landscapes.

Figure 6. **Management options for organic resources determined by their N, lignin and polyphenol contents**

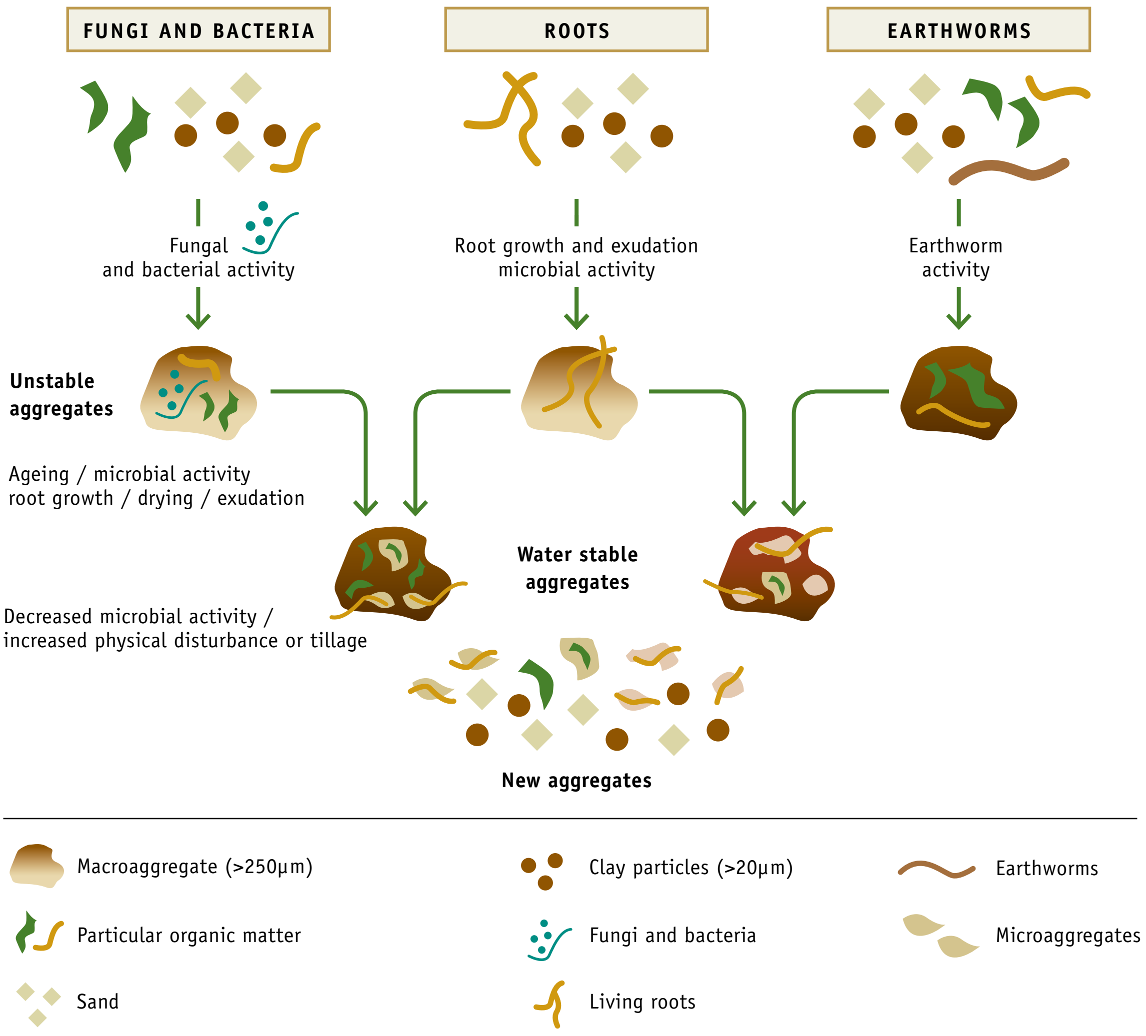


Source: adapted from Palm *et al*., 2001 (left), and Vanlauwe *et al*., 2005 (right)

Soil structure maintenance

Soil structure is the arrangement of sand, silt and clay particles, and soil organic matter (SOM) into aggregates of different size, held together by organic and inorganic agents. Soil organisms play a key role in soil aggregate formation at different scales, from bacteria producing cementing agents between clay particles to the enmeshment of soil aggregates by fungal hyphae and fine roots, contributing to the hierarchical organization of soil structure. The aggregate dynamic model highlights that soil aggregation is a dynamic process where aggregates are continually formed and continually destroyed, and where fungi and bacteria, plant roots and earthworms play a key role (Six *et al.*, 2002) (Figure 7).

Figure 7. **Biological mechanisms of soil aggregate formation and turnover**



Source: adapted from Six *et al.*, 2002 in Barrios, 2007

Soil ecosystem engineers contribute to soil structure through the production of biogenic structures. For example, earthworms ingest considerable quantities of soil, which become carbon- and nutrient-enriched earthworm casts following transit through the gut (Fonte *et al.*, 2010). Arbuscular mycorrhizal fungi produce biogenic structures through two key mechanisms: (i) soil enmeshment by fungal hyphae; and (ii) production of glomalin, a glycoprotein that acts as a gluing agent contributing to aggregate stability (Rillig and Mummey, 2006). Furthermore, the increased stability of biogenic aggregates to water disruption not only reduces the susceptibility of soils to erosion but also increases the potential for soil carbon storage through the physical protection of SOM from microbial action (Six *et al.*, 2002).

Biological population regulation

All soil organisms exist as part of soil food webs that keep population numbers under control through competition, predation and parasitism. This is a critical aspect of the self-regulating nature of ecosystems that is often disrupted during agricultural intensification.

Soil-borne pests and diseases cause enormous annual crop losses globally, which occurs when the impact of key biological control agents is reduced or lost because of land-use changes that affect their survival (Susilo *et al.*, 2004). Soil health and plant health are strongly related as nutrient deficient crops growing in poor soils are more susceptible to pests and diseases (Altieri and Nichols, 2003). For example, very significant reductions (of about 99 percent) in populations of the parasitic weed *Striga* were observed in maize following improved fallows incorporating BNF through *Sesbania sesban*. This was attributed to the increase in soil nitrogen availability (Barrios *et al.*, 1998). More modest reductions (close to 50 percent) were also observed following increases in phosphorus availability in maize and sorghum inoculated with AMF (Lendzemo *et al.*, 2005).

There are also numerous examples of direct biocontrol exerted by soil biota. For example, in an experiment with rice plants growing on soil infested with parasitic nematodes, the inoculation of the earthworm *Pontoscolex corethrurus* significantly decreased the number of nematodes. The underlying mechanism of biological control of parasitic nematodes when in presence of earthworms was related to the direct effect of transit through the earthworm gut which lowered the viability of nematode eggs (Lavelle *et al.*, 2004). The general consensus is that healthy soils, harbouring a diverse community of soil organisms will not only help prevent crop losses by soil-borne pests and diseases but also enhance other key soil biological functions (Barrios, 2007).

AGROECOLOGICAL MANAGEMENT, LOCAL KNOWLEDGE AND SOIL HEALTH

Natural ecosystems depend on biodiversity and biological processes to support ecosystem function. When natural ecosystems are converted to agriculture and subsequently intensified, there is a gradual replacement of these ecological functions (nutrient mineralization, biological control of pests, etc.) by external inputs such as agrochemicals (Figure 8). The net result of

this trend is the reduction in the capacity of agro-ecosystems for self-regulation and thus greater vulnerability to perturbations and environmental changes. There is growing interest in agro-ecosystems with increased internal resource-use efficiency, that are less dependent on external inputs, and are able to maintain a favourable balance between productivity and the provision of other ecosystem services (Barrios *et al.*, 2012b). This can be illustrated by the emerging concept of eco-efficiency in crop science, which is increasingly seen as fundamental to global food security (Keating *et al.*, 2010).

Figure 8. **The impact of agricultural intensification on biodiversity, ecological functions and external inputs in natural and agricultural ecosystems**

A number of agroecological management principles have been outlined to guide the identification of more resource use-efficient agricultural management options (Altieri and Nichols, 2005). These include:

- Optimizing the use of locally available resources (increased reliance on nutrient recycling);
- Minimizing losses of soil, nutrients, water and energy (maintain soil cover, reduced or no-tillage management);
- Optimizing soil conditions for plant growth (strategic use of external inputs);
- Promoting genetic and species diversification (diversifying systems with components adapted to local conditions);
- Favouring beneficial interactions and synergies among the components of agrobiodiversity (increased reliance on symbiosis and biological control of pests and diseases).

Case study: agroforestry and soil health

Close to half of all agricultural land has more than 10 percent tree cover, making agroforestry a significant component of global land-use systems (Zomer *et al.*, 2014). And, given that agroforestry practices rely on some or all the principles outlined above, we will use selected agroforestry examples to explore the interactions between agroecological management and soil health.

Agroforestry has been increasingly recognized and practised as a multifunctional land management option that can simultaneously contribute to income generation, food security and the conservation of biodiversity and ecosystem services (Sinclair, 1999; Tscharntke *et al.*, 2011). It can also be a valuable tool for climate change adaptation and mitigation in agriculture (Verchot *et al.*, 2007). This has led to the recognition of agroforestry as a key natural resource-management intervention and created demand for scaling up (in combination with other land management options and their potential synergies) to face the challenges of global change (Coe *et al.*, 2014).

Some of the effects of trees on soil health are mediated through an increase in soil biota abundance (Table 2). A recent literature review found that almost all groups of beneficial soil biota studied in tropical maize-based agroforestry systems (mostly in Africa) increased in number compared with contiguous cultivation without trees (Barrios *et al.*, 2012b). The response ratio (RR) is the ratio of the mean value of the agroforestry practice to that of the control (continuous cropping with fertilizer). Therefore, RR values greater than one indicate increased soil biota abundance in agroforestry systems.

Table 2. **Mean density of different soil biota and calculated response ratios**

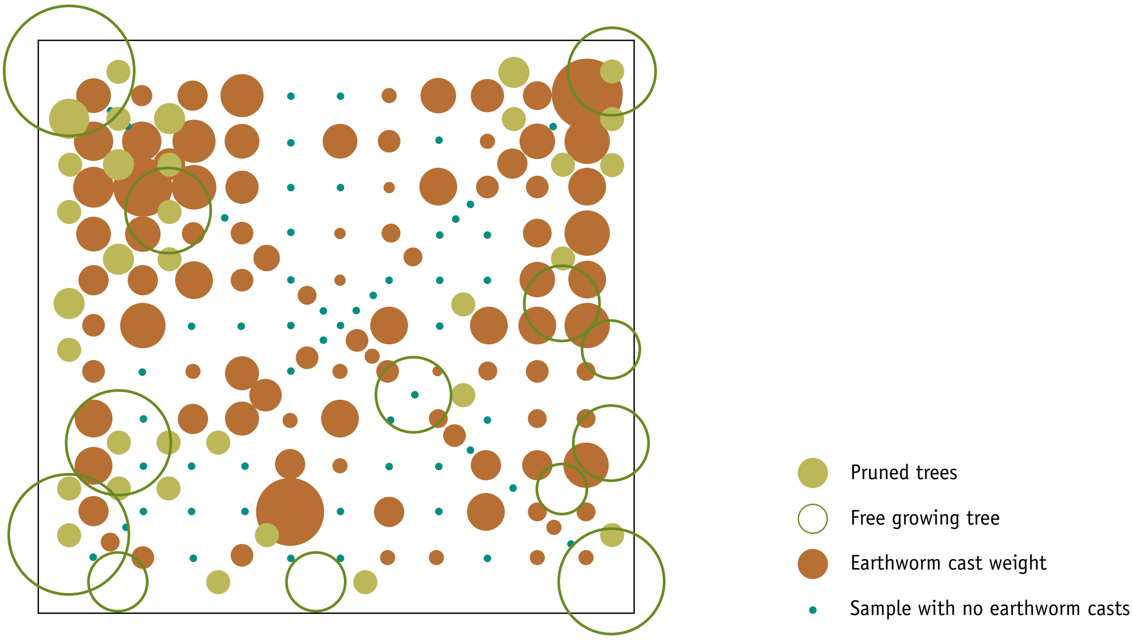
	AGROFORESTRY	AGRICULTURE	RR
Soil macrofauna	(individuals m^{-2})	(individuals m^{-2})	
Earthworms	54.4	17.6	3.1
Beetles	20.9	9.6	2.2
Centipedes	2.7	0.5	5.6
Termites	90.7	81.0	1.1
Ants	23.2	8.6	2.7
Soil mesofauna	(individuals m^{-2})	(individuals m^{-2})	
Collembola	3 890.1	2 000.7	1.9
Mites	5 100.7	1 860.1	2.7
Soil microfauna	(individuals litre^{-1})	(individuals litre^{-1})	
Non-parasitic nematodes	2 922	1 288	2.3
Parasitic nematodes	203.7	211.5	1.0

Source: adapted from Barrios *et al.*, 2012b

In addition, some effects of trees on soil health are mediated through increases in soil biological activity (Figure 9). Increased earthworm biological activity was observed near trees but the effect was greater for some tree species than others (Pauli *et al.*, 2010). Trees producing large quantities of fast decomposing biomass that is rich in nitrogen and low in lignin and polyphenol content (e.g. *Indigofera zollingeriana* Miqu. and *Gliricidia sepium* (Jacq.) Kunth ex

Walp.), have been reported to support high earthworm abundance and activity in tropical soils (Barrios *et al.*, 2005; Sileshi and Mafongoya, 2007). This suggests that tree attributes are likely to play a significant role in defining the positive or negative effects on soil biological activity. These observations, as well as others in the recent literature (Diedhiou-Sall *et al.*, 2013), provide evidence that trees play a significant role as hotspots of biological abundance and activity in agricultural landscapes. This becomes particularly important during periods of climatic stress (e.g. drought), the frequency and intensity of which are expected to increase with climate change.

Figure 9. **Spatial relationships between earthworm activity and the distribution trees in the Quesungual Agroforestry System**



Distribution of pruned trees (green circles), free growing trees (open circles) and earthworm cast weight (brown circles). The size of the circles represents the number of pruned trees found in each sampling cell, the size of the tree canopy and the weight of earthworm casts respectively.

Source: adapted from Pauli *et al.*, 2010

Agroecological management approaches benefit from synergies among agro-ecosystem components, such as those generated by tree-crop-soil-livestock interactions. However, trade-offs between productivity and the conservation of natural resources underpinning ecosystem functions and soil-based services can be a challenge for overall system sustainability. This suggests that the principles of agroecological management highlighted above should be expanded to include the need to minimize trade-offs and maximize synergies. Management options to reduce trade-offs include the identification of optimal spatial and temporal arrangements of crop components (e.g. rotations and intercropping) and how to best use limited organic resources. An example of a management practice that exploits synergies by addressing several constraints at once is the pruning of trees to reduce competition for sunlight with crops in agroforestry systems. This simultaneously generates biomass for mulching that can be used to conserve soil water and control erosion (Pauli *et al.*, 2012). The management of agro-ecosystems always involves the use of resources, principally labour in the case of managing soil health. Ultimately it is these trade-offs in terms of the resources required to produce a given benefit that determines what is feasible in the context of different farming systems.

The large number of farmers who manage soils around the world, across a diverse range of biophysical and socio-economic contexts, hold a wealth of accumulated experience and knowledge. This knowledge has been developed over generations and is an important resource that could provide valuable insights on the management of soil health (Barrios and Trejo, 2003; Barrios *et al.*, 2006). This knowledge is not only a legacy of tradition but a dynamic resource, constantly updated as farmers observe and experiment (Joshi *et al.*, 2004). Moreover, it relates to a range of ecosystem services in addition to productivity, as well as the trade-offs that exist among them (Cerdan *et al.*, 2012). The integration of local and technical knowledge is the focus of a novel methodology developed through South-South collaboration between Latin America and Africa, InPaC-S: Participatory Knowledge Integration on Indicators of Soil Quality (Barrios *et al.*, 2012a). This knowledge-sharing tool is designed to guide workshops and fieldwork, bringing farmers and technical agricultural professionals together to facilitate the joint development of farming solutions to support soil health, taking into account the local contexts and circumstances that farmers face. The integration of local and technical knowledge constitutes one of the central strategies of the 'research *in* development' paradigm proposed by Coe *et al*. (2014), in order to guide the scaling up of agroecological management practices and achieve large-scale impacts on farmers' livelihoods.

FUTURE CHALLENGES AND OPPORTUNITIES

We identify four key areas where future challenges and opportunities exist to advance the agroecological management of soil health.

Opening the black box:

The notion of the soil as a living resource whose health is essential for agricultural sustainability is emerging as it becomes possible to 'see' soil biota more clearly within what was previously considered a 'black box'. Using the growing suite of new technologies to open this black box will allow us to develop a more generalizable understanding about how to manage soil biodiversity and function. This is particularly important in the context of the demands of climate change adaptation.

Above-ground/below-ground interactions:

Developing a better understanding of the way in which agricultural management and soil biota interact is a necessary prerequisite to determine the plant densities, arrangements, species and management systems that are needed to generate a sufficient quantity and quality of biomass, while maintaining the essential ecosystem functions provided by soil biota in agricultural landscapes.

Mapping soil-based ecosystem services:

Identifying, quantifying and mapping hotspots of ecosystem service providers will contribute to a predictive knowledge of soil-based ecosystem services. This includes the temporal and spatial dynamics of ecosystem service provision resulting from various environmental factors.

Soil health monitoring systems:

Developing local soil health monitoring systems to evaluate ecosystem service provision performance can help to guide local policy (e.g. as part of payments for ecosystem services schemes), while complementing national and international monitoring systems that are aimed at high-level natural resources management and policy (Shepherd *et al.*, 2015).

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07

ECOLOGICAL APPROACHES: CONTRIBUTION OF ENTOMOLOGICAL DIVERSITY INCLUDING POLLINATORS IN FOOD PRODUCTION SYSTEMS IN EAST AFRICA

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Abstract

While pest organisms (including insect pests, diseases and weeds) have long been the focus of crop health research, singular approaches to their control have often resulted in escalating costs and pest resurgences. In contrast, agroecological approaches seek to restructure and manage agricultural systems so that an array of biological interactions are in place and serve to prevent or reduce pest damage. These interactions go beyond simple biological control to include measures such as: (i) cultural practices – often based on traditional knowledge – including polycropping, planting of diverse genetic mixtures and maintaining diverse multipurpose hedgerows; (ii) building healthy soils to grow plants that can tolerate or fend off pest attacks; (iii) enhancing or introducing natural enemies; and (iv) using insects' own chemical signals to alter their behaviour. A further ecological synergy, only recently well understood, is that by increasing diversity on a farm and reducing reliance on pesticides, the abundance of pollinating insects can be increased, resulting in better yields of pollinator-dependent crops. We highlight ways in which the complex management of these biological interactions has shown inherent strengths and delivered benefits to societies in Kenya and East Africa, including enhancing food and nutrition security, reducing production costs and improving health outcomes.

INTRODUCTION

The concept of agroecology and its application is not new, but it has been gaining interest from practitioners (both farmers and experts) in East Africa. Agroecology relies on maximizing the benefits of nature, by optimizing ecological processes for maximum, and often more diverse, farm outputs. External inputs play a secondary role in agroecological production systems and are not first choice for required farm inputs, while inputs generated on-farm to control pests, build soil fertility and promote pollinators are the main focus. Agroecological practices are knowledge based and depend on building experience. In recent times, agroecology has incorporated production systems as well as the economic and knowledge systems that support sustainable agriculture. This implies that agroecological farming systems have to be responsive to the socio-economic and broader livelihood needs of communities and information is required to support such systems.

East Africa is composed of countries that are reliant on agriculture for both economic well-being and for food and nutrition security. The majority of farmers have small-scale operations (with less than one ha per household). They are mainly subsistence producers, with the primary objective being production for household self-sufficiency, with any surplus being sold to the market. There are a few large-scale (>100 ha) farms in Kenya and other East African countries managed by large commercial companies.

The production sector in Kenya shows a range of intensification levels, including farms applying various aspects of agroecology. Very small-scale farmers growing for household self-sufficiency are more inclined to implement various agroecological practices, based on traditional knowledge. Small-scale farmers that are commercial in orientation are more dependent on external inputs. On the other hand, large-scale growers are highly mechanized and modernized in their farming operations and their farm operations have grown to include agroecological practices that conserve pollinators and natural enemies as well as building healthy soils through composting.

Small-scale farmers in East Africa used to be de facto organic growers, having little access to or use of agrochemicals, including both pesticides and inorganic fertilizers. However, there has been a vast expansion of pesticide use (including herbicides) throughout farming operations in East Africa especially among commercialized production in smallholder systems (e.g. Mbakaya *et al.*, 1994; Schaefers, 1996). The subdivision of land in the region has been a major concern for agricultural, land and food security experts (Mwagore, undated). Already households are subdividing their small land units to share amongst their children, which is a common inheritance culture. Recently in Kenya there were attempts to cap the lowest level of subdivision possible. While this has not yet succeeded, discussions on the issue still continue. With such small, often uneconomic pieces of land, farmers often overuse (in frequency and dosage) pest control products out of fear of losing the small production upon which their families depend (e.g. Ngowi *et al.*, 2007). However, farmers still depend primarily on natural processes to restore soil fertility, applying relatively small amounts of inorganic fertilizers. In addition, small-scale and family farmers have a wealth of local and traditional knowledge on managing their often marginal environments to sustain production. This knowledge is acquired through families and shared among farmers.

The convening of the International Symposium on Agroecology for Food Security and Nutrition in 2014 provided an opportunity to take stock of the status of agroecological approaches to pest control and pollination services in an East African farming context. Traditionally, agroecology has been highly elaborated in Latin America, and in North America and Europe to some extent.

The formal recognition of agroecology in Kenya and East Africa provides a framework for understanding how a transition to a more regenerative, sustainable agriculture can build on local and traditional knowledge, while introducing scientific understanding of biological interactions (particularly among insects) that control pest outbreaks and contribute to crop yields. The goal of applying an agroecological framework to farming systems research in Africa is not singularly focused on a narrow aim of reducing external inputs but is to build production systems that have stable and abundant yields, while generating multiple benefits for the health and livelihoods of farming communities.

This chapter explores the application of agroecology in the context of pests and useful insects in East Africa. It discusses ways in which practitioners and countries can gain from practical agroecology. It outlines practical strategies that are already in place and being implemented in the region and suggests weaknesses and threats that may slow agroecological application towards environment and economic responsive pest and pollination management.

CONTEXTUAL FRAMEWORK

Insects generally suffer from very poor publicity in the region. To most people, and particularly to farmers, they are seen as a problem. As such, farmers tend to place great importance on controlling infestations, particularly those that are easily visible. For example, farmers can observe whiteflies infesting crops and hence take action against them as not doing so may well lead to reduced or no yields.

Figure 1. **Damage to maize caused by stem borers in Embu District, Kenya**

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Pest organisms (including insect pests, diseases and weeds) have long been the focus of crop health research in East Africa. Yet singular approaches to their control have often resulted in escalating costs and pest resurgences. While integrated pest management (IPM) is encouraged, IPM research in East Africa has often been centred on a single-strategy solution, targeting pest control with a small array of control measures. Moreover, IPM has challenges in implementation that might be addressed by adopting a broader, more holistic agroecological approach. In a recent study of the obstacles to IPM adoption in developing countries (Parsa *et al.*, 2014),

IPM professionals and practitioners noted that major challenges are "insufficient training and technical support to farmers" and a sense that "IPM requires collective action within a farming community". Thus, the stress within agroecology on farmer training and knowledge management, as well as community and social empowerment, makes it a valuable approach to addressing some of the limitations of IPM. It is also important to note the most IPM systems in horticulture (especially greenhouses) currently rely on non-native, artificially reared biological control organisms that typically originate from Europe/North America. The use of local species in development of IPM in East Africa remains low. This is a potential area for increased research and development. One important reason for reducing use of non-native biocontrol agents is the impact they have on the native populations. Because they are often more aggressive, the non-native species tend to out compete the local species, contributing to a decline of these native species. With increased research, it would be possible to identify the best highly competitive biocontrol agents for use in the region.

It should be noted that local research systems largely lack experience in application of ecosystem-based pest management strategies. Thus, ecosystem-based pest control strategies that are promoted through agroecology are largely theoretical at this point (with the exception of the well-researched push-pull system, mentioned below). Nonetheless, the ability to manage diverse agro-ecosystems and optimize their production with minimal resources is something that farmers have been doing in East Africa throughout time; agroecology is built on the basis of this local knowledge.

Agroecological approaches seek to restructure and manage agricultural systems so that an array of biological interactions are in place, which serve to prevent or reduce pest damage to uneconomic levels[1]. These interactions are not only biological but also include knowledge intensive measures that work together to disadvantage pests, encourage natural control and pollinating agents, and enhance the growth of health crops. This study highlights ways in which the complex management of these biological interactions in relation to insects and their relatives has shown inherent strengths, in the context of East Africa. These relatives include invertebrate pests such as millipedes, mites and molluscs, which have increasingly become major crop pests in the region (e.g. Kasina *et al.*, 2012). The main focus is on the agroecological attributes for managing these organisms. Selected examples are given, illustrating how these approaches have been successfully applied. We concentrate on those strategies that already have wide application in East Africa, basing examples not only on published evidence but also on our experiences working in the region.

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[1] Uneconomic levels refer to a level of pest damage whereby the cost of pest control is higher than the expected gain. At this point it is not an economically sound action to initiate control measures.

AGROECOLOGICAL STRATEGIES WITH POSITIVE IMPACTS ON ARTHROPOD MANAGEMENT THAT ENSURE DELIVERY OF FOOD AND NUTRITION SECURITY

Cultural practices

These are crop management practices that are not necessarily targeted at managing crop pests but make the crop environment more disadvantageous to the pests and more advantageous to pollinators, such as bees. The practices are equally important in enhancing crop growth and are known to enhance crop yields. The strategies are often based on farmers' experiences as well as scientifically proven strategies that are promoted to ensure best-crop performance.

Early planting

This is a strategy for rain-fed agro-ecosystems. It involves sowing early before the onset of rains to ensure crops are well established early and hence avoid water stress if the rainfall lessens. By planting early, crops are better able to withstand pest pressures at the times when pests attack and during periods of outbreaks. Farmers in north Kitui County (Kenya) have learned to escape armyworm outbreaks by planting early so that the crop is less vulnerable, while late-planting farmers bore all the effects of the pest outbreak. Recently, there is evidence that suggests farmers in Kenya who plant maize early in the season are less affected by maize lethal necrosis disease (MLND) compared with those who are late in planting (*Daily Nation*, 2014).

Synchronized planting

Farmers are encouraged to sow at same period in a season. This helps by having crops of similar age in a wide area, which ensures farmers share pest problems, reducing the overall pest impact in the area. For example, the impact of MLND in Bomet, Kenya, which is a recent disease problem causing total maize loss, has been contained through synchronized seasonal sowing and observing a closed season. Farmers have been advised of which dates of the year to plant and there is an established monitoring plan by extension officers and farmers to ensure this is adhered to. Farmers were able to harvest a crop of maize after following these recommendations (e.g. *Daily Nation*, 2014).

Another example is the growing of pearl millet in north Kitui County. From the 1960s to the early-1990s, almost all farmers grew pearl millet and planting was synchronized. As a result, the impact of the Quelea bird pest was low, partly because of shared infestations. Another major contribution to pest management was scaring of birds using family labour. However, this has drastically reduced because of declining household sizes and an increase in children's school attendance. As bird pest management has become less effective, fewer farmers are cultivating millet. Because fewer farmers are growing millet, synchronized planting is no longer effective and the remaining millet farmers risk losing their entire crops to the Quelea birds.

An array of cropping systems, such as mixed cropping and intercropping

Farmers often grow various crops at the same time to spread the risk of failure by any single crop. At the same time, pest pressure is reduced (e.g. Risch, 1983; Hasheela *et al.*, 2010) as pests have difficulties in finding their preferred hosts. In other instances, plant volatiles may affect host searching by the pest. Challenges in implementing these systems depend on the end goal of the farmer, which determines the spatial arrangement of the polycropping system. For example, those farmers focused on growing crops for markets are more likely to implement monocropping in a single plot, whereas those growing for food have a more heterogeneous crop arrangement, including intra-cropping. In Uganda, it was observed that beans grown in a mixture of varieties contained fewer pests compared with those grown in a monoculture system (Mulumba *et al.*, 2012).

Push-pull strategy

This is a companion cropping system whereby plant volatiles are used to manage key pests; both to repel pests and to attract beneficial organisms. It has been used very successfully in East Africa particularly for maize pests and weeds (Cook *et al.*, 2006; Khan *et al.*, 2008; 2014). The original system was based on repelling stem borer (a major maize pest) by the smell of *Desmodium* spp. planted as an intercrop between maize and millet ('push'). Napier grass is planted as a border crop and it attracts the stem borers away from the maize field ('pull'). *Desmodium* spp. can also fix nitrogen and neutralize the *Striga* weed by facilitating mortality of *Striga* seeds. This increases yields without the use of inorganic fertilizers and pesticides. Farmers not only benefit from higher yields of maize but also two types of fodder, Napier grass and protein-rich *Desmodium* spp. To date this technique for stem borer and *Striga* control on maize farms has been adopted by about 90 000 smallholder farmers in East Africa, increasing maize yields from about 1 tonne ha^{-1} to 3.5 tonnes ha^{-1} (Khan *et al.*, 2014). The push-pull strategy is based on locally available plants, not expensive external inputs, and fits well with traditional mixed cropping systems in Africa.

Indigenous technical knowledge (ITK)

This strategy of pest management is based on traditional knowledge about the crop and pest relations. Over many years, farmers have built knowledge on how to deal with various crop pests. The current ITK strategies can fall in various pest management categories, especially the botanical pesticides and physical control methods. Just a few examples of the many ITK methods used in East Africa include:

- Use of plant extracts applied as spray or dust formulation (such as chilli, garlic or pyrethrum) (e.g. Infonet-biovision, 2014). Farmers use diversified methods of developing effective concoctions based on the target pest.
- Smoking pests with the smoke of specific plants. This is a common method for the management of stored maize pests and against aphids and other piercing-sucking insects that are pests of cowpea in north Kitui County.
- Use of ash from select plants, usually as a dust or spray formulation. Ash is also widely used to control ants and termites, with the added benefit of improving soil nutrient content.

Use of plant genetic diversity

Farmers inherently tend to plant multiple varieties. Research from Uganda (Mulumba *et al.*, 2012) shows the strong scientific logic behind this; growing different varieties of the same crop together consistently shows a decreased spread of pest and disease damage. Farmers in East Africa grow over 60 different varieties of beans and on-going research (Mulumba *et al.*, 2012) is showing how different mixtures of these varieties can be combined to be more effective in controlling pests and diseases. Therefore, diversity, even within a crop species, brings varying levels of resistance against the pest and thus contributes to resistance management of the pest. Further studies may be required to understand the best polycropping system that combines the various varieties of crops while securing farmer objectives of self-sufficiency or income generation.

Maintenance, planting and encouraging the use of hedgerows

Hedgerows that are intended for multipurpose usage (e.g. source of traditional medicines, browse/forage for livestock, aesthetic and security purposes) also have strong by-product benefits, providing resources for pollinators by serving as host plants for insects such as hawkmoths that pollinate papaya, and providing a habitat for beneficial insects to readily access the crop. For example, farmers in the Kerio Valley plant and maintain highly diverse hedgerows that include both nectar forage plants and larval host plants for hawkmoths (Lepidoptera: Sphingidae) that pollinate the dioecious crop papaya (Martins and Johnson, 2009).

Water Conservation practices

Farmers in dryland areas create bunds, seepage areas and terraces that are stabilized using natural vegetation, fallow or planting. These serve to increase on-farm biodiversity and serve as nesting areas for many ground-nesting bees. These areas also harbour spiders, dragonflies and praying mantises, and other natural enemies, all of which consume pest species (Martins, 2015).

Physical and mechanical control methods

Physical control methods include measures that create barriers so that the pests find it difficult to access the crop, thus lowering infestation. The most commonly used method is the greenhouse, where crops are grown in a favourable environment for growth. At the same time, the structures prevent pests from accessing the crop. A recent low-cost example for smallholder farmers in Africa is the use of low cover nets, usually placed about 10 cm from the plant canopy and supported by twigs (Martins *et al.*, 2009). Mechanical approaches are rarely used because many farmers believe they are tedious. However, these methods are highly effective and can drastically cut farm production costs associated with pest control. Examples include squashing of insects (i.e. killing them by squeezing). It is noteworthy that, for example, most adult moths lay 200-1 000 eggs in their lifetime. Therefore, squashing a caterpillar can prevent several new individuals infesting the crop. Caterpillars are the easiest to squash, as they are slow to move and are easily recognizable.

Figure 2. **A crop grown under low cover pest and microclimate management net at KALRO, Kabete**

Building healthy ecosystems to grow plants that can fend off attacks

Healthy crops are the first line of defence against pests. Plants that are weak, probably due to insufficient soil fertility, are unable to tolerate pest problems and are vulnerable to harsh weather conditions. To ensure crops are vigorous and productive, their supporting ecosystems have to be managed in a manner that ensures their ability to produce and deliver diverse services in a healthy manner. Building healthy ecosystems is highly reliant on practices and institutional support as described below:

- ***Agronomic practices:*** are practices that enhance crop growth through preventing/reducing weed competition and enhancing soil fertility to grow a healthy plant capable of tolerating other challenges such as weather and pests. Some of these practices include conservation agriculture (CA), minimum/zero tillage and organic fertilization. FAO has been at the forefront of promoting CA in smallholder farming systems in East Africa (e.g., Kaumbutho and Kienzle, 2007; Nyende *et al*., 2007; Shetto and Owenya, 2007). The system comprises a combination of various strategies: (i) minimum or no disturbance of the soil; (ii) permanent soil cover; and (iii) crop rotation. This is done using locally suitable methods to deliver the three key elements. CA has been practised in East Africa for more than two decades and the number of farmers adopting it is increasing every year (Derpsch and Friedrich, 2015). Where it is not fully adopted, the reasons vary, but may include aspects of land ownership, knowledge, policy support and socio-economic considerations (Friedrich and Kassam, 2009). Therefore, it is necessary to tailor CA to suit local conditions (Knowler and Bradshaw, 2007).

- ***Farmer training:*** Investment in farmer training and extension, particularly through the format of Farmer Field Schools in East Africa, has a long history of multiple rewards. However, support for farmer training is often project based and not sustained. Government recognition of the value of farmer training, particularly for knowledge-intensive agroecological approaches (rather than conventional input-intensive approaches), is critical.
- ***Regulatory measures:*** East Africa has enhanced its phytosanitary regulations, particularly among partner states during the past 10 years, and countries have been developing common regulations (EAC, 2014). The region has moved to standardize phytosanitary operations to improve trade and protect the region's agriculture from new pest problems. By having strong regulatory measures in place, new pest entries are reduced, ensuring the health of agro-ecosystems and crops.
- ***Quarantine strategies:*** In some instances, the region uses quarantine measures to halt the spread of a new pest in an area. This is effective for those entries that are noticed at an early stage and confined to an area. The objective here is to prevent further spread and find a mechanism for constraining the area of the pest.
- ***Integrated crop management policies:*** Governments in East Africa are keen to ensure that farmers adopt effective crop growing technologies. Policies that support crop development, including soil health and water conservation are promoted. Policies that go beyond soil and water conservation, to address the ecosystem services that underpin agroecology, are not yet well articulated in the region, or even globally.

Enhancing or introducing natural enemies to manage pests

All living organisms have natural enemies, which check their population through predation, causing disease or competition for resources. The natural enemies of pests are classified as predators, parasitoids or disease-causing pathogens. These occur naturally and co-evolve alongside each pest. Managing pests with natural enemies is also referred to as biological control, and has been a major success in East Africa against various pests. There are several ways that natural enemies have been used to manage pests.

Farmer training on natural enemies that occur in their farms

Farmers have been trained on the natural enemies that occur on their farms such as spiders, ladybird beetles and wasps. This training has been geared towards *in situ* conservation of natural enemies so that farmers, while using various crop management practices, can take care of these useful organisms.

Classical biological control

This includes importation and mass production of a given natural enemy for introduction in the country, in particular to control exotic pests. This approach has been successfully applied for various pests including cassava green mite, cassava mealybug, diamondback moth (pest of crucifers), stem borers (mainly on maize) and for larger grain borer (on maize and dried cassava).

Augmentation of natural enemies in the agro-ecosystem

Most of the natural enemies that have been imported and released in the wild have always been augmented to ensure the pest population is brought down. In addition, there is a growing market of natural enemies in Kenya and various companies have been established to produce and trade in biocontrol products. The biocontrol products include parasitoids, predators, entomopathogenic fungi and nematodes, and antagonists for soil borne diseases. This approach is being widely used in the horticultural sector for control of pests in greenhouses on both crops and flowers and has led to the growth of an industry for the production of these agents over the past decade. Notably, as with chemical control methods, there is evidence that targeted pest species can evolve resistance, especially to entomopathogens (e.g. Shelton *et al*., 1993). This requires careful selection of the product and the development of an effective resistance management package.

Using insects' own chemical signals to alter their behaviour

Insects use chemical signals (pheromones) to communicate within a species or across species. Over time, scientists have studied insect communication signals and identified molecules that can be used to manage pests by altering their behaviour. For example, sex signals are the most utilized in pest management to attract (mainly) males to a common place, for the purposes of killing them. The attractant is laced with an agent to kill males who are attracted by the cue, as they seek to find their mate who would be producing this signal under natural circumstances. Reducing the number of mating males results in fewer females being fertilized, and hence the population is reduced over time. The use of sex pheromones in East Africa has increased in the past two decades, and there are various products available for different pests (e.g. Thomson *et al*., 1999). For example, there are products for tomato leafminer, *Tuta absoluta* (the newest pest in the region), diamondback moth (*Plutella xylostella*) and African bollworm (*Helicoverpa armigera*).

Another form of attractant is the protein bait. Most insects seek protein and energy as food for their growth and reproduction. For example, female fruit flies require protein to attain normal fertility and stimulate egg production. The protein bait is used to attract insects and is usually laced with a chemical that kills them. In addition, the protein slurry can drown the attracted insects. In East Africa, protein baits are currently used in the management of fruit flies. While this method does use toxic chemicals, the impact is restricted to the insects that are attracted into the bait by using pheromones that are specific to the target pest species. Baiting is also used in horticultural settings to effectively control molluscs (slugs and snails). Passive traps that contain a chemical or biological bait and/or visual attractant to insects have also widely been employed in the control of tsetse flies (Dransfield *et al*., 1990; Holmes, 1997; Allsopp, 2001).

Utilizing Integrated pest management strategies

Integrated pest management is not a technology as such but a raft of measures put in place to manage pests. Such methods are supposed to be compatible to deliver efficient pest control solution, which is economically viable. IPM is a knowledge-based pest management strategy that relies on scouting to make decision on what options to use, after considering the pest threshold limits. In east Africa, IPM is widely promoted but has not been fully defined in terms of the minimum level of technology applications on a crop cycle that can be defined as applied IPM practices. However, by appreciating the need for IPM, farmers continue to improve and reduce their applications of pesticides.

Pollination management strategies

Pollination is a precursor to the fertilization of many flowering plants and hence an important process in crop production. In Kenya, pollinating insects make highly significant contributions to the crop yields of various pollinator-dependent crops. There have been efforts to develop strategies for conserving pollinators in the farmland. The idea is to ensure the farmland can sustain pollinator presence in sufficient numbers for the benefit of crops grown there. A further strategy is to enhance the contribution of protected areas in provision of pollination services in the bordering farmlands. Strategies for pollinator conservation are usually friendly to the environment and include (but are not limited to):

- ***Keeping hedgerows in the farmland:*** Such plants provide pollinators with pollen and nectar throughout the year. They also provide nesting sites for various bees.
- ***Agronomic practices:*** farmers are trained in practices that are friendly to pollinators, in order to protect and enhance pollinator floral resources and nesting sites. Examples include CA practices, polycropping and ensuring the presence of unfarmed patches of land within the farm, among others.
- ***Pest control practices:*** farmers are advised to adopt practices that are friendly to pollinators and avoid those harmful to pollinators. For example, increased adoption of IPM and reduction of toxic pesticides.
- ***Tailor-made bee nest provision in farms where farmers allow deadwood in strategic places for tunnel-nesting bees:*** This is a practical pollinator management strategy in Brazil for passion fruit growers and studies are being carried out in Kenya to establish ways of ensuring this strategy is implementable with success in passion fruit orchards.
- ***Supply of managed beehives for pollination on farms:*** While this is a limited practice at present, a number of growers in high-production intensive horticultural systems are using managed beehives for pollination of passionfruit, runner-beans and courgettes, so as to meet standards of yields for export.

Figure 3. **Farmers graduating after season-long Farmer Field School training on pollination**

CHALLENGES AND THREATS IN AGROECOLOGY PRACTICE IN EAST AFRICA

Any technological and innovative farming intervention usually faces challenges and threats during its implementation. Agroecological practices require an improved understanding compared with more widely known direct technologies that support single intervention solutions to a problem. There is much to learn from implementation of some practices such as CA. The following points provide some key areas for consideration:

» ***Lack of enabling government policies:*** Some food production policies in East Africa do not support the application of agroecological approaches. Rather, they promote practices that seem to go against agroecological principles, resulting in severe negative impacts on farmers. Inorganic fertilizer use in Kenya provides an example. The use of inorganic fertilizer has grown since the country's independence in 1963 and many farmers believe that they cannot grow crops without using fertilizers. Yet in the last two years there has been greater realization of the increasing problem of acidic and non-responsive soils as a result of the overuse of fertilizers. In such instances, policy measures to support CA and other alternative approaches to restore soil biodiversity would contribute to restoring soil health and preventing many soils from becoming non-productive.

- ***Limited research methods for pest management:*** where the main results are always from agronomic trials as opposed to using ecological approaches to test various management plans. A key research problem is that it is not possible to contain pests within plots, as described in agronomic trials. Most research designs are based on agronomic practices, where it is more important to control soil characteristics. The resulting methodologies create biases when carrying out trials on e.g. insect pests, which require an ecological approach to better understand the implications for management practices.
- ***Insufficient scientific information on biological interactions to support decision making for pest management,*** such as pest life tables and threshold limits.
- ***Major taxonomic impediments with a decline in experts who have provided backstopping for specimens from East Africa:*** The region has limited number of taxonomists of various pests and pollinators. This is a challenge for the adoption of agroecological practices because the foundation of pest management and utilization of biological resources in pest management is heavily reliant on the proper identification of organisms. It is practically impossible to develop any meaningful pest and pollination management programme for organisms that are not well known. For example, before the identification of MLND in Kenya, earlier reports suggested it was a fungal problem, which could have led to the ineffective and extremely costly use of fungicides in an attempt to manage it. The potential costs could have included wide-scale government emergency support to bring the disease to manageable levels, farmer costs of continuing with improper management practices, and aspects of environmental and human health impacts of fungicides, among others.
- ***Lack of capacity in the regulatory environment surrounding pesticides,*** including the growth in importation and use of unregistered pesticides that are causing public and environmental health issues in rural areas.
- ***New and emerging pests and diseases:*** as a result of climate change, environmental degradation, deliberate or accidental introductions and adaptation of existing pests or species undergoing irruptions (Martins *et al*., 2014).
- ***Lack of capacity within extension services available to farmers:*** This includes both a direct lack of access to extension services as well as a lack of current up-to-date practical information within the extension services, and little funding for farmer training. Providing basic information, fact sheets, case studies and best practices is an important step for building more effective agroecological approaches.

CONCLUSION AND THE WAY FORWARD

This chapter focuses only on one aspect of agroecology – those practices that impact negatively on pests and positively on biological control agents and pollinating organisms. Pests are important factors that directly and indirectly contribute to reduced crop yields. Directly, this occurs through damages and indirectly through trade impacts. For example, a consignment would be rejected by an importing country if a pest organism is observed during inspection. Therefore, it makes economic sense to invest in pest management practices to lower their effects on crops.

However, ‘modern’ practices of relying on pesticides have not demonstrated the full results in pest reduction that farmers often expect. This has led to abuses of pesticides and negative effects on humans, animals and the environment. Agroecology incorporates all aspects of pest control, with minimal reliance on pesticides and inorganic fertilizers, creating an agroecological system that is able to offer alternative solutions to pest problems. Natural enemies and antagonistic organisms are essential in reducing the pest population on cropped fields. Pollinating agents are essential for crops and plants that reproduce using flowers. The dependence on these agents extends up to 100 percent for crops where male and female flowers occur on different parts of the plant, such as in most cucurbits. Both natural control and pollinating agents rely on farmers to enhance and sustain their populations in the farmland. The array of practices discussed in this chapter shows plenty of potential for enhancing this important aspect of biodiversity in the farming landscapes in East Africa. Apart from pest control and enhanced pollination of crops, these practices enhance crop growth, leading to higher quality yields. This assures farmers of their food and nutrition sufficiency, and provides economic stability for their households. Benefits at the household level contribute to the economic well-being of countries.

As the agricultural community comes to understand agroecology better, we should recognize that its increased use as an important approach to sustainable food production and environmental sustainability cannot be achieved by only one or a few institutions. There were many aspects of agroecology that were presented in the FAO International Symposium, from people working all over the world. The Symposium can help us all to consider ways that we might work better together, through research networks and other means. We believe there is a strong interest in Africa among many researchers working on aspects of agroecology, whether or not the specific term is used. As discussed earlier, Africa lags behind in the implementation of agroecology *per se*. Nevertheless, based on their own experiences, farmers *are* implementing various forms of agroecology. Consequently, there is strong need for scientific knowledge and proof of practice in these systems. Some world regions have more experiences in agroecology and the sharing of this knowledge can contribute to establishing a strong foundation for agroecology in East Africa.

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08

BIODIVERSITY AND ECOSYSTEM SERVICES OF AGRICULTURAL LANDSCAPES:
REVERSING AGRICULTURE'S EXTERNALITIES

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Abstract

Agriculture faces the dual challenge of feeding a 9-12 billion global population by 2050 and reducing its footprint on the environment. While the impact of agriculture on the environment is well recognized, and there are growing calls for efforts to reduce or mitigate this impact, the ecosystem services approach presents an alternative where ecosystems are managed to support and improve

agriculture. As the world's single largest terrestrial ecosystem, agro-ecosystems must be managed for the multiple goods and services they provide. A principal question for agroecology is whether the large-scale adoption of ecosystem-based approaches is capable transforming agriculture's environmental externalities from negative to positive, while meeting food production needs. Ecosystem services science plays a significant role in this transformation by focusing attention on how biodiversity in agricultural land-uses and landscapes can be managed for multiple benefits. We provide an example from the Volcanica Central Talamanca Biological Corridor in Costa Rica, where significant research has been undertaken, and is beginning to show where synergistic interactions between conservation, agricultural production and hydropower generation can be managed for multiple benefits. We recognize that significant trade-offs can exist. However, focusing attention on these multiple services, understanding their mechanisms, and quantifying the benefits of the trade-offs between the multiple services of agricultural landscapes provides novel solutions and spaces for managing positive interactions between agriculture and the environment.

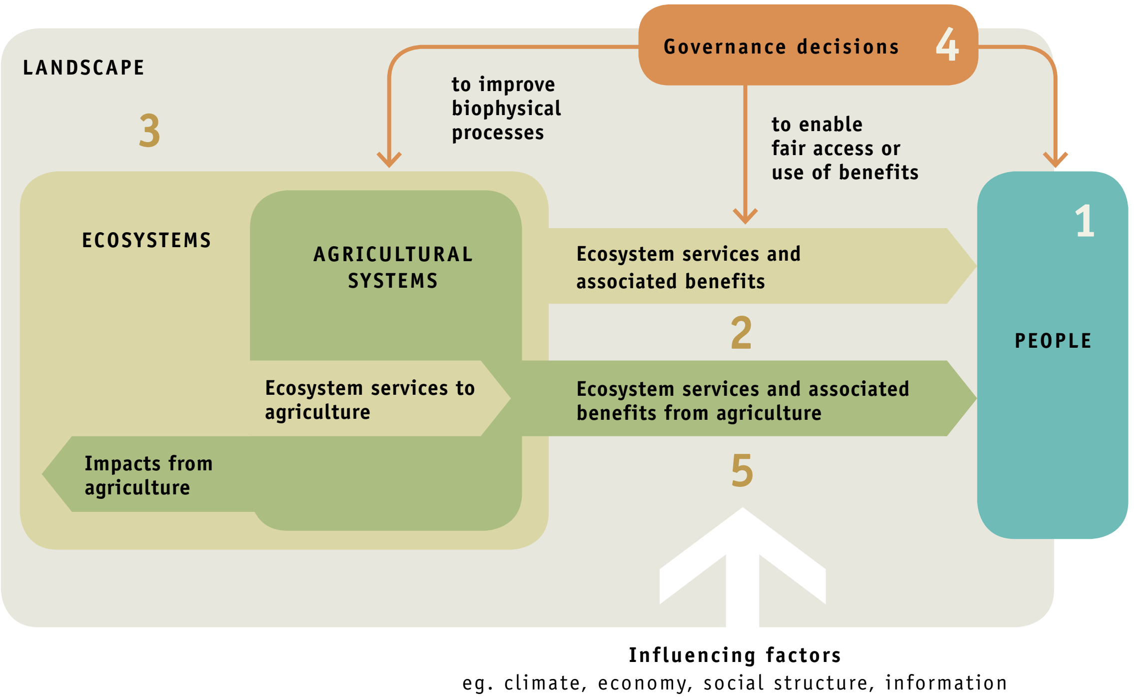
INTRODUCTION

Agriculture is faced with several critical challenges as it enters the twenty-first century. First and foremost agriculture must be managed, or even transformed to ensure that it can provide both the calorific and the nutritional needs of a 2050 population estimated at between 9 and 12 billion. It must achieve this goal without the significant environmental cost of land, water and ecosystem degradation and transformation that have been the signatures of agricultural growth during the second half of the twentieth century – leading to the emergence of the Anthropocene, the proposed name for our current geological era that recognizes the impact of human activities on geological scales (Monastersky, 2015). In reviewing the nine planetary boundaries proposed by Rockström *et al*. (2009) and now Steffen *et al*. (2014), agriculture's footprint is all too visible. This calls for a new vision of agriculture that recognizes the multifunctionality of agricultural systems, and which emphasizes and rewards management options that transform agriculture's externalities from negative to positive.

In their proposed *Solutions for a Cultivated Planet*, Foley *et al*. (2011) identify four key strategies for meeting the dual goals of agricultural production and environmental conservation: (i) stop expanding agriculture; (ii) close yield gaps; (iii) increase agricultural resource efficiency; and (iv) shift diets and reduce waste. While these steps are indeed critical to meeting the dual goals of agriculture, they stop short of proposing how agriculture itself needs to be transformed. As the world's largest and most managed terrestrial ecosystem, covering nearly 40 percent of the global landmass, we believe that agriculture provides the single largest opportunity for ecosystem services-based approaches. Ecosystem services-based approaches to agriculture, which rely on agroecology, are important because they shift our perspective from viewing the environment as a principal victim of agricultural management and expansion, to one where agriculture's dependency on the environment is highlighted, understood and managed.

The ecosystem services-based approach to agriculture recognizes the dual role of agriculture (Figure 1). It recognizes that agriculture is fundamentally dependent on ecosystem services as the foundation of agricultural sustainability (e.g. soil nutrients, water for irrigation and growth, pollination services, pest and disease regulation). It also recognizes agriculture's capacity to provide multiple goods and services in addition to its primary crop production function. Agricultural management can be guided to increase the capacity to store carbon, contribute to biodiversity conservation, and improve water quality and soil fertility (Figure 2A). With growing global pressure on food and environmental systems, we must paradoxically expect more from agriculture; focusing on ecosystem services is one approach that contributes to increasing the capacity of agricultural landscapes to provide these multiple functions (Figure 1).

Figure 1. **The CGIAR Water Land and Ecosystems framework for managing ecosystem services and resilience**



The framework highlights the dual role of agriculture as both depending on, and being a provider of, ecosystem services. The framework emphasizes the need to measure the livelihood impacts of ecosystem services-based approaches, and the need for specific institutions capable of managing services and their benefits. The numbers indicate five principles that are critical to managing the ecosystem services of agricultural landscapes: (**1**) meeting the needs of poor people is fundamental; (**2**) people use, modify and care for the environment, which provides material and immaterial benefits to their livelihoods; (**3**) cross-scale and cross-level interactions of ecosystem services in agricultural landscapes can be managed to positively impact development outcomes; (**4**) governance mechanisms are vital tools for achieving equitable access to, and provision of, ecosystem services; (**5**) building resilience is about enhancing the capacity of communities to sustainably develop in an uncertain world.

Figure 2. **The multifunctional goals of agricultural systems**

(**A**) While the production role of agriculture is fundamental in meeting the needs of a 2050 population, meeting both global production and conservation goals requires important contributions from agriculture. This requires a shift in thinking from a single function vision of agriculture to a multifunction vision where agricultural systems are expected to contribute to development goals, environmental goals and food security goals.

(**B**) Murray (2014) identifies the components of a low risk diet and compares the demands for these components to their supply from global production systems. This comparison makes the link between food production systems and human health. It also highlights the critical need to diversify production systems to increase the production of seeds, nuts, fruit and vegetables.

This is the fundamental hypothesis posed by the CGIAR research programme on Water Land and Ecosystem's framework for ecosystem services and resilience (WLE, 2014; Figure 1). Notably, it recognizes agricultural ecosystems as ecosystems, or agro-ecosystems, in and of themselves rather than as separate entities (i.e. agricultural systems and ecological systems). While the relationship between natural and agricultural systems is retained, this recognition facilitates the management of agricultural systems and agricultural landscapes for ecosystem services provision, rather than the more traditional notion of focusing on how natural systems embedded or adjacent to agricultural landscapes provide services to agriculture. Second, it highlights the strong link between agricultural systems and human well-being, and the capacity of agro-ecosystem services to contribute to those livelihood outcomes. Because agricultural systems are fully managed (in comparison with protected areas), the scope and opportunity space for managing services though land use and landscape change is much greater than with natural systems that often have specific protections. A further distinction that arises when considering agricultural landscapes is that the conservation focus can become secondary to the livelihood benefits. The growth of research on the ecosystem services of agricultural landscapes, particularly in the developing world, is driving new research aimed at better describing, defining and measuring the specific impacts of ecosystem services provision on human livelihoods and well-being (DeClerck *et al*., 2006; Ingram *et al*., 2012; Wood and DeClerck, 2015). Finally, the framework highlights the need for new or adapted institutions that are capable of fostering the coordination, negotiation and implementation of landscape management for multiple goods and services.

The vision we propose is one of agricultural multifunctionality, where agricultural systems and landscapes are valued and managed for the multiple benefits they provide. The challenges of twenty-first century agriculture necessitate a vision of agriculture that contributes to environmental protection rather than environmental degradation, and of an agriculture that moves beyond the boundaries of its primary function of food or calorie production. For example, can we envisage an agriculture that provides not just calories, but also a nutritionally complete production? In a presentation at the EAT Stockholm Food Forum, Murray (2014) highlighted that the global production system is unable to provide the current population with the ingredients of a low-risk diet; the current global food system under-produces fruit (-44%), milk (-49%), seeds and nuts (-68%), and vegetables (-11%). At the same time Murray estimates that we have a greater proportion of fish (+48%), red meat (+468%), and grains (+54%) being harvested and produced, than is needed in the low-risk diet (Figure 2B).

In addition to shifting agriculture so that it provides nutritionally complete diets, we increasingly expect that agricultural systems will contribute to improving human health, while enabling equitable access to healthy foods (Figure 2A). However, agricultural systems must also contribute to global environmental goals and thus we must push for the management of agriculture so that it contributes to carbon sequestration, biodiversity conservation, soil formation, water quality and conservation, and provides an increase in farmers' livelihoods.

While this vision or challenge for agriculture may seem idealistic, there is evidence that agricultural systems can provide these multiple benefits. In a review by Milder *et al*. (2012), 104 studies were examined, including 574 comparisons between yield and ecosystem services provision in five systems of agroecological intensification: (i) organic agriculture; (ii) System

of Rice Intensification; (iii) conservation agriculture; (iv) holistic grazing management; and (v) precision agriculture[1]. While there certainly is evidence of trade-offs between yields and ecosystem services provision, the majority of the cases demonstrated that yields can remain stable and/or increase with simultaneous increases in ecosystem services provision. The System of Rice Intensification (SRI) was particularly effective in this domain. What was difficult to find however, were specific studies that considered the multiple ecosystem services objectives and the yields of production systems simultaneously. These are increasingly needed to understand the conditions and contexts that support agricultural multifunctionality, and to identify the trade-offs that are most often encountered.

REVIEW OF THE EVIDENCE BASE

Whether trying to increase the capacity of agricultural systems to provide nutritionally complete diets, or aiming to increase the capacity of these systems to provide multiple goods and services, biodiversity is fundamental. The combinations of species in space and time determine what services are provided, when, where, and to what degree (Naeem *et al.*, 2012). Biodiversity in essence serves as the global operating system. Similarly to the operating systems that run computers, allowing users to complete both simple and complex functions, biodiversity serves the same role for ecosystem services. The abundance, combination and configuration of species in space and time determine which services are provided, where, and to what degree. Failure to recognize this decreases the resilience of the global operating system, and fundamentally impacts its capacity to provide for human well-being. In their revision of Earth's planetary boundaries, Steffen *et al*. (2015) place "biosphere integrity" as one of two core boundaries along with climate change, "each of which has the potential on its own to drive the Earth System into a new state should they be substantially and persistently transgressed." Biodiversity is given special attention for two reasons:

> *"The first captures the role of genetically unique material as the 'information bank' that ultimately determines the potential for life to continue to co-evolve with the abiotic component of the Earth System in the most resilient way possible. Genetic diversity provides the long-term capacity of the biosphere to persist under and adapt to abrupt and gradual abiotic change. The second captures the role of the biosphere in Earth System functioning through the value, range, distribution and relative abundance of the functional traits of the organisms present in an ecosystem or biota."*

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[1] Although precision agriculture is not commonly associated with agroecology, we included it because it fits into the broader conceptualization of agroecological intensification as an integrated approach that seeks to boost productivity and efficiency of food systems based on a nuanced understanding of specific crop requirements and environmental conditions (Francis *et al.*, 2003). Including precision agriculture permits explicit consideration of the ways in which technologically intensive practices may contribute to managing agro-ecosystems for multiple ecosystem services.

Unfortunately most Anthropocene indicators show that the state of biodiversity is decreasing, while pressure states continue to mount despite a growing global response to biodiversity loss (Butchart *et al.*, 2010). Steffen *et al.* (2015) similarly highlight that in comparing nine planetary boundaries, the loss of biosphere integrity has passed proposed allowable thresholds which are "beyond the zone of certainly" or high risk. Only the two biogeochemical boundaries of phosphorus and nitrogen cycles share this state and all three of these share important pressures from agriculture. If agriculture is such a significant part of the problem, it can and must be part of the solution. Kolbert (2014) captures the concern well in her book *The Sixth Extinction*: "we are deciding, without quite meaning to, which evolutionary pathways will remain open and which will forever be closed. No other creature has ever managed this, and it will, unfortunately, be our most enduring legacy."

The loss of biodiversity is not only a function of agriculture and its impact on land-use change and invasive species – two major drivers of biodiversity loss – but the feedback effects of this loss on agricultural production functions in a myriad of ways. Measures of agricultural change and biodiversity loss have increasingly been a core tool of ecologists. The research of Daily *et al.* (2001) on countryside biogeography has shown how agriculture drives changes in species composition and richness, as well as the capacity of mosaic landscapes to retain significantly high levels of species richness. A study by Frishkoff *et al.* (2014) took this analysis several steps further. Using avian biodiversity in a Costa Rican landscape, Frishkoff and colleagues demonstrated an important gradient between forests, diversified coffee systems and intensive coffee monocultures in terms of phylogenetic diversity. They conclude that diversified agricultural systems supported 600 million more years of evolutionary history than intensive monocultures but 300 million years fewer than forests. The important message is not only how much evolutionary history we are losing, but also how much we are capable of retaining through agricultural interventions.

Species diversity and evolutionary history are important measures, and relate to the first element of biosphere integrity alluded to by Steffen *et al.* (2015). The second element is more related to functional diversity, and the particular role that species play in the provision of ecosystem functions and services. Several studies show similar trends – shifts from natural to semi-natural and intensive agricultural systems tend to drive changes in both functional composition and richness (Flynn *et al.*, 2009; Laliberte *et al.*, 2010). The implications are that as agriculture intensifies, the functional capacity of organisms to provide services (e.g. to pollinate certain types of flowers or control insect pests) may be eroding faster than the simple loss of species.

Several ecological conditions determine the capacity of biodiversity to provide agroecological services. Understanding these conditions and their interactions are important to the agroecological management of cropping systems. Even for a single ecosystem service, such as pest control, both field- and landscape-scale ecological processes occur simultaneously and interact to keep pest populations from reaching epidemic proportions. Perfecto *et al.* (2004) showed how changes in the canopy structure of a coffee agroforest, from simplified to complex, increased avian functional diversity and subsequently pest removal from test plots. Ricketts (2004), and more recently Karp *et al.* (2013), suggest that proximity to forests is an important driver for bee or bird species spilling over from natural habitats into coffee systems to provide pollination

or pest control services, respectively. Steffan-Dewenter (2002) showed the relationship between landscape complexity and pollinator functional diversity in an eloquent study which highlighted how different species respond to landscape complexity at different scales. This study demonstrated the need to maintain landscape heterogeneity from fine to coarse scales in agricultural landscapes, in order to retain the function and resilience of the pollinator community and the services they provide. This highlights the need for agroecological research and practices to foster an increasing ability to manage the interactions between multiple processes in space and time, to provide the multiple functions and services sought from agricultural landscapes.

CASE STUDY: THE VOLCANICA CENTRAL TALAMANCA BIOLOGICAL CORRIDOR

Setting the scene

The Volcanica Central Talamanca Biological Corridor (VCTBC) provides a good case study for demonstrating some of these interactions within and between scales (field, farm and landscape), and highlights three directions in which agroecological research should proceed in order to support the transformation of agriculture's externalities from negative to positive. In this case study, we focus on two specific functions of agricultural landscapes: pest control, and connectivity for wild biodiversity. Other agroecological functions have been studied in this same landscape, notably sediment reduction linking the erosion control needs of hydropower structures with up-stream farm management through a payment for ecosystem services scheme. Sediment control interventions can have important interactions with the pest and connectivity functions (Estrada-Carmona and DeClerck, 2012). The focus in this chapter is on a specific pest, the coffee berry borer, and connectivity for avian biodiversity. We chose this case study for several reasons, but most importantly because it demonstrates a specific example of an ecosystem services-based approach to landscape management, and of the need to consider multiple agroecological functions simultaneously and across scales, even when considering a single ecosystem service.

The case study focuses on three scales. At the coarsest scale, we focus briefly on the Mesoamerican isthmus, followed by more detailed descriptions of the VCTBC, and finally on a single farm at the centre of the corridor and its land uses. These three scales interact; in particular, the actions taken to manage farmscapes at the finest scale can be scaled up and contribute to preserving functions at the largest scale of the Mesoamerican region (DeClerck *et al.*, 2010).

Mesoamerican Biological Corridors

The Mesoamerican Biological Corridor (MBC) is an ambitious project launched in the 1990s by conservation organizations, aiming to foster biological connectivity between southern Mexico and northern Colombia. Conceptually, the corridor would allow a jaguar to traverse though the isthmus without leaving forest cover (hence the association of the MBC with *Paseo Pantera*, the panther's trail). The initiative struggled to gain broad support, in part because of the challenge of motivating local populations to alter land-use practices to facilitate jaguar mobility. However the notion of the corridor continues to develop and is particularly strong in Costa Rica where regional corridors receive national recognition. This is the case of the VCTBC located on the country's Caribbean slopes. Unlike the biological corridors that conjure images of linear strips of forest connecting two forest patches, the biological corridor is a 140 000 ha mixed-use matrix comprised of sugar cane, pastures, coffee plantations and forest. The primary livelihood functions of the corridor centre around agricultural production, energy generation through three dams located on the Reventazón River, which bisects the corridor from southwest to northeast, and to a lesser degree on tourism via rafting on the adjacent Pacuare River.

The corridor itself was initiated by the Association of Organic Farmers of Turrialba (APOT), who were concerned about the impact of land-use activities on environmental quality and conservation in the region. The conservation of ecosystem services became one of the ways that APOT was able to galvanize support for the creation, coordination and management of the corridor. Currently, the corridor management committee includes representatives of public and private stakeholders who make use of the landscape. For these stakeholders, biodiversity conservation, hydropower, water quality and agroecological services support their economic and social priorities. Linking increased efficiency of hydropower to soil conservation in erosion-prone regions of the corridor has been an interesting case study in and of itself. For this example, Estrada-Carmona and DeClerck (2012) demonstrate how a specific ecosystem service beneficiary can be linked to an ecosystem service provider, targeting land-use change for service provision.

Connecting conservation and fragmenting agriculture

From an agroecological perspective, through consultation with farmers in the region, pest and disease control was identified as the principal ecosystem service of interest to coffee producers – specifically the control of the coffee berry borer (*Hypothenemus hampei*) – an important agricultural pest of coffee landscapes in Central America. Unlike pollination, which can remain a rather abstract service to some farmers, the control of the coffee berry borer resonates very clearly.

Where coffee is present all year-round, as it is in the VCTBC corridor, the coffee berry borer exceeds eight generations a year. The female coffee berry borer pierces coffee beans laying her eggs in the endosperm. The larvae feed on the endosperm, effectively destroying the bean. The adult female then emerges from the fruit in search of new fruit to colonize. Drilling of a new berry in optimum conditions may take a female up to 8 hours, and this is likely to be one of the stages when the pest is most vulnerable to predation. There are several control mechanisms. One of the most effective (but most labour intensive) is the complete removal of coffee beans (both ripe and unripe, on and off the plant) from the coffee plantation during the harvest. This works to disrupt the reproductive and dispersal cycle. More common is the use of agrochemicals, including the highly toxic pesticide, endosulfan.

From an agroecological perspective there are four leverage points for the control of the coffee berry borer. As described above, clearing farms during harvest is effective, but labour intensive. A second method is to increase the genetic diversity of the cultivated crop to reduce pest and

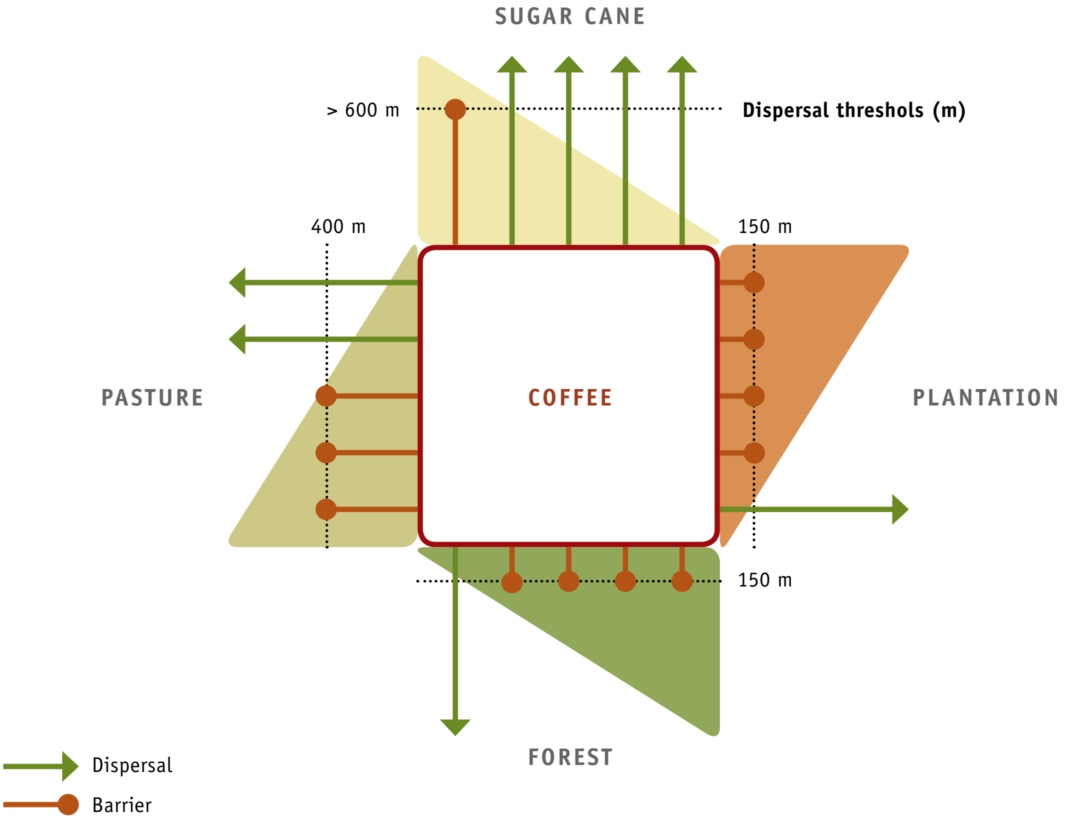
disease risk, though this is not a common or explicit practice used for coffee. The third method is to alter the agroecological conditions of the plot to make the habitat inhospitable for the coffee berry borer. This can be accomplished by several ecological processes, for example utilizing agroforestry to change the environmental conditions of the plot (i.e. temperature, humidity, exposure, wind velocity). There are some studies in the corridor to this effect, though these are more focused on the management of fungal pathogens with narrower environmental limits. Altering the habitat can also include increasing the predator density. This was demonstrated by Perfecto *et al*. (2004) where increasing the structural complexity of the tree component in coffee agroforests increased the functional diversity of avian insectivores, and increased predation on exposed prey. More recent exclosure studies have demonstrated this effect in coffee agroforests (Karp *et al*., 2013) with prey removal rates of up to 50 percent.

Fourth, landscapes can be managed for the same effects, increasing the mobility and access of predators to the pest populations, and/or the inverse, reducing the mobility of the pest population. Several studies have been conducted on these processes. Avelino *et al*. (2012) working in the VCTBC located 29 coffee plots and characterized the landscape context around these coffee plots in 12 nested circular sectors ranging from 50 to 1 500 m in radius. This permitted classifying the coffee plots as either intact or fragmented at the fine to medium scale, and identifying whether that fragmentation of coffee was surrounded by forest, sugar cane, or pastures. Correlation analysis between the proportions of each land use at scales between 100 and 3 000 m, and coffee pest and disease incidences, then allowed for the assessment of whether fragmenting coffee parcels in the landscapes had an effect on disease incidence. The results from this study showed a significant negative correlation between forest cover and the coffee berry borer, peaking at the 150 m radius, and a significant positive correlation with coffee area, peaking at the same scale (Figure 3). Interestingly, the authors also found a significant negative correlation between the coffee berry borer and pastures, peaking at 400 m.

Olivas (2010) further tested these correlations at finer scales using paired transects of coffee berry borer traps located every 10 m, crossing from 40 m inside coffee plots to 140 m into the adjacent forest, pasture, or sugar cane plots. Checking these traps every two weeks for 120 days during the peak coffee berry borer dispersal period it was found that borer densities were significantly the highest in the coffee plots (95 percent of captures in coffee), with very little evidence of dispersal into adjacent land uses (5 percent of captures). The little dispersal that was observed was found to be highest in the sugar cane (0.035 females day^{-1}), second in pasture (0.023 females day^{-1}), and nearly non-existent in forest (0.005 females day^{-1}). Dispersal was greatest in the first 10 m immediately adjacent to the coffee edge, and dropped off significantly beyond this point, with a much more graduate taper between 20 and 140 m, indicating strong edge effects. These results complement the landscape study of Avelino *et al*. (2012), suggesting that the coffee berry borer does not handle landscape fragmentation well and that there are differentiated dispersal barriers controlled by the characteristics of the adjacent land use. Forests are the greatest barriers to coffee berry borer dispersal, pastures second, and sugar cane is the most porous barrier.

These observations have led us to hypothesize that while forest fragmentation is largely perceived as a negative attribute in conservation, it may very well be a positive attribute

Figure 3. **Graphical representation of the distance weighted dispersal effects of heterogeneous landscapes**



Landscape composition and configuration impact the flow of organisms between adjacent parcels. Work in Costa Rica suggests that forests, pastures and sugar cane can all serve as barriers to the movement of the coffee berry borer, although much greater extents of pasture (400 m) and sugar cane (>600 m) are needed compared with forests (150 m). The results of the borer study and avian research in Costa Rica suggest that matrix landscapes may inherently maintain more services that those dominated by a single land use.

in agricultural landscapes. We propose that there are distance weighted dispersal effects of heterogeneous landscapes (Figure 3). In other words, pests originating from a land use (in this case coffee production), will have a differentiated difficulty/ease of dispersing across a landscape based on the adjacent land uses. In the case of the coffee berry borer, forest land uses serve as an effective barrier at distances of 150 m or more. Pastures can also serve as an effective barrier, but at least 400 m of pasture are required for the barrier effect to be manifested. While such numbers can be determined for specific pest populations and land uses, we can also generalize that landscape homogenization, particularly in tropical environments, facilitates pest infestation and increases the need for pest control interventions. In contrast, the fragmentation of agricultural landscapes by increasing the complexity of land use composition and configuration provides a natural break against pest epidemics. This is in effect what Fahrig *et al.*

(2011; Figure 1) have proposed regarding the impact of land use heterogeneity and biodiversity conservation: increasing the complexity of landscape composition and configuration should increase the biodiversity conservation value of agricultural landscapes, as well as reducing the risk of pest and disease incidence. This hypothesis, which has growing support in both temperate and tropical regions, suggests that land-sharing is an important strategy for addressing the dual goals of agriculture, to enhance food production and reduce its environmental impact.

While the ecological mechanisms are becoming increasingly clear, with both field-scale and landscape-scale mechanisms contributing to pest control, understanding the social variables can be much more difficult. Field-scale interventions are somewhat easier where land tenure rights are clearly defined. Good agroecological evidence on best practices, supported by public or private extension services can support farmer decision-making and implementation of these best practices. However, the discussion on landscape effects highlights that the ecosystem service of pest regulation shares the same attributes of common pool resources (Ostrom, 2009). That is, their benefits are shared by many, but controlled by no single individual. Coordination or communication between farms is needed to secure these services.

In our discussions with farmers of the VCTBC regarding the coffee berry borer, some frustration was evident regarding the pest, including a preoccupation that the individual efforts of farmers were often lost if not replicated on adjacent parcels of land. A certain degree of peer pressure regarding the coffee berry borer could also be recognized – while yield losses to the pest are important, being identified as the source of the pest to neighbouring farms is humiliating. In this way farmers were indirectly familiar with the notion of pest dispersal, and quickly became keen to understand how it might be limited. This highlights a fundamental point in managing ecosystem services; while many services are provided by agricultural landscapes, a subset of these have greater social values, and are capable of motivating behaviour change.

These innovations have been tested on the CATIE farm, a 1 000 ha farm located in the centre of the corridor, which shares many of the same land uses as the larger VCTBC. The relatively large size and composition of the farm mimics the larger VCTBC, including the interactions between multiple individual farms. For the past seven years birds have been mist-netted in the various land uses of the farm in order to understand the conservation value of these land uses (forests, simple/complex coffee agroforests, sugar cane, cacao agroforests and pastures) (Martinez-Salinas and DeClerck, 2010). These data have provided rich insights into how avian biodiversity uses agricultural landscapes, most notably, that while agroforests can play an important role in creating habitat for wild biodiversity, it can also provide important corridors to connect sufficient patches of native habitat. Notably, more than 118 bird species have been detected on the farm. Eighty-five percent of these species include invertebrates as part of their diet and 25 percent are exclusively insectivores.

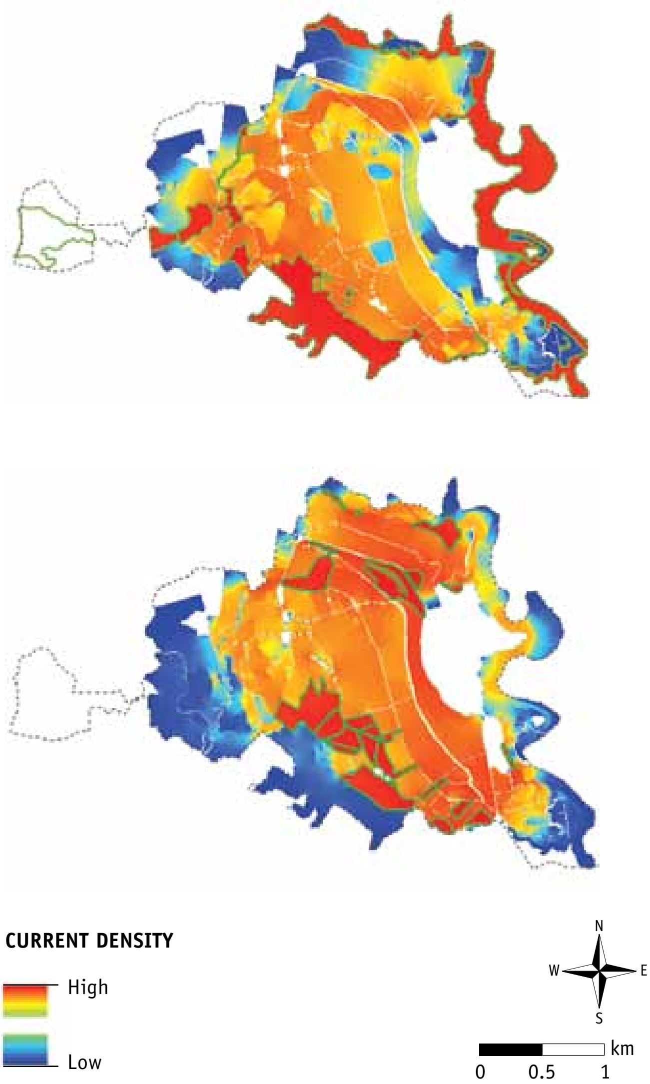
Seeking win-wins and supporting innovation

An opportunity to work on these ideas in practice was provided in collaboration with the CATIE farm manager, Rainforest Alliance, and the United States Fish and Wildlife Service. In an effort to make the CATIE farm one of the first Rainforest Alliance certified farms for livestock production, the planting of live fences was increased around all pastures and their pruning intensity was reduced. The aim is to create a veritable network of paths and corridors by which wild biodiversity can access the protected forest habitats in and around the CATIE farm in the next 5-10 years. While it will take time to produce the evidence that the intervention has the desired impact on avian biodiversity, particularly dispersal measures, computer-based models using the mist-netting data support the notion that the interventions will provide significantly increased connectivity. Figure 4A is a Circuitscape map (McRae *et al.*, 2008) which highlights the connectivity status of the farm for the ochre-bellied flycatcher (*Mionectes oligeaneus*), a forest dependent species commonly found in the Reventazón River riparian forest adjacent to the CATIE Campus, but rare in the agricultural land uses. In the map, forest patches are shown in bright red with a green border. The mixed-use matrix between the patches has been converted to conductance values, borrowing from electrical circuit theory. High conductance (bright red), indicates a high current flow, or in this case, a high probability of movement for the flycatcher. The colour gradation to blue indicates low connectivity. Unfortunately, the map shows a landscape which is fragmented for the flycatcher, with some movement supported along the southern edge of the farm.

This same modelling exercise was repeated for the coffee berry borer using data from borer trapping experiments in the VCTBC landscapes (Figure 4B). Rather than considering whether the coffee berry borer was capable of moving between forest patches, the coffee patches were identified as the core habitat and the dispersal ability of the pest throughout the farm was assessed. The results are nearly the opposite of those found with the flycatcher exercise, and the farmscape is largely connected for this pest species. The combined results from Avelino *et al*. (2012), Olivas (2010) and this modelling exercise suggest that landscape configuration can be critical for providing ecosystem services, or in the case of the coffee berry borer, ecosystem disservices. Fragmenting coffee landscapes plays the dual role of facilitating spillover effects of functional biodiversity, enhancing the movement of coffee berry borer predators in this case, while simultaneously providing a barrier to the pest's emigration from one coffee parcel to another. We affectionately call this project 'bridges and barriers' for the win-win solution it highlights providing conservation benefits through connectivity, and barriers to pest dispersal.

The data do not suggest that agroecological methods are capable of eliminating the coffee berry borer entirely. What they do show, however, is the need to manage multiple ecological functions simultaneously to increase the efficiency of practices (i.e. genetic diversity, making habitat inhospitable/hospitable to the pest/predator, increasing/decreasing mobility of predator/pest populations). These functions must be further complemented by supporting management practices, such as cleaning. As this case illustrates, whether the ecosystem provides services or disservices is a function of management decisions regarding land use composition and configuration. Agroecology is at a critical point in its evolution to foster a focus on the ecosystem services provided by agro-ecosystems and improving their management in order to change agricultural externalities from negative to positive.

Figure 4. **Connectivity modelling of the 1 000 ha CATIE farm in Costa Rica for two species: the forest dependent ochre-bellied flycatcher *(Mionectes oligeaneus)* and the agricultural pest, the coffee berry borer *(Hypothenemus hampei)***



Ochre-bellied Flycatcher (*Mionectes oligeaneus*)

Coffee berry borer (*Hypothenemus hampei*)

The primary habitat of each species is indicated by the red patches encircled by green (forests for the flycatcher and coffee parcels for the beetle). The matrix between the habitat patches is modelled for connectivity, with bright red indicating high degrees of connectivity, and dark blue indicating low connectivity.

CONCLUSIONS

The VCTBC case study provides an example of researchers, farmers and other landscape stakeholders attempting to understand how to manage a shared landscape for its multiple ecosystem benefits and services. The past ten years of engaging in this process has taught us the importance of matching ecological and governance scales in securing the provisioning of ecosystem services (Fremier *et al.*, 2013). Our initial assessment of the land uses and priorities in the corridor identified several stakeholder priorities which are also shared by many other landscapes in Latin America (Estrada-Carmona *et al.*, 2014). What stands out as significant is the desire of communities to have options and institutions for managing common pool resources – such as biodiversity and the services that it provides.

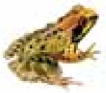
Specifically in the VCTBC, sediment reduction was identified as a priority for increasing the efficiency of hydropower, managing biological connectivity was a priority to support the function of the corridor, and farming communities expressed an interest in pest regulation. For each of these services, several ecological processes can be identified, the provider of the service can be identified using targeting mapping tools, and the beneficiary is also readily identifiable. These are the necessary prerequisites for ecosystem services management. The absence of any of these three elements puts ecosystem services management at risk. The identification of ecological mechanisms is crucial for assuring that the process by which services function can be understood and that management options are grounded in a recognized evidence base. The identification of a specific service provider and beneficiary (individuals, groups of individuals, or public entities) then determines the appropriate intervention options and management scales. These can range from individual farms or farming families serving as both the ecosystem services provider and beneficiary in the case of farm-scale agroecological services; to farming communities in the case of adjacency-based functions such as pollination and pest control; to larger landscape-scale functions as in the case of sediment reduction for increasing the efficiency of hydropower generation in the corridor, or for managing biological connectivity.

We highlight three additional considerations which we consider to be fundamental in ecosystem services management. First, if ecosystem services-based approaches are to become viable options for managing agroecological landscapes, we must become better equipped to understand and manage the multiple processes that interact to provide a single function. In the case of pest and disease control, this includes managing genetic diversity for resilience, and habitat suitability/unsuitability for predator/pest populations, respectively. Similarly, understanding functional diversity and its connectivity is important to manage immigration and emigration rates of predator and pest communities, as well as possible predator spillover effects and distances. The combination and interaction between these multiple processes contributes to pest control functions, yet these are rarely studied simultaneously. Rather, most studies consider a single ecological process in isolation to measure its effect.

The second point is similar to the first. Scale plays a critical role in ecosystem services management from fields to landscapes. The agroecological processes mentioned above operate at different scales. Therefore, understanding these scales provides an insight into which management functions are available, and more importantly, which types of institutions are needed to secure the service – agricultural extension for field-based services, farmer cooperatives for farm-scale functions, and eventually payments for ecosystem services for landscape-scale functions.

The third point refers to the need to better recognize the value of biodiversity for the services it provides in agricultural landscapes. In some cases this can be through economic valuation. For example, Ricketts (2004) estimated that the pollination services provided by forests adjacent to two larger farms in Costa Rica provide US$60 ha^{-1} year^{-1} in pollination services. Similarly, Karp *et al*. (2013) estimated that pest control services provided by forests adjacent to coffee plantations are worth US$75-310 ha^{-1} year^{-1}. These values are already higher than payments from the national Costa Rican payments for ecosystem services scheme that are in the order of US$80 ha^{-1} year^{-1}. Valuation does not necessarily imply monetization; it can also be social, or individual. However, it must be high enough to influence decision-making including changes in land use composition and configuration.

To conclude, the rather singular focus on production functions in agriculture, while understandable and a principal priority for agricultural landscapes, has been achieved at an all too high environmental cost. Although it may seem that our world is becoming more digital, with the expectation that technological fixes will resolve the majority of our problems, the reality is that we inhabit a biological planet where critical life-support systems are provided by biological interactions. We urgently need novel technologies that support biological, or agroecological functions, rather than supplant them. Similarly, institutions and incentive mechanisms that recognize the efforts of farmers and farming communities in providing multiple ecosystem functions are needed to support the transition to make positive agricultural externalities the norm, rather than the exception. Agroecology is no panacea, but the central role that agriculture plays in environmental and human health places it squarely in the centre of renewed global efforts to meet sustainable development goals.



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09

ECOLOGICAL APPROACHES FOR REDUCING EXTERNAL INPUTS IN FARMING

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Abstract

Reducing the production costs of purchasing external inputs such as fertilizers, pesticides, seeds and energy, while still producing high yields, is an important step towards achieving economically viable farming systems. Not only are external inputs costly, at times they can be logistically difficult to obtain for smallholders in developing countries – who make up the majority of the world's farmers. The ability to generate effective alternatives to external inputs on-farm at no or low cost reduces the reliance on and financial costs of external inputs.

Organic agriculture is part of the agroecology paradigm. Modern ecological organic agriculture is not the same as the way people farmed in the past; rather contemporary organic agriculture combines tradition with innovation and science. Scientific studies show that organic systems have higher yields under conditions of climatic extremes such as drought or heavy rain events (Drinkwater *et al.*, 1998; Welsh, 1999; Lotter *et al.*, 2003; Pimentel *et al.*, 2005). Moreover, organic practices have been shown to increase yields in traditional farming systems. For example, a review by Hine *et al.* (2008) found that organic practices increased yields in sub-Saharan Africa by an average of 116 percent.

Innovative and science-based organic methods provide the necessary practices and inputs to improve soil nutrition, control pests, diseases and weeds, and ultimately obtain high yields. Eco-functional intensification, using functional biodiversity, natural minerals and agroecological methods can ensure that the required inputs for soil nutrition and pest, disease and weed control can be generated on-farm or sourced locally at little or no financial cost. For instance, the use of organic matter to provide biogas not only provides partial energy self-sufficiency, the residues can provide 100 percent increases in crop yields (Edwards *et al.*, 2011). Through the combination of higher yields, resilient biodiverse production systems and lower production costs, organic systems can achieve both food and income security for farmers.

INTRODUCTION

The ability to generate effective alternatives to external inputs (e.g. fertilizers, pesticides, seeds and energy) on-farm at no or low costs reduces farmers' reliance on external inputs and the financial costs of purchasing them. Agroecological systems, including organic agriculture, have numerous ways of achieving this. By reducing production costs, while still maintaining high yields, farmers are able to earn higher net incomes (Bachman *et al.*, 2009; Nemes, 2013).

Agroecology is simultaneously a social movement, a range of practices and a scientific discipline. Although agroecology has been variously defined, the UN Special Rapporteur on the Right to Food, Olivier De Schutter (2013), favours the definitions of Altieri and Gliessman, two of the leading and founding authorities on agroecology:

> *"Agroecology has been defined as the 'application of ecological science to the study, design and management of sustainable agroecosystems' (Altieri, 1995; Gliessman, 2007). It seeks to improve agricultural systems by mimicking or augmenting natural processes, thus enhancing beneficial biological interactions and synergies among the components of agrobiodiversity (Altieri, 2002)."*

Organic agriculture fits well within this definition of agroecology. IFOAM[1] Organics International has developed a definition of organic agriculture clearly showing that organic systems are based on environmental and social sustainability by working with the ecological sciences, natural cycles and people:

> *"Organic agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved."*
>
> (IFOAM, 2014a)

In addition, IFOAM (2014b) has worked by consensus with the sector globally to develop the Four Principles of Organic Agriculture:

1. **The principle of health:** Organic Agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible.
2. **The principle of ecology:** Organic Agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them.
3. **The principle of fairness:** Organic Agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities.
4. **The principle of care:** Organic Agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment.

There are a wide variety of practices that are called organic. This chapter focuses on practices that meet IFOAM Organics International's definition and the Four Principles of Organic Agriculture that are described above. The key principle discussed in this chapter is the Principle of Ecology.

Modern organic agriculture is not the same as the way people farmed in the past and it is not about going backwards or farming by neglect. It negates the need for synthetic pesticides

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[1] IFOAM Organics International (The International Federation of Organic Agriculture Movements) is the only global umbrella body for the organic sector, incorporating around 800 organizations in 125 countries.

and fertilizers by improving soil fertility using composts, natural minerals, cover crops and recycling organic materials. Cultural and ecological management systems are used as the primary control of pests, weeds and disease. Some examples of cultural management systems include: light tillage to reduce weeds; crop rotations to reduce weeds, pests and diseases; cover crops to reduce weeds, increase nitrogen and add soil organic matter; and mulching to reduce weeds, add organic matter and conserve water. Examples of ecological management systems include: introducing functional biodiversity such as host plants for the natural enemies of pests; using selective allelopathy to suppress weeds; using soil micro-organisms to control soil pathogens and make nutrients available to plants; and using trap crops, repellent plant species and barrier plants to control pest and diseases.

Organic agriculture combines tradition with innovation and science. The new innovative and science-based organic methods provide the necessary techniques and inputs for improving soil nutrition and managing pests, diseases and weeds. However, organic farming systems have largely been ignored by the agricultural research community, with less than 0.4 percent of the US$52 billion spent annually on agricultural research being directed specifically to organic systems (Niggli, 2015). Nevertheless, published scientific studies do show that organic systems can achieve equal or higher yields compared with good practice conventional systems. For example, in the United States Agricultural Research Service (ARS) Pecan Trial, organically managed pecans out-yielded the conventionally managed, chemically fertilized orchard in each of the five years of the trial. Yields at the ARS organic test site surpassed the conventional orchard by 8 kg of pecan nuts per tree in 2005 and by 5 kg per tree in 2007 (Flores, 2008). The Wisconsin Integrated Cropping Systems Trials found that organic yields were higher in drought years and the same as conventional in normal weather years (Chavas *et al.*, 2009). The long-term Rodale Farming Systems Trial (FST), conducted over 22 years, found that because the system improved the soil, organic land was able to generate yields that were equal to or greater than conventional crops after five years (Pimentel *et al.*, 2005).

BUILDING GREATER RESILIENCE TO ADVERSE CONDITIONS BY REDUCING EXTERNAL INPUTS

According to the Intergovernmental Panel on Climate Change's *Fifth Assessment Report*, the world is experiencing increases in the frequency of extreme weather events such as droughts and heavy rainfall (IPCC, 2013). Even if we stopped polluting the planet with greenhouse gases tomorrow, it would take many decades to reverse the effects of climate change. This means that farmers will have to adapt to the increasing intensity and frequency of adverse and extreme weather events. This is one of the most critical issues in order to ensure global food security. Research shows that organic farming systems are more resilient to the predicted weather extremes and can produce higher yields than conventional farming systems under such conditions (Reganold *et al.*, 1987; Drinkwater *et al.*, 1998; Welsh, 1999; Lotter, 2005; Pimentel *et al.*, 2005).

Reducing water inputs – improved efficiency of water use

Research shows that organic systems use water more efficiently because of better soil structure and higher levels of humus and other organic matter compounds (Lotter *et al.*, 2003; Pimentel *et al.*, 2005). Based on over 10 years of data, Lotter *et al.* (2003) showed that the organic manure system and organic legume system (LEG) treatments improved the soils' water-holding capacity, infiltration rate and water-capture efficiency. On average, LEG maize soils had a 13 percent higher water content than conventional systems at the same crop stage. The more porous structure of organically treated soil allows rainwater to quickly penetrate the soil, resulting in less water and soil loss from run-off and higher levels of water capture. This was particularly evident when Hurricane Floyd struck the eastern coast of the United States of America in September 1999. During two days of torrential downpours, organic systems captured approximately double the amount of water that conventional systems captured (Lotter *et al.*, 2003).

The importance of organic matter for water retention

There is a strong relationship between levels of soil organic matter (SOM) and the amount of water that can be stored in the root zone of a soil. SOM is primarily composed of soil organic carbon (SOC) fractions that substantially increase the water holding capacity of soils while allowing them to be well aerated. Complex SOC polymers such as humus are key components of SOM, contributing to the greater stability and water-holding capacity of organic soils. SOC has the ability to hold up to 30 times its own weight in water and acts as a 'sticky' polymer that glues soil particles together, providing greater resistance to water and wind erosion (Stevenson, 1994).

In a meta-analysis including data from 41 published comparison trials from around the world, Gattinger *et al.* (2012) reported that on average, organic systems sequestered 550 kg C per ha, per year. Compared with conventional systems, organic systems contained more SOM (a difference of 946 kg SOM per ha, per year). Similarly, a meta-analysis conducted by Aguilera *et al.* (2013) analysed 24 comparison trials in Mediterranean climates in Europe, the United States of America and Australia. The results showed that organic systems sequestered more carbon than conventional systems (a difference of 970 kg C per ha, per year) and contained more SOM (a difference of 1 666 kg SOM per ha, per year).

These results are consistent with other comparison studies that show that organic systems lose less soil because they have better soil structure and contain higher levels of organic matter (Reganold *et al.*, 1987; Reganold *et al.*, 2001; Pimentel *et al.*, 2005). Reganold *et al.* (1987) compared the long-term effects of organic and conventional farming on selected properties of the same soil since 1948. The organically farmed soil had a significantly higher organic matter content, thicker topsoil depth, higher polysaccharide content, lower modulus of rupture and less soil erosion than the conventionally farmed soil. Another long-term scientific trial lasting 21 years was conducted by the Research Institute of Organic Agriculture (FiBL) in Switzerland. The study compared organic, biodynamic and conventional systems. The results showed that

organic systems are more resistant to erosion, with 10-60 percent higher soil aggregate stability observed in the organic plots compared with the conventional plots (Mäder *et al.*, 2002).

The relationship between the volume of water retained in soil and levels of SOM can be seen in Table 1. This should be taken as a rule of thumb, rather than as a precise set of measurements. Different soil types will hold different volumes of water when they have the same levels of organic matter because of pore spaces, specific soil density and a range of other variables. For instance, sandy soils generally hold less water than clay soils. However, the table gives an understanding of the potential amount of water that can be captured from rain and stored at the root zone in relation to the percentage of SOM.

Table 1. **Volume of water retained in relation to SOM**

SOM (%)	WATER RETAINED (LITRES HA^{-1} TO 30 CM)	CHARACTERISTIC FARMING SYSTEMS
0.5	80 000	Common farm level in much of Africa, Asia and Australia
1.0	160 000	
2.0	320 000	
3.0	480 000	
4.0	640 000	
5.0	800 000	Pre-farming levels

Source: adapted from Morris, 2004

Table 1 indicates that there are large differences in the amount of rainfall that can be captured and stored depending on the percentage of SOM. This is one of the reasons why organic farms do better in times of low rainfall and drought because when they are well managed they can increase the levels of SOM compared with conventional farms. The Rodale FST showed that organic systems produced more corn than conventional systems in drought years. The average corn yields during the drought years were 28-34 percent higher in the two organic systems. The yields were 6 938 kg ha^{-1} in the organic system that used animal manure and 7 235 kg ha^{-1} in the organic system that used legumes in the farming rotation to build soil fertility, compared with 5 333 kg ha^{-1} in the conventional system (Pimentel *et al.*, 2005).

This is of particular interest considering that the majority of the world's farming systems are rainfed. The world does not have the resources to irrigate all agricultural lands. Nor should such initiatives be undertaken as damming the world's watercourses, pumping from all the underground aquifers and building millions of kilometres of channels would cause an environmental disaster. The use of water in many current irrigation systems is regarded as unsustainable as they are depleting the water sources faster than the rates of recharge (MEA, 2005). Improving the efficiency of rainfed and irrigated agricultural systems through practices that increase SOM levels are among the most cost-effective, environmentally sustainable and practical solutions to ensure reliable food production in conditions of increasing weather extremes caused by climate change.

TRADITIONAL SMALLHOLDER FARMER YIELDS

A critical area where research is showing that organic systems are capable of providing higher yields than conventional methods is in traditional smallholder farming systems – a category that includes the majority of the world's farmers. Hine *et al*. (2008) reviewed 114 projects in 24 African countries covering 2 million ha and 1.9 million farmers. They found that organic practices increase yields by 116 percent on average (range: +54% to +176%). The report notes that since the introduction of conventional agriculture in Africa, food production per person is 10 percent lower now than in the 1960s. In the report, Supachai Panitchpakdi, Secretary-General of UNCTAD, and Achim Steiner, Executive Director of UNEP, stated that:

> *"The evidence presented in this study supports the argument that organic agriculture can be more conducive to food security in Africa than most conventional production systems, and that it is more likely to be sustainable in the long term."*
>
> (Hine *et al*., 2008)

REDUCING EXTERNAL FERTILIZER INPUTS

Many people are under the impression that because organic standards prohibit the use of synthetic chemical fertilizers for macronutrients, organic farmers do not add any nutrients into the soil. While this can be true of some organic systems, most organic standards have management requirements mandating that farmers document the methods and inputs that they use to build soil fertility to provide adequate nutrition to crops. In my experience as an organic farmer, and having visited thousands of organic farms on every arable continent over 40 years, the best organic farmers actively improve soil fertility by adding composts, natural minerals, green manures, legumes and other allowable sources. These systems can be based on soil tests to accurately determine the needs of all the necessary macronutrients such as nitrogen, phosphorus, calcium, magnesium, sulphur and potassium as well as trace minerals. Cultural techniques to build soil fertility and allowed inputs are articulated in most organic standards. Because most of these are produced on-farm or can be sourced locally, they can be provided at lower costs than synthetic fertilizers that are usually imported and (when not subsidized) expensive for smallholder farmers.

Composts and green manures (that come from plants) are generally complete sources of nutrients containing all the macro and micronutrients needed by plants. Plants bioaccumulate all the nutrients that they need, and processes that recycle and increase organic matter in farms will assist in improving soil fertility by releasing these bioaccumulated nutrients so that they can be used by crops. In cases where soils are grossly deficient in nutrients, these can be provided by inputs such as rock phosphate, limestone, gypsum, ground basalt and other natural minerals, to correct the deficiencies. The major organic standards allow the use of water-soluble trace elements such as zinc sulphate and sodium borate where there is a demonstrated deficiency. These types of trace elements are the only exception as organic systems work on

the basis that the majority of plants' nutrients are made available through biological processes, rather than through the addition of large amounts of water-soluble ions from synthetic chemical fertilizers. There is a considerable body of scientific literature showing that in natural systems, a substantial proportion of nutrients are made available in organic forms through these biological processes, rather than primarily as water soluble ions – the dominant paradigm in conventional farming (Paungfoo-Lonhienne *et al.*, 2012). Because trace elements are generally used in significantly smaller amounts than macronutrients, the use of trace elements to correct demonstrated deficiencies does not contradict the position that most nutrients should be made available through biological processes. Moreover, the costs of purchasing trace elements are not as onerous for famers compared with the costs of purchasing external inputs of macronutrients.

Plant roots and micro-organisms have enzymes and acids that biologically 'weather' the parent soil material to produce nutrients in forms that are available to plants. Annual and perennial legumes can be used to fix nitrogen as cover crops, intercrops, cash crops and as biomass harvested from marginal areas. Furthermore, significant amounts of plant-available nitrogen and phosphorus can be fixed by free living, symbiotic and endophytic micro-organisms in biologically active soils with good levels of organic matter. These organic sources of nutrients are well studied, including studies showing that many crops readily take up nitrogen in organic forms such as amino acids and peptides (Paungfoo-Lonhienne *et al.*, 2012).

REDUCING PESTICIDE INPUTS THROUGH ECO-FUNCTIONAL INTENSIFICATION

One of the most effective ways to reduce the costs of purchasing expensive synthetic pesticides, as well as eliminating their associated health and environmental risks, is to replace them with non-chemical methods. Organic systems negate the need for synthetic pesticides by using cultural and ecological management systems as the primary control for pests, weeds and disease, with a limited use of natural biocides of mineral, plant and biological origin as tools of last resort.

The biocides used in organic systems are from natural sources. They are only permitted to be used if they rapidly biodegrade, which means that there are no residues on the products that people consume. By using cultural and ecological methods as the primary management tools, organic systems aim to first prevent pests and second control them. Therefore, the use of these natural biocides is minimal. Research shows that where natural biocides are used in organic systems, the amounts are 97 percent less than synthetic pesticides used in conventional farming (Mäder *et al.*, 2002).

One of the most effective ecological approaches to pest management is eco-functional intensification. Eco-functional intensification optimizes the performance of ecosystem services by utilizing functional biodiversity. Ecological processes, based on the science of agroecology, are used in organic production systems rather than chemical intensification. The aim is to actively increase the biodiversity in agricultural systems to deliver a range of services such as pest control, weed management and nitrogen fixation, rather than using the conventional approach, based on reductionist monocultures reliant on externally sourced synthetic inputs.

Eco-functional intensification allows farmers to replace costly herbicides and insecticides with freely available, living functional biodiversity. Over time, as new systems become established, they can require considerably less labour resulting in savings in both time and money.

Push-pull system

The push-pull system in maize is an excellent example of an innovative eco-functional intensification method that integrates several ecological elements to achieve substantial increases in yields. This is significant because maize is the key food staple for smallholder farmers in many parts of Africa, Latin America and Asia. Corn stem borers are one of the most significant pests in maize. Conventional agriculture relies on a number of toxic synthetic pesticides to control these pests. More recently genetically engineered varieties have been developed that produce their own pesticides. The push-pull system was developed through collaboration between scientists at the International Centre of Insect Physiology and Ecology (ICIPE), Rothamsted Research and other partners (Khan *et al.*, 2011).

In the push-pull system, silverleaf desmodium (*Desmodium uncinatum*) is planted in the crop to repel stem borers and to attract the natural enemies of the pest. The desmodium gives off phenolic compounds that repel the stem borer moth. Napier grass (*Pennisetum purpureum*) is planted outside of the field as a trap crop for the stem borer. The desmodium repels (pushes) the pests from the maize and the Napier grass attracts (pulls) the stem borers out of the field to lay their eggs in the Napier grass instead of the maize. The sharp silica hairs and sticky exudates on the Napier grass kill the stem borer larvae when they hatch, breaking the life cycle and reducing pest numbers. Desmodium root exudates also stop the growth of many weed species including *Striga*, which is a serious parasitic weed of maize. The use of desmodium to suppress weeds is an example of an emerging science in weed control called selective allelopathy, where functional biodiversity is used to suppress weeds and enhance the cash crop.

High maize yields are not the only benefits of the push-pull system. The system does not need synthetic nitrogen as desmodium is a legume and fixes nitrogen. Soil erosion is prevented because of a permanent ground cover. Moreover, the system provides quality fodder for stock. One farmer innovation to improve this system has been to systematically strip harvest the Napier grass and desmodium to use as fresh fodder for livestock. Livestock can also graze down the field after the maize is harvested. Many push-pull farmers integrate a dairy cow into the system, feeding it Napier grass and desmodium, and sell the milk that is surplus to their family's needs to provide a regular source of income. These farmers often also grow kitchen gardens to provide the bulk of their food, reducing the need to purchase food while providing a nutritious and diverse diet for the family. The result is the elimination of the 'hungry months' when families did not have enough to eat, as well as more income at the end of the year so that the families can afford medical care, send their children to school and build comfortable houses. The adoption of push-pull systems combined with a dairy cow and kitchen gardens has helped empower families to emerge from conditions of poverty, enhance their well-being and live in dignity.

Push-pull systems are now being adapted by farmers in many crops such as millet, wheat, teff, oats, mangos, chillies and tomatoes. In Tigray, Ethiopia, farmers have applied an improved

version of push-pull to many crops. As well as using desmodium as a pest repellent and Napier grass as a trap crop, they have incorporated alfalfa (*Medicago sativa*) as host plants to attract the natural enemies of pests. Both desmodium and alfalfa are legumes so they fix all the nitrogen needed as well as suppressing weeds. The biomass from these systems is harvested for livestock feed, biogas digesters and compost, providing an extra income, energy and improved crop nutrition. These systems produce high yields of quality produce.

Insectaries – host plants to attract beneficial insects

Insectaries are groups of plants that attract and host beneficial arthropods and other animal species, which are the natural enemies of pests in farms, orchards and gardens (Flint *et al.*, 1998; Walliser, 2014). Many beneficial insects have a range of host plants. Some useful species such as parasitic wasps, hoverflies and lacewings have carnivorous larvae that eat pests, while the adult stages live mostly on nectar and pollen from flowers. Flowers provide beneficial insects with concentrated forms of food (pollen and nectar), to increase their chances of surviving, immigrating and staying in the area. Importantly, flowers also provide mating sites for beneficial insects, allowing them to increase in numbers.

Without these flowers in a farm the beneficial species do not reproduce. Most farming systems eliminate these types of plants as weeds and as a consequence they do not have enough beneficial insects to provide effective pest control. Farmers who have planted these host plants in their fields as ‘insectaries’ no longer have to spray, yet they have similar levels of pest control as their neighbours who are heavily spraying toxic chemicals. A further benefit is that by eliminating insecticides, essential pollinators such as bees can thrive, increasing the pollination and yields of pollinator-dependent crops (Roubik, 2014).

Encouraging nectar and pollen rich flowers in and around the farm improves the efficiency of these areas by changing the species mix in favour of beneficial insects. This occurs naturally in most organic farms because of a higher biodiversity within and surrounding the crop (Hole *et al.*, 2004). Ongoing research is focused on determining the most effective mixes of plant species and distances between these nature strips. Research has shown that high levels of vegetation species diversity will ensure a constant low population of many species that serve as ‘food’ for the beneficial insects. The vegetation also helps to protect the beneficial insects and will ensure that they will stay in the area (Flint *et al.*, 1998; Walliser, 2014).

REDUCING ENERGY COSTS THROUGH ON-FARM ENERGY PRODUCTION

Energy is a major cost on farms. Alternative ways exist to provide energy on farms in an appropriate and cost effective way through a combination of small-scale solar panels and biogas digesters. There are now many hundreds of thousands of smallholder farms effectively using these low-cost technologies on-farm for lighting, heating, cooking, electricity and for small-scale equipment (Ho, 2013).

Biogas has many advantages in that the digesters can be built on-farm with local equipment and labour at low costs and can use second-generation biomass such as crop residues, human wastes and animal manures as the feedstock. The process of digesting these improves the sanitation of farms and the slurry provides an excellent compost to improve soil and crop yields. The use of biogas slurry has increased yields in Tigray, Ethiopia by over 100 percent (Edwards *et al*., 2011).

There are major concerns about biofuels competing with food production where the biomass is grown as the primary crop (first generation biomass) for biofuels, including biogas digesters. This is especially important for smallholder farms, where land is a scarce resource and it is important for families to produce as much food as possible. However, biomass can come from secondary sources (second generation biomass) such as crop residues as well as animal (and human) manures. Apart from using some of the carbon and hydrogen, the rest of the nutrients can be recycled back into the fields as compost to fertilize the crops. This prevents the conflict in land use between food and fuel crops.

REDUCING THE COSTS OF SEEDS

Farmers have traditionally bred and saved their own seeds. These 'farmer landraces' were open pollinated varieties that have consistent traits each generation. This tradition began to change during the Green Revolution with the introduction of hybrid seeds to take advantage of the phenomena of hybrid vigour. The first generation of a hybrid is called 'F1'. This generation generally combines the traits of both parents and gives a uniform outcome. The next generation of these seeds is called 'F2' and this generation is not uniform in its traits. These seeds will result in a mixture of plants, some with the separate traits of each parent, as well as a range of hybrids with a wide variety of traits. The implication is that farmers who save these seeds are saving the unreliable and non-uniform F2 generation. Consequently, many of the world's farmers now have to purchase the seeds of improved varieties rather than saving them and planting them as farmers have done for thousands of years.

The disruption of the practice of farmers breeding/saving their own seeds and the trend towards commercial seeds has also led to the loss of the tremendous agrobiodiversity of farmer-bred landraces. Fortunately, in many areas of the world these valuable landraces are still being actively conserved. For example, BARSIK is an organization that works with indigenous farmers in the Sundarbans region of Bangladesh to conserve a living collection of over 250 farmer-developed rice landraces including saline tolerant and underwater varieties of rice. Several organizations, such as MASIPAG in the Philippines, also have living collections of thousands of rice landraces, and are working with farmers through participatory breeding programmes to develop and select varieties that give high yields under low-input conditions. Organizations like MASIPAG and the Institute of Sustainable Development in Ethiopia have found that they can achieve their highest yields in organic systems with the best farmer-bred landraces compared with commercial hybrid seeds (Bachmann *et al*., 2009; Edwards *et al*., 2011).

The fact that farmers can breed and save their own seeds at no cost and achieve higher yields than commercial hybrids in organic systems is extremely important to support the viability of these farms.

ACHIEVING HIGHER NET INCOMES BY REDUCING THE COSTS OF EXTERNAL INPUTS

A viable income is an essential part of farm sustainability. Studies comparing organic farms with conventional farms have shown that the net incomes are similar. However, organic systems that adopt good practices can achieve even higher net incomes. Nemes (2013) analysed over 50 economic studies, concluding that:

> *"Overall, the compiled data suggest that organic agriculture is economically more profitable: net returns, taking total costs into account, most often proved to be higher in organic systems. There were wide variations among yields and production costs, but either higher market prices and premiums, or lower production costs, or a combination of these two generally resulted in higher relative profits from organic agriculture in developed countries. The same conclusion can be drawn from studies in developing countries, but there, higher yields combined with high premiums seemed to be the underlying reasons for higher relative profitability."*

Likewise, Hine *et al.* (2008) found that not only did organic production increase the amount of food produced, it also gave farmers access to premium value markets. Farmers were able to use the additional income to pay for education, health care, adequate housing and achieve relative prosperity.

A research project conducted by MASIPAG in the Philippines, comparing the income between similar-sized conventional and organic farms, found that the average income for organic farms was 23 599 Pesos compared with 15 643 Pesos for conventional farms. While rice yields were similar between the two systems, the most significant result from this study was when the normal family living expenses were deducted from the net income. At the end of the year, organic rice farmers had a surplus income of 5 967 pesos on average, whereas the conventional rice farmers had a loss of 4 546 pesos on average, driving them into debt (Bachman *et al.*, 2009).

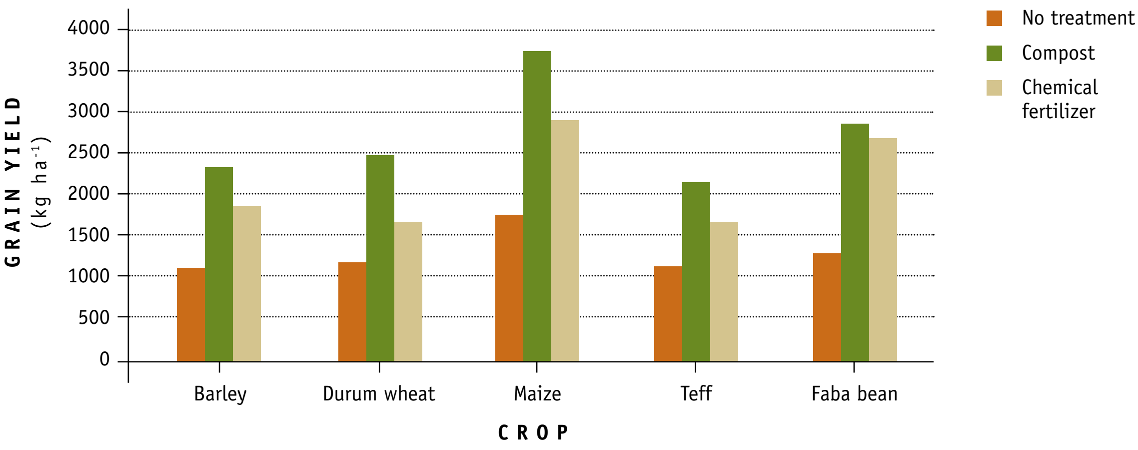
CASE STUDY:
WHOLE SYSTEMS APPROACH IN TIGRAY, ETHIOPIA

A good example of using alternatives to external inputs as part of a whole systems approach can be demonstrated by a project managed by the Institute of Sustainable Development in Tigray, Ethiopia. They worked in cooperation with farmers to re-vegetate their landscape in order to restore the local ecology, biodiversity and hydrology. The biomass from this re-vegetation was then sustainably harvested to make compost and to feed biogas digesters.

Re-vegetating marginal areas such as water courses, gullies, steep slopes, roadsides, lane ways and field borders, and sustainably harvesting the biomass, provides a steady source of nutrients on top of those that are generated through good organic practices in the fields. This is particularly important to build up soil fertility and to replace the nutrients that are lost when exporting crops from the farm. When combined with functional biodiversity, such as the use of deep-rooted legumes for nitrogen production, host plants for natural enemies of pest species and taller species as wind breaks, these re-vegetated marginal areas provide a range of ecosystem services.

The use of biogas enabled a level of energy independence in the villages by supplying all the energy needed for cooking and for lighting, as well as reducing the need to cut down vegetation for cooking fires. The residues from the biogas digesters were applied to the crop fields. After a few years, this resulted in more than 100 percent increases in yields and better water-use efficiency.

Figure 1. **Average yields by treatment in kg ha^{-1} for 5 crops in Tigray, 2000-2006**



Source: Edwards *et al.*, 2011

The farmers used the seeds of their own landraces, which had been developed over millennia to be locally adapted to the climate, soils and the major pests and diseases. The best of these farmer-bred varieties proved to be very responsive to producing high yields under organic conditions. The major advantage of this system was that the seeds and the compost were sourced locally at little or no cost to the farmers, whereas the seeds and synthetic chemical inputs in the conventional systems had to be purchased from external sources. Not only did the organic system have higher yields; it produced a much better net return to the farmers (Edwards *et al.*, 2011). According to Dr Sue Edwards, the net income for a farmer purchasing synthetic fertilizer after repaying credit was US$1 725 per ha, compared with US$2 925 per ha for a farmer making their own compost (Edwards pers. comm.).

CONCLUSION

To conclude, organic systems can be considered as an agroecological approach; through eco-functional intensification and harnessing functional biodiversity, they have numerous ways to generate effective alternatives to external inputs, providing multiple benefits for farmers:

- Alternatives to external inputs can generated on-farm at no or low costs;
- The financial costs and reliance on external inputs such as synthetic fertilizers and pesticides are reduced;
- Organic systems can attain higher yields, particularly under conditions of climate extremes;
- Resilience is built and ecosystem services are enhanced to improve soil nutrition and structure as well as to control pests, diseases and weeds.

The combination of achieving higher yields, fostering resilient production systems and lowering production costs can assist in enhancing biodiversity, assuring food security and achieving poverty alleviation in a changing climate.

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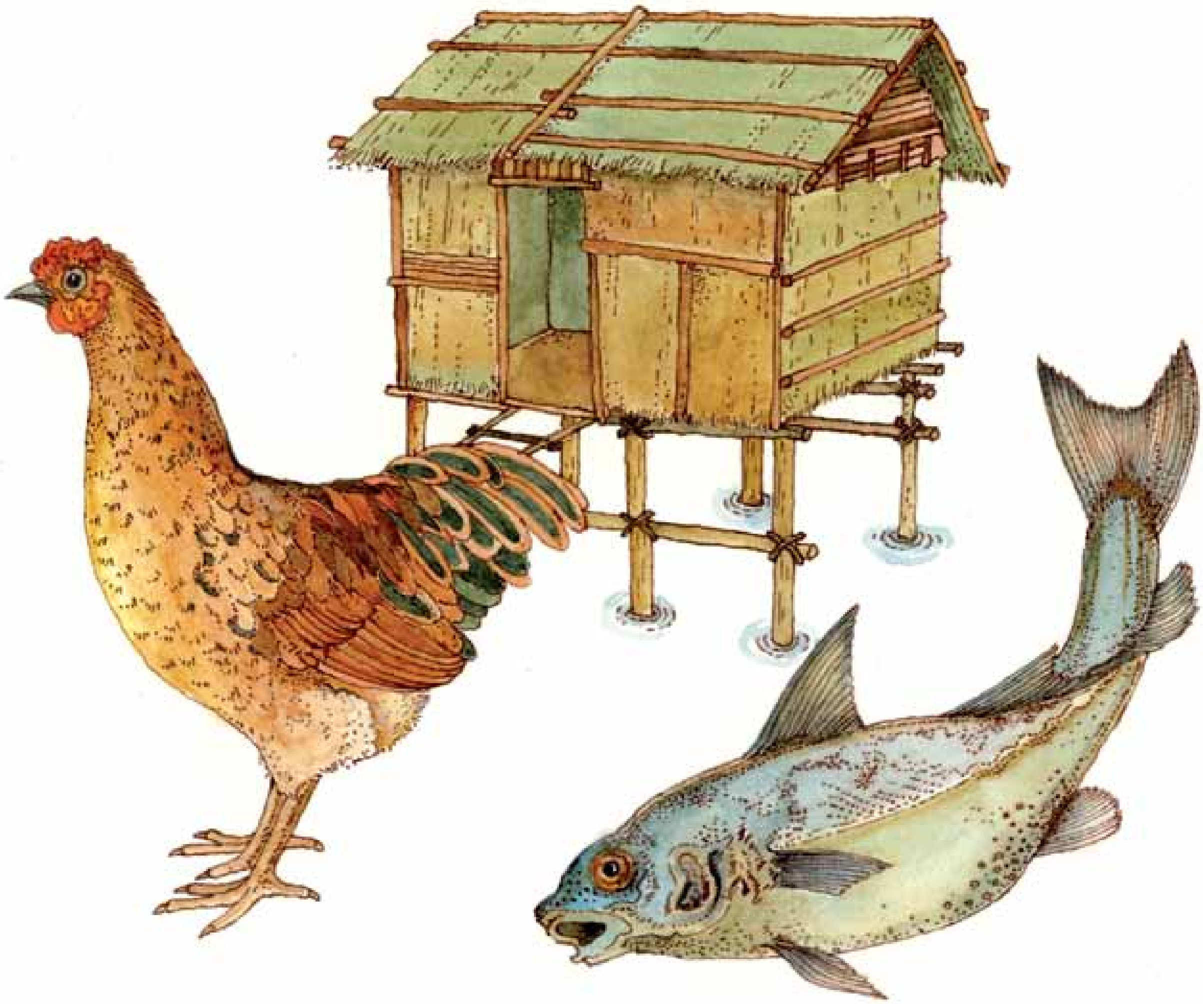

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AGROECOLOGICAL APPROACHES TO WATER SCARCITY

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Abstract

Low and unpredictable precipitation in the arid and semi-arid lands (ASAL) has posed daunting challenges to farmers, who in turn, have gained ecological knowledge and experience in building resilience and developing coping strategies. However, recent policy reforms in developing countries and global changes have posed new challenges to farmers' ecological

knowledge and livelihoods in the ASAL. In particular, new policies and strategies in developing countries have not taken into account farmers' ecological knowledge and customary institutions. This has rendered untenable some traditional livelihoods of farmers in the ASAL. For example, even though empirical evidence shows that mobile pastoralism enhances biodiversity and sustainable pasture and water management in the ASAL, recent trends of individualization of land tenure in sub-Saharan Africa and land grabbing by foreign investors, have made nomadic and transhumant livelihoods untenable in some areas. This chapter examines the land and water management of production systems in the ASAL, using case studies to illustrate farmers' solutions. Some new challenges are examined, that have resulted from new polices and strategies, and global change. The chapter concludes by offering some policy recommendations for enhancing sustainable agroecological systems in the ASAL.

INTRODUCTION

Water scarcity is increasingly posing a challenge to development in the ASAL in developing countries.[1] This challenge is exacerbated by climate change, increasing human population, land and water degradation, and other drivers. Drought, flooding and other extreme events are expected to increase (FAO, 2008; Rockström *et al.*, 2010) and this will lead to a loss of ecosystem services in fragile ASAL environments. Climate change is also expected to decrease precipitation and increase its variability in the ASAL (IPCC, 2007; Williams and Funk, 2011).

Given that water supports all forms of life, its shortage causes large agroecological imbalances, leading to a loss of ecosystem services (Barron, 2009). Agriculture began sometime in the past 5 000-10 000 years in Africa (Mazoyer and Roudart, 2006) and farmers in the ASAL have developed a rich indigenous agricultural water management (AWM) knowledge for tackling water and soil moisture scarcity. Farmers have developed a number of rainwater harvesting (RWH) technologies, traditional irrigation systems, and soil and water conservation (SWC) techniques, which have helped improve crop and water productivity in the ASAL. However, some AWM approaches are not well developed to optimize their effectiveness, particularly under the increasingly urgent conditions of water scarcity in present times. For example, the water-use efficiency of bunded basin flood irrigation (*majaluba*) systems – which account for 74 percent of rice production in Tanzania (Seck *et al.*, 2010) – is only 15-35 percent (Keraita, 2011). Unfortunately, research and extension services in developing countries have not made significant efforts to use science to build on and improve traditional AWM systems.

Livestock is a major production sector in the ASAL of sub-Saharan Africa and Southern Asia. The sector is dominated by pastoralists who have developed a strong indigenous knowledge

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[1] ASAL are areas with low and erratic precipitation ranging from 0-300 mm for arid to 300-600 mm for semi-arid regions (FAO, 1987).

of sustainable land and water management practices (Fernandez-Gimenez and Le Febre, 2006; Nkonya and Anderson, 2015). Nomadic and transhumance livestock production systems have been shown to be sustainable and necessary coping strategies in the ASAL's fragile environment (Scoones, 1995; Niamir-Fuller, 1999). However, recent economic and institutional changes have made these sustainable nomadic and transhumant livelihoods less amenable to livestock movement. Land privatization has restricted livestock movement, while recent land grabbing trends have led to a loss of grazing land, impacting on the ability to achieve sustainable grazing management (Banjade and Paudel, 2008; Sulieman, 2013). Additionally, public expenditure on the livestock sector in sub-Saharan Africa is less than 2 percent, despite the increasing demand for livestock products.

Intercropping and other multiple cropping systems are common in the ASAL of developing countries (Young, 1987). The multiple crop farming systems have been shown to conserve more moisture. Consequently they face reduced production risks, are more profitable, lead to greater soil fertility and provide more diverse diets than monocropping systems (Mead and Willey, 1980; Malézieux *et al.*, 2009; Frison *et al.*, 2011; Lupwayi *et al.*, 2011). However, breeding programmes have not placed sufficient emphasis on developing cultivars that are adapted to mixed cropping systems (Haugerud and Collinson, 1990). For example, leguminous cultivars that are shade-tolerant could enhance cereal–legume intercropping, which increases nitrogen fixation and reduces the need to use inorganic fertilizer and the associated greenhouse gas (GHG) emissions (Lupwayi *et al.*, 2011). Diversification is one of the most common coping strategies in the ASAL, which suffer from frequent droughts and consequent crop failures and livestock mortality (Hassan and Nhemachena, 2008). Accordingly, mixed crop and livestock production systems have greater risk-coping mechanisms among poor farmers in the ASAL than is the case for specialized crop or livestock production systems (Potter and Ramankutty, 2010). Additionally, mixed crop and livestock production leads to better nutrition, soil fertility and mechanization (Kennedy *et al.*, 2003; 2004; Potter and Ramankutty, 2010).

Local institutions play a key role in water management (Meinzen-Dick, 2007), and communities in the ASAL have developed strong traditional institutions to effectively manage water resources. Strong local institutions have also been shown to improve the management of ecosystem services (Ostrom *et al.*, 1999), through bottom-up, inclusive, holistic approaches that enhance ownership and aid social relations.

However, local institutions are not a panacea (Meinzen-Dick, 2007). For example, customary and other informal local institutions face challenges in ensuring equity across gender and when operating in multi-cultural communities. Nevertheless, they have been shown to be more effective in managing grazing lands, water resources, forests and other natural resources, compared with formal local and national institutions (Lund, 2006; Mowo *et al.*, 2013).

This chapter examines land and water management practices in the context of agroecology. The focus is on the ASAL in developing countries, where farmers face daunting challenges due to their limited resources and the new policies and global changes that threaten traditional systems.

The next section reviews the literature on land and water management practices that have enhanced the sustainability of farmers' agro-ecosystems in the ASAL. The emphasis is on local knowledge systems, which lead to improved land and water productivity in an environment of water scarcity. The review focuses on the management of livestock and crop production systems in the ASAL, and the strategies farmers have used to cope with persistently low and unpredictable precipitation and production risks that this entails. The challenges and opportunities presented by these policy changes and global trends are also examined to determine their impacts on traditional land and water management practices. The third section discusses case studies to illustrate the major themes of the chapter. The last section concludes with a discussion, including implications for the up-scaling of agroecology.

REVIEW OF THE EVIDENCE ON LAND AND WATER MANAGEMENT IN THE ASAL

To cope with production risks and other challenges, management systems and livelihoods in the ASAL are highly diversified. To structure the discussion, this section is divided into livestock and crop production systems. We also discuss tree planting and protection programmes, which could be implemented either on cropland/grazing land (agroforestry) or woodlots/forests.

Livestock production systems and land and water management in the ASAL

This discussion is focused on rangelands – open grazing lands, which cover about 61.2 million km^2 or 45 percent of the global ice-free land area (Asner *et al.*, 2004; Reid *et al.*, 2008). Rangelands represent 78 percent of the grazed area and support about 200 million pastoral households (Nori *et al.*, 2005). Pastoral communities and other farmers in the ASAL rangelands have developed a rich knowledge and the skills to sustainably manage their land and water resources and cope with low and unpredictable rainfall (Reid *et al.*, 2008). A number of studies have shown that the pastoral systems in the ASAL are generally sustainable even in the face of large biomass productivity changes, which are largely due to the unpredictable precipitation and other natural shocks.

In such highly unpredictable, water-scarce systems, pastoralists and agro-pastoralists have adopted a number of measures to sustain productivity even when precipitation is highly variable; here we will discuss pastoralist mobility, crop-livestock systems, and the use of rangeland enclosures as traditional measures to address water scarcity.

Based on an extensive review of African pastoral community studies, Niamur-Fuller (1999) concludes that rangeland management systems are in a disequilibrial state, i.e. they change from one state to another. External factors, including droughts, fires, and locust or other insect attacks, drive the disequibrial state. There is a misconception that overgrazing is a major factor driving the disequibrial state (Niamur-Fuller, 1999); yet empirical evidence has shown that in fact it is precipitation that is the most important driver of grassland biomass productivity (Le Houérou and Hoste, 1977; Coppock, 1993), and with great variability in precipitation, grassland productivity is also highly variable. In the new rangeland paradigm (Turner, 2011), pastoral mobility is regarded as a sustainable livelihood strategy that responds to pasture and water availability and the occurrence of unpredictable shocks such as fires and pest outbreaks. Additionally, migration across agroecological zones (AEZ) enables each AEZ to sustainably support more livestock than is possible with a sedentary system (Scoones, 1995; Niamir-Fuller, 1999).

Past destocking campaigns were aimed at maintaining a predefined carrying capacity proved unpopular and have been viewed as a failure. For example, a study in northern Kenya showed that destocking rangelands leads to a significant decline in livestock productivity and is not likely to prevent land degradation (Hary *et al.*, 1996). This evidence suggests that the strategy of livestock mobility is more ecologically sound than destocking campaigns (Nkedianye *et al.*, 2011).

Livestock production in sedentary systems have also developed water management systems that allow relatively stable production. Higher soil carbon increases moisture conservation (Reeves, 1997) and crop farmers with livestock are more likely to apply manure and other organic inputs that build soil carbon (Nkonya *et al.*, 2015). Additionally, crop-livestock production systems provide greater nutrition diversity and quality compared with specialized crop or livestock systems (Kennedy *et al.*, 2003; 2004). This is especially important among poor farmers in developing countries, who have limited market participation and where household production is the major determinant of dietary diversity. In terms of soil fertility, a global study has shown that land areas characterised as supporting livestock have a greater propensity to achieve sustainable land management than those without livestock (Nkonya *et al.*, 2015). This is not surprising given that livestock manure accounts for 54-64 percent of total nitrogen and 64 percent of phosphorus applications at the global level (Sheldrick *et al.*, 2004; Potter and Ramankutty, 2010). Different types of rotational grazing systems are used by sedentary farmers in sub-Saharan Africa (Teague and Dowhower, 2003). The resting period between rotations helps to improve the composition of plant species, maintains the health of grazing land, reduces soil erosion and increases carbon sequestration (Bosch, 2008).

In response to water scarcity and seasonal variability, sedentary farmers who grow crops and keep livestock also set aside fodder banks or enclosures – areas set aside during the rainy season and used in the dry season when there is a shortage of forage in the surrounding rangelands (Verdoodt *et al.*, 2010). Rangeland enclosures are common in Ethiopia, Somalia, Nigeria, Kenya, Tanzania and Sudan (Verdoodt *et al.*, 2010; Barrow and Shah, 2011; Angassa *et al.*, 2012). Enclosures help to reduce the pressure on grazing lands, while restoring and preserving degraded forage. The fodder banks enhance biodiversity and soil ecology and prevent soil erosion and other forms of land degradation (Kamwenda, 2002; Verdoodt *et al.*, 2009; Abate *et al.*, 2010). There is greater species diversity in enclosures than in continuously grazed areas (Oba, 2013). Additionally, enclosures contribute to carbon sequestration. For example, Barrow and Shah (2011) have shown that the *Ngitili* (enclosures) of northwestern Tanzania sequestered about 23.2 million tonnes of carbon between 1986 and 2002. Strong customary institutions are used to manage *Ngitili* in northern Tanzania (Nkonya, 2008). Local village security guards (*Sungusungu*) are used to enforce rules and regulations enacted by customary institutions (*Dagashida*) (Barrow and Shah, 2011).

Challenges of achieving sustainable rangeland management in the ASAL

For traditional rangeland management systems used to address water scarcity (e.g. mobility, crop-livestock interaction, use of enclosures) to remain viable under current conditions, a number of considerations need to be addressed. Three key challenges are examined below: policies impinging on mobility; land degradation; and minimal investment in livestock development.

Policies impinging on mobility:

Livestock mobility faces many challenges, the first of which is crop expansion onto grazing lands. Cropland expansion has contributed to limited livestock mobility and consequently to violent conflicts between nomadic or transhumant pastoralists[2] with farmers (Adriansen, 2008). For example, the movement of Chadian herdsmen to Central African Republic led to violent clashes between pastoralists and the local population (ICG, 2014). Continuing land registration efforts have allocated communally owned grazing lands to private people. For example, the recent trend of land grabbing has seen an allocation of grazing lands to foreign investors (Babiker, 2011), resulting in a loss of grazing access for herders. Additionally, the establishment and enforcement of political and administrative boundaries, the usurpation of local institutional control and disruption of local practices have also led to restricted mobility and have reduced the effectiveness of customary pastoral institutions to effectively manage grazing lands (Fernandez-Gimenez and Le Febre, 2006).

Land degradation:

There has been significant degradation of grazing lands in the past 30 years. Le *et al.*, (2014) estimated that about 40 percent of the world's grasslands experienced degradation between 1986 and 2006. This degradation causes a loss of biodiversity and ecosystem services. The major drivers of land degradation have been overgrazing, wild fires and other forms of land degrading management practices. Land degradation can interact with the disequilibrial state of rangelands – leading to even more severe land degradation. In particular, overgrazing causes changes in species composition and intraspecies competition (FAO, 2009). The major driver of overgrazing and overharvesting of forage is the increased demand for livestock products, which is influenced by increasing income in low and medium income countries. For example, global meat and dairy consumption is projected to increase by 173 percent and 158 percent respectively, from 2010 to 2050 (Asner and Archer, 2010).

Minimal investment in livestock development:

Budget allocations to livestock development in developing countries are low. As a result, livestock productivity is low, especially in pastoral systems. For example, in Mongolia during the late-1990s, a third of the population and 50 percent of the labour force were dependent on livestock

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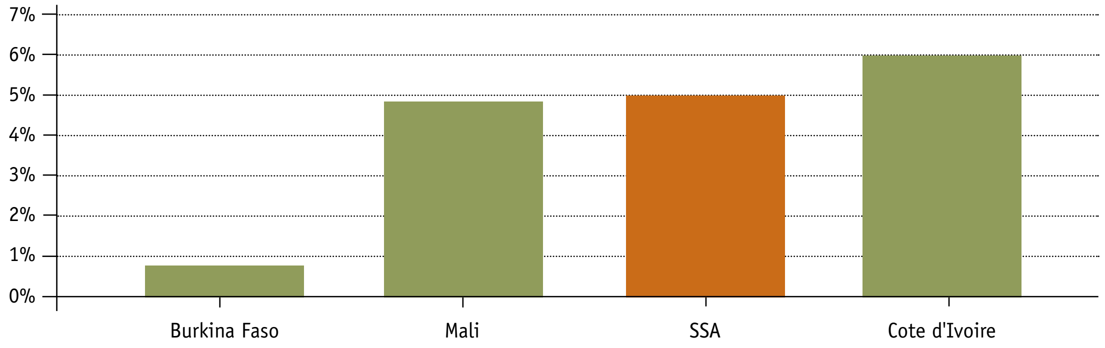
[2] Nomadic pastoralism involves movement of livestock and people in search of pasture and water and in patterns that are not regular. Transhumance is movement of livestock in a predetermined pattern – not always involving movement of the families of the herders.

for their livelihoods (Mearns, 2004). Yet, government budget allocations to livestock have been minor, resulting in a decline in breeding and agricultural research in areas such as irrigation maintenance, supplementary feed provision, management of drought and *dzud* (harsh winter/ spring weather conditions) risk, and marketing (Mearns, 2004). Government budgetary allocations to the livestock sector in sub-Saharan Africa is only about 5 percent (Figure 1), even though this sector contributed 35 percent to agricultural GDP in 2002 (Ehui *et al.*, 2002). Moreover, about 170 million people in the region are entirely or partially dependent on livestock production (FAO, 2006) and livestock occupies a much larger land area than crops Kamuanga *et al.*, (2008).

Figure 1. **Agricultural budget allocation to livestock as share of total government budget in SSA**



Source: calculated from Kamuanga *et al.*, 2008

Agroecological water management in croplands

Smallholder crop farmers in the drylands have developed various methods for addressing the risks and shocks related to low and highly variable precipitation (Mortimore and Adams, 2001). One of the most common approaches is to promote crop diversity, which has many ecological and economic benefits. Mixed cropping and intercropping (hereafter simply referred to as mixed cropping) have been associated with better soil cover and thus enhanced moisture conservation (Ghanbari *et al.*, 2010), soil fertility improvement, enhanced integrated pest management, and nutritional diversity (Young, 1987; Frison *et al.*, 2011). Mixed cropping breaks the disease cycle through increased microbial diversity and nitrogen fixation (Lupwayi *et al.*, 2011). Even though legumes may contribute to GHG emissions, Lupwayi *et al.*, (2011) observed that the amount of GHG emissions from cereal-legume intercropped systems is less than the amount released from monocropped cereals receiving fertilizer. Using land equivalent ratios – the relative land requirements for intercropped versus monocropped systems (Mead and Willey, 1980) – studies have shown that farmers with land constraints will realize greater harvest under intercropping than under monocropping systems (Malézieux *et al.*, 2009). Economic analyses have also shown that farmers earn greater profits using mixed cropping compared with monocropped systems (Shaxson and Tauer, 1992).

Studies have shown that in areas experiencing water scarcity, crop diversity reduces the risk of crop failure and other climate-related shocks due to the variation in rooting depth and canopy cover – both of which enhance moisture conservation (Lupwayi *et al.*, 2011). Other studies have also shown that agroforestry and land regeneration have enhanced farmers' food security, income and resilience in the drylands (Reij *et al.*, 2009; Place and Binam, 2013; Bayala *et al.*, 2014). Agroforestry trees could also provide fuelwood, forage, nitrogen fixation and other benefits (Pimentel and Wightman, 2010) and could simultaneously contribute to food and energy security. Additionally, recent studies have demonstrated that integrated soil fertility management (ISFM) – the use of organic inputs, improved seeds and judicious amounts of inorganic fertilizer (Vanlauwe *et al.*, 2010) – increases agricultural productivity, reduces climate-related risks and is associated with higher profits compared with the use of inorganic fertilizer or organic inputs alone (AGRA, 2014). Yet, the adoption rate of ISFM is low, mainly due to poor market access, high labour intensity of organic inputs and low capacity of agricultural extension services to provide ISFM-related advisory services. ISFM also increases the nutrient-use efficiency of mineral fertilizers (Marenya *et al.*, 2014), an aspect that contributes to a cleaner environment.

The review of crop production above suggests that crop diversity and the inclusion of organic and inorganic soil fertility management practices are important for achieving higher yields, profit and reducing production risks, while simultaneously dealing with water scarcity. However, extension services and access to markets are major challenges for their further diffusion among farmers.

Challenges of achieving sustainable agricultural water management in the ASAL

Irrigation, rainwater harvesting (RWH) and soil and water conservation (SWC) practices have been key AWM strategies to address water and moisture scarcity in ASAL. The discussion below first looks at irrigation and then SWC and RWH practices.

Irrigation:

Globally, there has been a significant increase in use of AWM practices, which has contributed to greater agricultural water productivity – the quantity or value of produce per amount of water used (FAO, 2003). Agricultural water productivity more than doubled between 1961 and 2001, largely due to the increased use of improved crop varieties (FAO, 2003). Other strategies used to improve agricultural water productivity include: improvement of irrigation infrastructure to reduce losses of water due to drainage, seepage and percolation; synchronizing irrigation with plant water demand during sensitive growing periods; minimum- or no-tillage and other moisture conservation tillage methods; RWH; construction of water storage structures; and techniques for recovering wastewater (FAO, 2003; Toze, 2006).

Adoption rates of AWM strategies and the subsequent agricultural water productivity measures vary significantly across the world. Sub-Saharan Africa ranks lowest in terms of agricultural water productivity measures and the extent of irrigated area (World Bank, 2006; Egeru, 2012). As an example, sub-Saharan Africa has 5 195 km^3 of harvestable runoff and if only 15 percent of this rainwater was harvested, it would be enough to meet the region's water needs (Malesu *et al.*, 2006). Given that sub-Saharan Africa faces the most daunting challenges in increasing water productivity, the discussion below focuses on the ASAL zones of the region.

Following the failure of various large-scale irrigation development projects in sub-Saharan Africa (Inocencio *et al.*, 2007; Turral *et al.*, 2010), both governments and their development partners have focused on small-scale irrigation development. In addition to the negative impacts on ecosystems that result from the diversion of large rivers (Falkenmark *et al.*, 2007), large-scale irrigation schemes were centrally managed and used a top-down approach, which failed to strengthen local institutions to efficiently deal with water allocation and management (Inocencio *et al.*, 2007; Turral *et al.*, 2010). A comparison of returns to irrigation investment has also shown that the internal rate of return for small-scale irrigation investment was 28 percent compared with 7 percent for large-scale irrigation (You *et al.*, 2011). For example, Nigeria heavily invested in large dam irrigation in the 1970s and 1980s, but shifted to supporting small-scale farmers in the 1990s. These smallholders utilized the shallow aquifer floodplains and low-lying areas (*fadama*) to irrigate crops in the dry season and provide supplementary irrigation during the rainy season (Nkonya *et al.*, 2010).

Small-scale irrigation has made a significant contribution to irrigation development in sub-Saharan Africa but still faces many challenges. The most important challenge is the limited involvement of farmers in the planning and implementation of irrigation schemes. An assessment of project performance showed that projects in which farmers contributed to irrigation development investment and management were more likely to be successful than those without farmer contribution (Inocencio *et al.*, 2007). Community-driven development approaches that were used to run the *fadama* project also realized significant impacts in the improvement of human welfare (Nkonya *et al.*, 2010). However, even for small-scale irrigation schemes initiated by government and/or donor-supported projects, the focus is generally on developing irrigation infrastructure. The involvement of beneficiaries (farmers) in planning and developing the local institutional capacity to manage the irrigation scheme has been limited (Cleaver and Franks, 2005; Nkonya *et al.*, 2013). Additionally, advisory services for irrigation infrastructure maintenance and water management have been poor (Nkonya *et al.*, 2013). The major advisory services have been provided by farmers themselves (Ouedraogo, 2005). For traditional irrigation schemes that are initiated and managed by farmers, irrigation management institutions are strong but the irrigation infrastructure is poorly planned and its maintenance is limited due to budgetary restrictions. The case study from Tanzania that is described in the following section, illustrates some of the challenges.

Soil and water conservation and rain water harvesting practices:

Water and moisture conservation structures and rainwater harvesting (RWH) are common agricultural water management practices in the ASAL. RWH and integrated SWC approaches increase the provisioning capacity of crops, fodder and other biomes (Barron, 2009). Farmers have developed a variety of moisture and water conservation and RWH practices to suit their needs. For example, an evaluation of indigenous SWC methods in Kenya revealed that a number of structures are used, including trash lines[3], stone bunds, terracing (*Fanya Juu*) and log lines[4]. The choice of specific SWC practices is influenced by household capital endowment, soil type and fertility, farm productivity, level of rainfall and ecological variability (Tengberg *et al.*, 1998). For example, poor farmers may prefer to intercrop a cereal with a legume. The general conclusion from the analysis of the SWC in Kenya was that the farmer choices were logical and prudent and that they enhanced the agroecological functions of their production systems (Tengberg *et al.*, 1998; Fox *et al.*, 2005).

Other SWC and RWH practices in sub-Saharan Africa include *zaï* planting pits, which were invented by Mr Yacoubou Sawadogo, a farmer from Burkina Faso who subsequently conducted his own extension services to advise other farmers (Ouedraogo, 2005). *Zaï* are capable of increasing rainfed crop yields by 47 percent when used in combination with organic inputs (Pender, 2009), while also reducing production risks in arid regions. Recently, there has been a strong promotion of conservation agriculture, which reduces soil erosion and improves water-use efficiency through improved infiltration and reduced evaporative water losses (Giller *et al.*, 2009). For example, Bouza (2012) observed that 30 percent continuous cover of land reduced wind erosion by 80 percent in Argentina.

The adoption rate of SWC and RWH is low (SIWI, 2001) due to limited promotion. New strategies are required to increase their uptake in order to enhance sustainable agroecological production in the ASAL.

TREE PLANTING AND FARMER MANAGED REGENERATION PROGRAMMES

Tree planting enhances water conservation as the tree canopy cools the soil and serves as a windbreak (Schoeneberger, 2009). Additionally, deep-rooted trees utilize water from deeper horizons, avoiding water competition with shallow-rooted plants (Kassam *et al.*, 2009). A number of tree-planting programmes in the ASAL have been initiated around the world. Sub-Saharan Africa is currently implementing an initiative to create a "Great Green Wall", which is anticipated to be a 15 km wide and 7 100 km long tree belt running from Dakar to Djibouti (GEF, 2011). This programme takes its cue from China's great green wall, which is 4 480 km long, running across the desert in northwestern China (Levin, 2005). A number of farmer managed natural regeneration (FMNR) programmes have also been successful in the Sahelian region (Reij *et al.*, 2009; Place and Binam, 2013; Bayala *et al.*, 2014). FMNR is a low-cost strategy for the restoration of degraded biomes using practices that are aimed at increasing land productivity. Similarly, Mongolia has implemented FMNR for restoring forests and grasslands in dryland areas through protection and planting of indigenous trees (Zhao *et al.*, 2007).

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[3] Trash lines are formed by placing crop residues in lines along the contour line.

[4] Log lines are formed on recently cleared land, with tree logs are arranged along the contour.

A number of factors have contributed to the general success of tree planting, protection and FMNR:

- Use of indigenous tree or grass species is important for ensuring higher survival rates in the fragile ASAL environment. For example, China's great green wall, which was started in 1978, first used exotic trees whose survival rate was as low as 15 percent (Cao *et al*., 2011). Native trees were introduced after the low survival rate became a problem.
- Long-term studies of forest management have also shown that local institutions are more effective in natural resource management than central governments (Poteete and Ostrom, 2004).
- A review by Cooke *et al*., (2008) showed that tree planting programmes have been successful in areas where farmers have experienced significant losses of tree cover leading to a loss of ecosystem services provided by trees (e.g. building material, firewood for poor communities and other services). However, successful programmes often require incentive mechanisms and institutions to ensure that efforts by land owners and/or operators are safeguarded.
- Strong support from the government and NGOs and religious organizations can also play a key role in successful tree planting, protection and FMNR. A case study from Niger is featured in the following section to demonstrate the role played by NGOs and government policies to provide incentives for tree planting, protection and FMNR.

CASE STUDIES

To illustrate the main findings of the literature review, the following section introduces case studies of rangeland management, AWM and tree planting, protection and FMNR programmes. The focus is on traditional or introduced land management practices that are fully implemented by farmers without significant external support. The management practices are knowledge-intensive rather than input-intensive. This high local knowledge intensity is a central feature of agroecological management (Altieri, 2002).

Sustainable pastoral livelihoods in Asia and sub-Saharan Africa

Pastoral communities in Mongolia have sustainable nomadic livelihoods whose temporal and spatial movements are driven by the availability and condition of pasture and water resources (Zhang *et al*., 2007). Livestock is moved to drier areas during the rainy season and towards more humid areas during the dry season. This allows the pastoral communities to have access to both high-quality and sufficient pasture and water during dry and wet seasons. This reduces grazing pressure, relieves and restores previously grazed pastures, and helps to maintain and/or improve biodiversity and heterogeneity in rangeland ecosystems. The Mongolian herders have a rich ecological knowledge, which dictates their use of diversity, their flexibility and reciprocity, and their development and use of pasture and water reserves (Fernandez-Gimenez and Le Febre, 2006). To manage such fragile ecosystems, the Mongolian pastoral communities have developed

strong customary institutions that guide management of the rangeland and water resources (Fernandez-Gimenez and Le Febre, 2006).

Like Mongolian livestock farmers, there are a number of pastoral communities in sub-Saharan Africa with strong customary institutions and ecological knowledge that support sustainable rangelands management (Selemani *et al.*, 2012). For example, the moon cycle is used to determine livestock mobility by the Wodaabe Fulani of southwestern Niger (Stenning, 1994; Folke and Colding, 2001). The Rufa'a al Hoi of Sudan are pastoralists who move to new pastures after every 204 days, while the Fulani of northern Sierra Leone move their livestock after every two years to allow pasture to rejuvenate for some years (Folke and Colding, 2001). The Himba pastoral communities in northwestern Namibia set aside emergency pasture reserves for use only when there is drought (Kuckertz *et al.*, 2011). Such ecological knowledge and practices have helped communities to sustainably manage their resources for centuries. For example, the Maasai in Kenya and Tanzania have unique, environmentally friendly traditions that set them apart from surrounding communities. One of the strong features of the Maasai tradition is that they do not eat wild game meat (Asiema and Situma, 1994) or cut a live tree. The Maasai regard trees as landmarks of water sources, cattle routes and medicinal herbs (Ole-Lengisugi, 1998). This is one of the reasons that the government of Tanzania allows only the Maasai to live in the game parks. These examples show the rich indigenous ecological knowledge used to sustainably manage rangelands.

Pastoralist communities are however facing daunting challenges in continuing their traditional way of life. Mongolian pastoral livelihoods are facing challenges due to policy reforms. The Mongolian government has implemented policy reforms to move from a socialist to a market economy – a strategy that has led to massive layoffs from state owned companies, with the labour force largely being absorbed by the livestock sector (Mearns, 2004). Due to this, livestock population increased by 75 percent from 1993 to 1999, and the number of herders doubled between 1990 and 1997 (Mearns, 2004). Such a dramatic rise in livestock population and herders has exerted increasing pressure on rangelands.

As stated earlier, pastoralist communities in sub-Saharan Africa are also experiencing pressure due to land tenure formalization, individualization and foreign investments, which have led to the allocation of grazing lands to foreign investors. Land tenure formalization has restricted livestock mobility in Africa and other regions with poor land tenure security.

Indigenous knowledge systems are an essential element in managing arid lands and allowing them to remain productive despite highly variable rainfall and general water scarcity. However, policy measures to sustain both indigenous livelihoods and ecosystems are poorly developed and often contradictory.

Patagonia rangelands and merino wool production

Wool production in Argentina mostly takes place in the Patagonia steppe, an area that covers about 800 000 km^2 (Ares, 2007). The pastoralist communities in Patagonia have raised their sheep using traditional extensive and continuous grazing practices, in which grazing is carried out with minimal human control of livestock movement (Ares, 2007; Oliva *et al.*, 2012). Because sheep are highly selective grazing herbivores (Cibils *et al.*, 2001), continuous grazing has led to a depletion of preferred forage such that even after fallowing, palatable forage does not fully recover (Ares, 2007). Long-term studies have shown that full recovery of preferred forage required two to three decades of resting in eastern Patagonia (Bisigato *et al.*, 2002).

Rotational grazing has been shown to sustainably keep the preferred forage productivity. The recommended rotational grazing method involves putting sheep in wetlands (*malines*) during the dry season and highlands during the spring season (Golluscio *et al.*, 1998). A special type of rotational grazing has been developed by the rangeland research programme at the national research institute, INTA (Instituto Nacional de Tecnología Agropecuaria). The recommendation is a low input management technology, Tecnología de Manejo Extensivo (TME), which is appropriately nicknamed, "take half leave half". TME is a grazing plan that is developed after a remote sensing assessment is carried out to determine the carrying capacity of land. The farmer is advised to manage their grazing so that half of the above-ground biomass of the preferred forage is left before animals are moved to another paddock (Anderson *et al.*, 2011).

There has been a degradation of wetlands in Argentina. Table 1 shows that by 2009, about 12 percent of the 6.4 million ha of wetlands in grasslands and woody biomes that were recorded in 2005, had been lost. The loss is estimated to have cost Argentina about US$4 billion[5] or 2 percent of its GDP in 2007 (Aranda-Rickert *et al.*, 2015). The major reason behind the loss of wetlands in grasslands in Patagonia has been overgrazing. For example, the Molihue wetlands were inadvertently drained because overgrazing occurred upstream and sheet and gully erosion formed gullies that drained the wetlands. In highly populated areas however, the loss of wetlands has been due to the construction of canals connecting inland wetlands with rivers, valleys and other natural drainage systems (de Prada *et al.*, 2014). The construction was in response to sporadic flooding, which prompted farmers and rural communities to ask local and federal governments to build the canals. The wetland draining canals changed hydrologic systems and resulted in significant losses of wetlands (de Prada *et al.*, 2014).

Table 1. **Wetlands loss in Argentina**

CLASS	2005	2009	NET LOSS
	(000 ha)		
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - fresh, brackish or saline water	6 366.3	5 615.9	11.8%
Cost of loss (US$ million)			19 271.78
Cost of loss per year (US$ million)			3 854.36
Loss as % of GDP			1.5%

Note: Inland wetlands are worth about US$25 682 ha^{-1} (de Groot *et al.*, 2013)

Source: Nkonya *et al.*, 2015

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[5] 2007 US$.

Wool prices have been falling since the 1950s, largely due to increased use of synthetic fibre (Jones, 2004). As a result, the sheep population in Argentina fell from about 50 million in 1961 to 15 million heads in 2013 (FAO, 2015). However, despite the decrease in sheep population, rangeland degradation has continued to occur due to continuous grazing. According to Golluscio *et al.*, (1998), the widespread adoption of rotational grazing is constrained by three major challenges:

1. Slower recovery of preferred forage: fallowing should occur during pasture growth, which is in the spring and early summer period when there is ideal precipitation and temperature. In drier areas, livestock movement during this time is more difficult;
2. Animal movement increases the mortality of lambs and therefore is not an attractive option for farmers;
3. The cultural system of uncontrolled grazing is the most significant constraint to the adoption of rotational grazing. Traditional continuous grazing systems are strongly held on to and only 6 percent of sheep farmers in southern Patagonia have adopted TME (Anderson *et al.*, 2011).

In contrast to the case study of pastoral livelihoods in Asia and sub-Saharan Africa, traditional practices in Argentina need to adapt to changing and deteriorating conditions. In water-scarce environments, a mobile and sensitive management system is needed to enable recovery and regrowth of pasture lands. Hydrological systems have been manipulated, often to the detriment of healthy ecological systems. A systems perspective, considering the interaction of wetlands, highlands, water ways and communities is needed.

Small-scale irrigation schemes in Tanzania

Tanzania's Agricultural Sector Development Programme (ASDP) supported a number of irrigation schemes, which included the construction of new irrigation schemes and rehabilitating old irrigation schemes. Rehabilitation efforts included traditional irrigation schemes, which account for 56 percent of the 828 000 ha of irrigated area (Nkonya *et al.*, 2014). An assessment of the ASDP irrigation schemes showed that the average water user association fees paid by irrigators covered only 13 percent of the required amount to maintain the irrigation schemes (Table 2). This is a general problem observed by other studies (e.g. Lankford, 2004; Inocencio *et al.*, 2007; Evans *et al.*, 2012), which casts doubt on the sustainability of the irrigation schemes after the end of the ASDP. An analysis of the amount of annual membership fees paid shows that schemes in severe poverty areas contributed a comparable amount with those in low poverty areas (Figure 2). These results indicate that severity of poverty was not an important driver of the amount of annual membership fees collected, rather the capacity of communities to organize themselves seems to play a pivotal role.

The second major problem of the irrigation schemes in Tanzania was the state of the irrigation infrastructure. Most irrigation schemes were not properly planned and many schemes experience water insufficiency/stress due to unplanned expansion and poor irrigation infrastructure. There is a lack of irrigation engineering advisory services due to the limited number of irrigation engineers in the country. The lack of advisory services on traditional farmer technologies is a common problem in sub-Saharan Africa, as extension messages are generally based on technical information originating from agricultural research institutes, ignoring the traditional and local knowledge and innovations of farmers in the ASAL. The design of agroecological crop watering systems needs to be based on farmer experience and input.

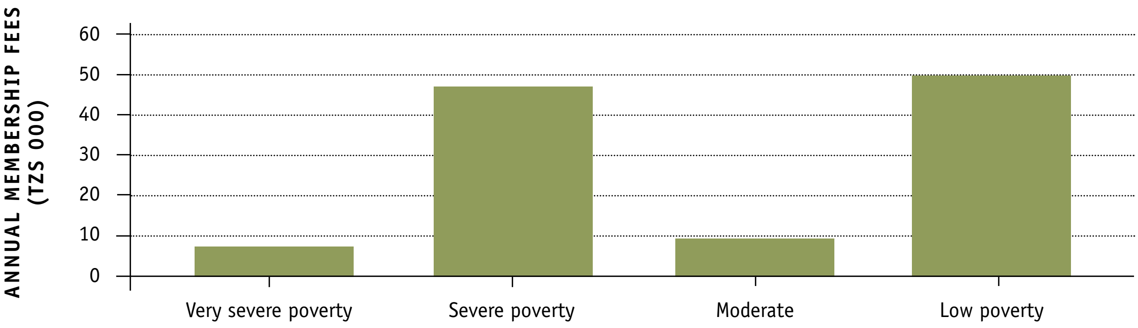
Table 2. **Tanzanian irrigation schemes with farmers' annual contribution across irrigation zones**

IRRIGATION ZONE	TOTAL AREA IRRIGATED (000 HA)	NUMBER OF SCHEMES	% WITH MEMBERSHIP FEE	AVERAGE AREA (HA) PER HOUSEHOLD	ANNUAL MEMBERSHIP FEE (PER HA EQUIVALENT)	
					(US$)	**% of operation and maintenance cost per ha**
Dodoma	22.39	48	62	0.3	3.13	4
Kilimanjaro	29.41	63	72	0.6	17.50	22
Mbeya	27.22	61	100	1.0	11.31	14
Morogoro	43.18	44	82	0.6	85.94	107
Mtwara	6.66	41	30	0.4	1.88	2
Mwanza	9.86	53	72	0.6	18.65	23
Tabora	7.88	43	100	0.7	7.68	10
Total	**146.59**	**353**	**77**	**0.6**	**10.02**	**13**

Note: The annual average maintenance cost per ha for small-scale irrigation is US$80 (You *et al.*, 2011).

Source: Nkonya *et al.*, 2014

Figure 2. **Annual irrigation membership fees and their relationship with the severity of poverty in Tanzania**



Source: Nkonya *et al.*, 2013

A success story of tree planting, protection and farmer managed natural regeneration in Niger

A classic example of the successful tree planting and protection is the regreening of the Sahel in Niger (Anyamba *et al.*, 2014). Before colonialism, Niger had a customary unwritten right of axe law, which stipulated that a farmer who clears land then owns that land (Gnoumou and Bloch,

2003). The 'Law of the Axe' was made worse by the French colonial laws. The 'Aubreville Decree' of 1935, made all vegetation the property of the government and farmers were required to purchase permits to cut and use wood, even for trees that were on their own farms (Brough and Kimenyi, 1998; Montagne and Amadou, 2012). Another decree from the same year stipulated that all lands not occupied or used for more than ten years would become state property – even when the land belonged to a farmer but was under fallow (Boffa, 1999). Both laws were only slightly modified after independence. However, due to weak enforcement of the forest code, naturally occurring trees were cut without replacement and this led to severe losses of tree cover. A prolonged drought from 1977 to 1985 caused further loss of vegetation and decimated over 50 percent of livestock (RoN, 2000). Firewood collection became a one-day task, which was mostly undertaken by women. The scarcity of natural resources also contributed to the intensification of conflicts between transhumant and nomadic pastoralists and sedentary farmers over water and terrestrial biomes (trees, croplands and grazing lands).

Tree scarcity and the massive loss of livestock and other impacts of land degradation prompted the government to reconsider its natural resource management policies and strategies. The Rural Code (Principe d'Orientational du Code Rural Ordinance), enacted in 1993, conferred tree ownership to those who plant or protect trees on their farms (Abdoulaye and Sanders, 2005; Adam *et al.*, 2006; Stickler, 2012). The new laws provided a strong incentive for farmers to plant and protect trees. The returns on tree planting and protection were also high due to the severe scarcity of trees. An evaluation of the vegetation cover in southern Niger showed a significant improvement as rainfalls increased from 1994 to 2012 (Anyamba *et al.*, 2014). After controlling for precipitation, Herrmann *et al.*, (2005) observed a residual increase in greenness where tree planting and protection programmes such as the Projet Intégré Keita operated (Reij *et al.*, 2009; Pender, 2009). There were also large increases in pastureland due to FMNR (Ouedraogo *et al.*, 2013).

In ASAL, policies promoting vegetation and tree cover are essential to agroecological approaches to water scarcity, to ensure healthy water-holding capacity of the land. In addition to the change of statutes that provided incentives to land operators, the strong support of NGOs and other members of civil society played a key role by helping to provide technical support and build local institutional capacity to manage natural resources (Reij *et al.*, 2009).

CONCLUSIONS AND IMPLICATIONS

Farmers in the ASAL have acquired rich ecological knowledge and experience, including land and water management practices that have proven to be resilient in their fragile environment. The communities in the ASAL have also used customary and other local informal institutions to effectively manage natural resources. However, new policies and global changes are posing challenges to livelihoods and local institutions in the ASAL. Additionally, policies in many developing countries have not fully exploited the traditional ecological knowledge and institutions for land and water management. As part of efforts to develop sustainable agroecological systems in the ASAL, there is a need to take steps to enhance the understanding of indigenous knowledge and institutions. Such efforts should include identifying strategies for exploiting the strengths of the indigenous ecological knowledge and institutions while addressing their weaknesses.

Farmers in the ASAL have embraced integrated crop and livestock production systems. Empirical evidence has shown that these systems have environmental, economic and nutritional advantages compared with specialized production systems. A review of crop production systems suggests that crop diversity and the inclusion of organic and inorganic soil fertility management practices are important for achieving greater nutritional diversity, higher yields, profit and reducing production risks. Indigenous SWC practices are also highly diversified and can be used in a logical and prudent way to enhance agroecological functions in the ASAL. However, extension services often offer blanket recommendations that fail to effectively address farmers' needs and their diverse biophysical and socio-economic contexts. Interventions for achieving sustainable agroecological systems should take into account ecological and socio-economic diversity, including the underlying complex interactions that drive diversity in traditional land and water management practices. The low capacity of extension services to provide advisory services on integrated soil fertility and agroecology should be addressed via short-term training to re-equip extension agents with new knowledge and paradigms.

Traditional mobile rangeland management systems have shown resilience over centuries but are now challenged with ongoing land tenure formalization and increased land investments, which have been prompted by an increasing demand for land. Both of these processes restrict livestock mobility. Recent foreign land investment in sub-Saharan Africa, has concentrated on lands held under customary tenure and/or communal lands with no formal tenure. This has resulted in grazing land expropriation and has increased pressure on rangelands. Efforts to protect customary tenure systems against arbitrary expropriation require immediate policy action. Additionally, long-term strategies for enhancing women's access to land under customary tenure need to be adopted as customary institutions in many communities inhibit women from acquiring land through inheritance. Short-term strategies for improving women's access to land include improvements in land markets. It is especially important to legalize land sales in sub-Saharan African countries where land belongs to the state and selling and buying land is illegal.

Public investment in the livestock sector has remained low in many developing countries. For example, the budget allocated to livestock in sub-Saharan Africa is only 5 percent. These trends and patterns are contrary to expectations given that the increasing demand for livestock products in middle- and low-income countries offers a large opportunity for increasing livestock productivity and reducing poverty, which is severe in the ASAL. Rangeland grazing and its related livestock systems have evolved over millennia, and are one of the most viable means of sustaining productivity in water-scarce regions.

Traditional irrigation and RWH systems in the ASAL have a number of structural weaknesses that lead to lower water-use efficiency, and greater investments are required for their development. In cases where governments invest in small-scale irrigation systems, the focus has been on developing irrigation infrastructure and little effort has been made to design systems based on farmer knowledge and inputs or to build the capacity of local institutions to sustainably manage irrigation infrastructure and other AWM programmes. Technical advisory

services on irrigation infrastructure maintenance and expansion are often poor in developing countries. Climate change and the future demand for water suggest that this pattern must urgently change.

Healthy vegetation cover is essential for managing water scarcity through agroecological approaches. Success stories in tree planting, protection and FMNR suggest that when governments give the mandate to local people to manage their natural resources, and provide a supportive policy environment, including the right incentives for planting and protecting trees and/or pasture, this can be an effective approach even in very poor countries.

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11

AGROFORESTRY:
REALIZING THE PROMISE OF AN AGROECOLOGICAL APPROACH

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Abstract

Agroforestry is a dynamic, ecologically-based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production and contributes to more resilient rural livelihoods. Drawing on the most recent science and case studies, especially from the work of the World Agroforestry Centre (ICRAF) and its partners, this chapter explores the contributions of agroforestry to the management of agricultural landscapes and the strengthening of rural livelihoods, taking account of the fine-scale variation and heterogeneity that are a feature of these landscapes. There is growing evidence from across the developing world that the adoption of agroforestry is helping to restore the productivity and resilience of landscapes, as well as contributing to the goals of food, nutrition and income security for smallholders and other vulnerable groups in society. Because development challenges are emergent properties of a complex system they can only be tackled by systems approaches, such as agroforestry, based on a sound understanding of ecology and a better understanding of the social and economic systems of the people who inhabit these landscapes. The case studies focus especially on the contributions of agroforestry to improving the agroecology of large-scale plantations as a means of testing the scalability of this body of work. Investments, including from the private sector, are helping to scale up agroforestry-based agriculture and this chapter touches on the evolving nature of these investments as an important contributor to the widespread adoption of agroforestry. It closes with an identification of opportunities and challenges for agroforestry in the context of rising populations, climate change, shifting demographics and changing consumption patterns.

INTRODUCTION

In the next four decades, all those who are engaged in improving the way agriculture is practised on this planet are faced with the requirement of producing 60 percent more food, on about the same amount of agricultural land, to meet the needs of a rapidly growing population, unless there is a change in diet from current trends (Alexandratos and Bruinsma, 2012). We are challenged to do so in a manner that is both equitable and sustainable, at requisite scales and in lockstep with demand, but with less negative impacts on the environment and with greater benefits to those who farm, especially smallholder farmers in developing countries. Restated, the challenge is to support or induce productive resilience in agricultural landscapes while countering rapid, pervasive change that is threatening to undermine the agroecological basis of the farming systems involved. This chapter examines whether and how agroforestry – *a dynamic, ecologically based, natural resource management system that integrates trees on farms and in*

the agricultural landscape – can rise to this challenge by diversifying and sustaining production while contributing to more resilient rural livelihoods.

Agroforestry offers potential tools, technologies, evidence and practical experience without forcing a 'one size fits all' approach. We explore whether it can deliver all this at relevant nested scales (patch, plot, farm, landscape, ecoregion) that retain basic similarity in interactions (Minang *et al.*, 2015). For example, can agroforestry provide solutions for individual farms or farmers nested within communities, and in time to tilt the balance away from approaches that degrade the productive potential of agricultural landscapes while often exacerbating greenhouse gas (GHG) emissions and inequity? Our intention is to show that:

1. Optimizing the contribution of trees to agricultural systems at nested scales will deliver multiple benefits to people and the planet;
2. Fine-scale variation and diversity of species, systems, life-forms, contexts and options are assets rather than hurdles;
3. It is possible to go to scale up agroforestry in time because we have the tools, evidence and an understanding of the kinds of partnerships that will succeed. However, challenges remain.

At the same time we must remember that we are dealing with complex adaptive systems that are nested and connected in many different ways. These systems are scale dependent, which is potentially confounding as the choice of each scale will affect what is revealed and what remains hidden. Boundaries are neither innate nor natural and there can be more than one useful boundary; uncertainty is a hallmark of these systems.

Agro-ecosystem functions provide human benefits, or services, at multiple nested scales, often involving lateral flows (e.g. water, sediment, biota, fire, modified air) as the physical basis for the nesting (van Noordwijk *et al.*, 2004; 2014). Management of these lateral flows, with water as the most immediate, direct and visible resource, has given rise to collective action and local institutions that clarify rights and responsibilities in local contexts. National legislation is often poorly aligned with these local institutions and may be based on an incomplete understanding on the part of policy-makers and most scientists of landscapes as dynamic socio-ecological systems, with several two-way and indirect interactions of the social and ecological aspects (van Noordwijk *et al.*, 2012; 2015).

Performance-based management of landscapes across scales is still an exception rather than the rule, requiring the reconciliation, contrasting and recognition of the multiple knowledge systems involved. An elaborate toolbox for doing so is now available (van Noordwijk *et al.*, 2013); the methods centre on recognition and respect of differences between three knowledge systems: local ecological knowledge, the knowledge and perceptions on which public opinion and policies are based, and the insights that science has to offer. These methods include participatory landscape appraisal and a focus on gender in relation to land use and markets, water flows and tree diversity.

In the next section some of the key outcomes and resources (including tools/approaches) of agroforestry are introduced. These provide a source of optimism that agroforestry, as an agroecological approach, can succeed and the conditions under which this has happened are revealed. We then explore selected case studies that illustrate the challenge of transforming large landscapes to more agroecologically sound practices. We conclude with some thoughts on possible ways forward.

FOUNDATIONS FOR OPTIMISM

Diversity as a resource and as an essential outcome

Despite mounting evidence that higher biological diversity promotes (agro-)ecosystem stability and productivity (e.g. Loreau *et al.*, 2001; Cardinale *et al.*, 2011), simplification of agricultural systems is a major driver of biodiversity loss, threatening the provisioning of ecosystem services (Hulvey *et al.*, 2013; Zuppinger-Dingley *et al.*, 2014).

Agroforestry shapes an agro-ecosystem that can create environmental, economic and social benefits, such as combining high agricultural and high biodiversity goals on-farm. Besides the positive effects of diversity on ecosystem functioning and contributions to biodiversity conservation (including farmer-based conservation), there is evidence that the diversification of tree species can lessen seasonal variation in the provision of goods and services and thereby protect farmer incomes (Kindt *et al.*, 2006a; Dawson *et al.*, 2013). The health and productivity of these agroforestry agro-ecosystems and communities relies on diversity both within (intraspecific diversity) and among trees (interspecific diversity) (Graudal *et al.*, 2014; Ruotsalainen, 2014; McKinney *et al.*, 2014).

To estimate the value of agroforestry trees to tropical rural communities, Dawson *et al.* (2014b) considered the diversity of species that smallholders consider important for planting and the recorded uses of these species, as illustrated in Table 1, based on the compilation of information from ICRAF's open-access *Agroforestree Database*, the AFTD (Orwa *et al.*, 2009). Most tree species listed by the AFTD are indicated to have a range of possible uses in agroforestry systems. Multiple uses illustrate the flexibility in the products and services that agroforestry trees can provide, which can help support diverse livelihoods and promote production-system resilience (Garrity, 2004). An analysis of the 650 species in the database reveals that many tree species perform several functions, while smallholders are able to use a wide range of trees on or around their farms. In parallel, these trees also provide environmental services such as erosion control and shade/shelter, as well as global services such as carbon sequestration. Given the immense diversity that is available at species level in trees – a total of 80 000-100 000 tree species are estimated to exist today (FAO, 2014) – local people have a wide choice for a given product or service (see Figure 1). While providing opportunities, this extensive genetic resource of species can also present challenges in ascertaining which species to prioritize regionally for research or for planting projects.

Both inter- and intra-specific diversity within agroforestry landscapes can support crop yields and promote agricultural resilience. Diversity, especially genetic and functional diversity, is one of the principle sources of resilience, providing a strong justification to maintain diversity (Bos *et al.*, 2007; Hulvey *et al.*, 2013). Clough *et al.*, 2009 have also emphasized that mixed farmland production regimes that combine tree commodities with fruit trees, staple crops and/or vegetables can maintain commodity yields and promote resilience. In the right circumstances, the integration of commodity crops such as coffee, cacao and rubber with trees, or in forest mosaics can increase production (Ricketts *et al.*, 2004; Priess *et al.*, 2007). Further, trees that are often used for shade have been documented to improve cocoa production, provision of timber, fruits and other products and ecosystem services at landscape levels (Somarriba *et al.*, 2013).

Table 1. **Number of tree species providing specific functions of importance to smallholders' livelihoods and the known geographic distribution of these species**

FUNCTION	NUMBER OF SPECIES IN THE AFTD DATABASE BY REGION						
	Africa	Oceania	South America	South Central Asia	Southeast Asia	Western Asia and Middle East	Total (regions)
Apiculture	177 (50)	84 (31)	83 (39)	108 (31)	121 (38)	34 (47)	607 (40)
Erosion control	175 (54)	70 (29)	57 (40)	120 (48)	117 (48)	32 (53)	571 (47)
Fibre	141 (40)	93 (38)	60 (33)	133 (45)	149 (45)	32 (56)	608 (42)
Fodder	295 (55)	101 (30)	96 (45)	217 (52)	191 (47)	61 (57)	961 (49)
Food	295 (54)	124 (35)	119 (43)	220 (49)	225 (49)	62 (55)	1 045 (48)
Fuel	357 (53)	147 (35)	126 (42)	243 (45)	249 (47)	62 (56)	1 184 (47)
Medicine	390 (57)	159 (36)	144 (40)	298 (50)	314 (50)	67 (55)	1 372 (50)
Shade/shelter	281 (51)	131 (40)	104 (42)	193 (44)	202 (48)	46 (57)	957 (47)
Soil improvement	194 (51)	83 (33)	73 (45)	143 (42)	154 (45)	26 (46)	673 (45)
Timber	419 (53)	192 (38)	158 (42)	313 (49)	347 (50)	70 (51)	1 499 (48)
Total (functions)	**2 724 (53)**	**1 184 (35)**	**1 020 (42)**	**1 988 (47)**	**2 069 (47)**	**492 (54)**	**9 477 (47)**

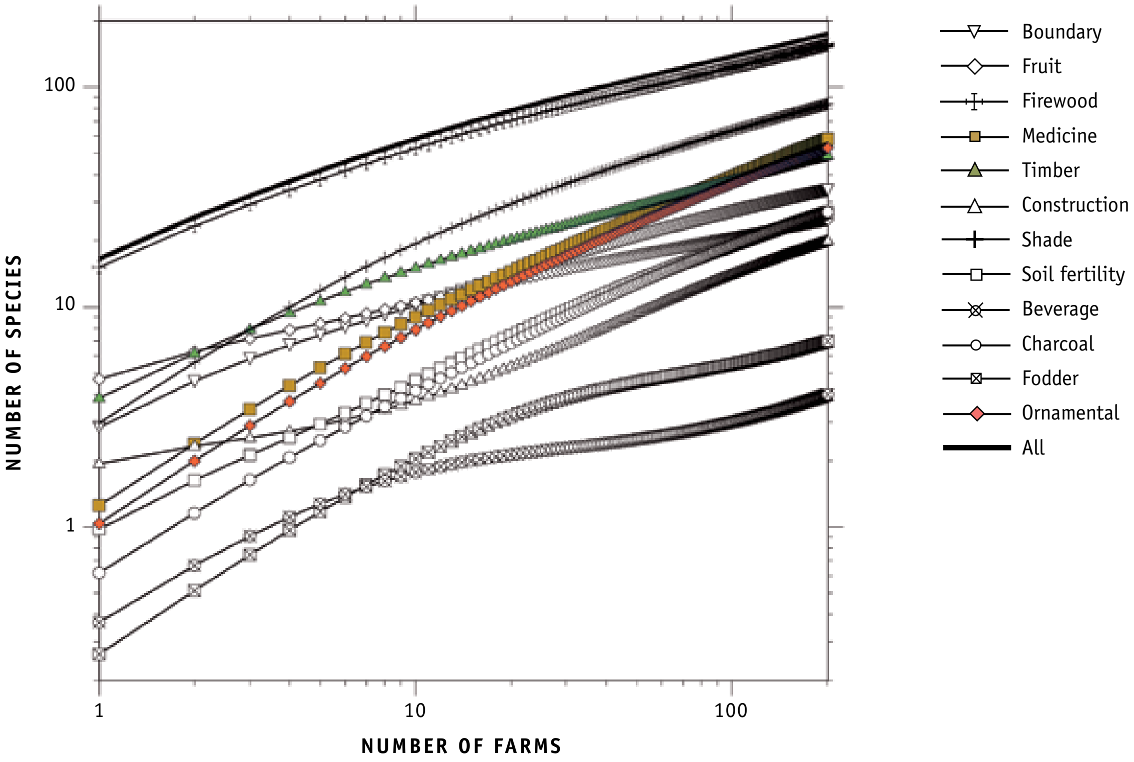
Regions are classified according to www.wikipedia.org/wiki/List_of_sovereign_states_and_dependent_territories_by_continent for Africa, Oceania and South America, and www.nationsonline.org/oneworld/asia.htm for Central Asia, Southeast Asia, and Western Asia and the Middle East. The greater number of total references to the African continent is partly due to the focus of the AFTD on documenting species found there. The percentage of references to indigenous species is given in brackets.

Source: Dawson *et al.*, 2014b

Zuppinger-Dingley *et al.*, (2014) also demonstrate that diverse plant communities enable higher crop yields than monocultures because of selection for niche differentiation; plant species in communities occupy all niches available in ecosystems, enabling a more effective use of soil nutrients, light and water. A further understanding of how agroforestry mechanisms can diversify agro-ecosystems at species level and bring about direct benefits and resilience in specific aspects of agricultural production (e.g. the role of trees as hosts for pollinators needed to pollinate cash crops such as coffee) is key (Carsan *et al.*, 2014). These aspects have applications for agroforestry systems as their functioning depends on interaction and management of both the diversity of species present in landscapes and the genetic variation within these species. Intraspecific diversity within species is a contributor of ecosystem functioning by increasing productivity and stability of plant populations (Carroll *et al.*, 2014). Exploration of intraspecific diversity and subsequent breeding has been done for a number of forest trees (FAO, 2014; Ruotsalainen, 2014), but much less systematically for agroforestry trees (FAO, 2014; Dawson *et al.*, 2014a) despite their huge potential (Foster *et al.*, 1995; Graudal *et al.*, 2014).

To optimize agroforestry systems and capture the production-enhancing niche approach described by Zuppinger-Dingley *et al.*, (2014), species suitability maps have been developed at

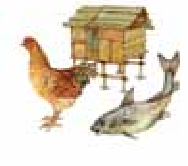
Figure 1. **Average species richness of different functional groups of trees at varying landscape scales (from 1 to 201 farms) in western Kenya**



Source: Kindt *et al.*, 2006a

ICRAF to visualize and analyse the distribution of different vegetation types and tree species, including locally available and/or suitable tree options for different ecological conditions (Kindt *et al.*, 2006b). However, more research is needed to systematically design agroforestry systems that incorporate functionally important tree species and genotypes with staple and annual crops in diverse planting regimes to create mixtures that generate higher levels of multiple desired functions and services. To date, much selection of agroforestry tree species has been done in isolation from their interactions with the key crops they are associated with on farmers' fields (and vice versa). This will have to change – for trees and their associated crops – if sustainable productivity increases for the entire system are to be realized.

Uncertainties about the direction of climate change and the likelihood of greater variability in future climates is another reason to promote assemblages of tree species on-farm that are adapted differently to climatic ranges (Dawson *et al.*, 2014a; 2014b; Koskela *et al.*, 2014; Alfaro *et al.*, 2014). A breeding seed orchard approach in agroforestry (Barnes, 1995; Isik, 2006) would conserve productive intraspecific diversity, allowing breeders to continue to select and develop improved and adapted germplasm to cope with the new demands and growing conditions associated with climate change. This is important to support the production of multiple agroforestry products including timber, fuel, fodder, fruits, nuts, pharmaceuticals and nutriceuticals as sources of antioxidants, anti-inflammatories, and other chemoprotective natural compounds that are important directly for food and nutritional security.



Fine-scale variation and the need for co-learning approaches

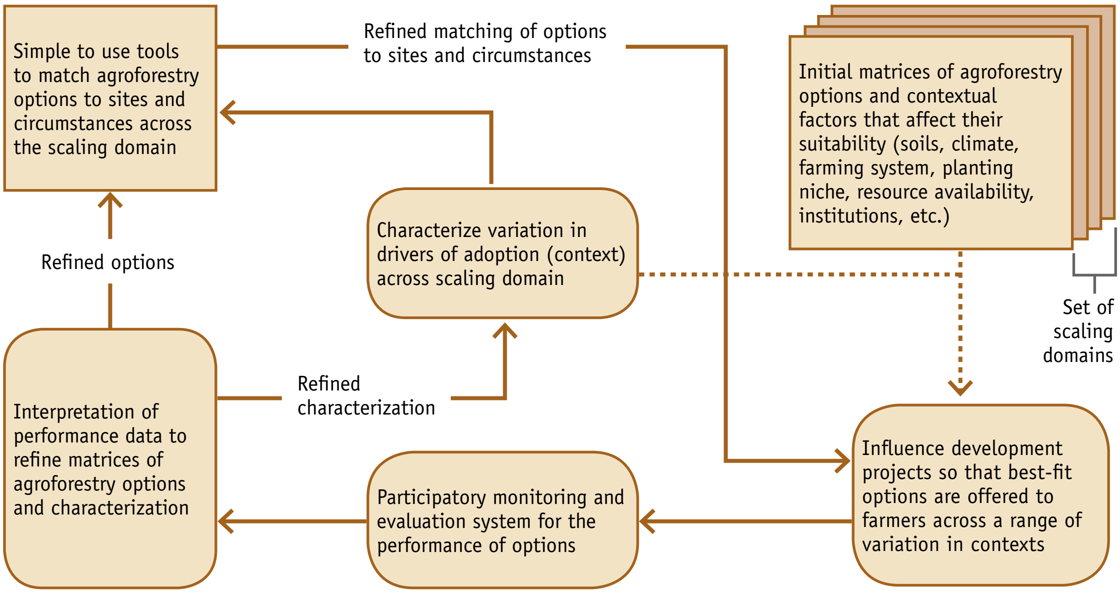
From an ecological standpoint, different tree species grow spontaneously in different places and segregation around these ecologies to promote tree-based systems may appear to be appealing. For instance, characterizations of the Sahelian 'parkland' systems (and to some extent agroforestry systems) have adopted a latitudinal climatic gradient approach. However, this simple approach at global and continental levels is insufficient to adequately represent the diversity of systems trajectories observed at the lower scales where socio-economic processes occur. Indeed, sampling derivatives such as agroecological zones may miss the socio-economic context that shapes these production systems. Therefore, sampling approaches should also consider the dominantly socio-economic nature of drivers of change. Both biophysical and socio-economic (through management options) factors may explain the large variation in the performance of tree-based practices (Sileshi *et al.*, 2010; Bayala *et al.*, 2012). By applying sampling designs that implicitly take scaling into consideration, linkages can be made between social and ecological systems allowing for the development of analytical frameworks that address the complexity of managing agro-ecosystems for increased resilience.

Taking into consideration multilevel variation will also increase the chance of acceptance by the various actors in the sector. Ultimately this will lead to co-learning opportunities that will generate transformative technologies and innovations to improve livelihood, food and nutrition security. This co-learning paradigm should be seen as an iterative process that offers communities best-fit technologies now (with quite large uncertainty regarding their impact), while capturing experience through 'research in development', in order to refine the matching of options to sites and people's circumstances, progressively reducing the uncertainty and risk around adoption decisions (Figure 2). This is particularly true with tree-based systems where pseudo-adoption may occur during the intervention period of a typical development project but not last beyond the intervention period. Sustained adoption requires broader changes in service delivery, market function and policies and institutions. Longer-term and larger-scale evaluations have revealed that policy issues were important for wide-scale adoption (Coe *et al.*, 2014).

Once these constraints are lifted, resource-conserving options like agroforestry can sustain agricultural intensification by regulating ecosystem functions such as (Barrios *et al.*, 2012; Bayala *et al.*, 2014; Vaast and Somarriba, 2014):

- ***Nutrient recycling:*** through a non-thermal biomass management (mulching or composting) to increase soil organic matter and physical properties like soil porosity and infiltration capacity as a result of increased and diversified soil fauna and its activity. This leads to an increased water holding capacity of soils.
- ***Microclimate modification:*** through reduced temperature and increased humidity that buffers the effects of water stress caused by droughts and high rainfall variability.
- ***Water-use efficiency:*** through the increased water holding capacity of soil because of its higher soil carbon content, helping to keep this resource in the root distribution soil depth layer and make it available to the crops, thus reducing water stress and countering the effects of drought.
- ***Species diversity:*** leading to diversified products including food, feed and medicine.
- ***Reduced agrochemical pollution:*** because of reduced use of chemicals as the existence of diverse niches created by trees are associated with reduced outbreaks or attacks of pests and diseases.

Figure 2. **The co-learning paradigm aims to reduce uncertainty and risk in the adoption of agricultural technologies**



Source: adapted from Coe *et al.*, 2014

Economic benefits of agroforestry

The economic benefits of agroforestry accrue to smallholders through increased on-farm profitability, as well as through higher and more diversified income flows from the sale of agroforestry products and services. Various authors have highlighted the benefits to farm profitability through agroforestry. In Malawi and Zambia, for example, planting specific shrubs in fallows for two years, cutting them back, then following them with two to three years of maize cultivation increased maize yields compared with planting continuous unfertilized maize (Franzel *et al.*, 2002). In the highlands of central Kenya, smallholders planted fodder shrubs to use as feed for their stall-fed dairy cows (Franzel *et al.*, 2003). The farm-grown fodder increased milk production and substituted for relatively expensive purchased dairy meal, thus increasing smallholders' income. Place *et al.*, (2007) identified a major increase in maize yields derived from soil fertility replenishment (SFR) practices in western Kenya, even if the overall household impact was limited because of the small percentage of land under SFR. In the case of multi-strata perennial systems, biodiversity richness (shade level and species richness) does not necessarily yield higher profits, as in the examples of cocoa (Bisseleua *et al.*, 2009) and coffee (Gordon *et al.*, 2009). In these cases, the benefits of diverse shade may relate more to ecological resilience and livelihood security, rather than higher economic returns.

The other pathway by which agroforestry contributes to strengthened livelihoods is through higher and more diversified income sources. Agroforestry provides raw and semi-processed materials to some of the world's most globally traded agricultural commodity markets, including

cocoa, coffee and oil palm. In Indonesia, for example, cocoa contributes about US$1.2 billion per annum in terms of export value and serves as a means of livelihood for 1.4 million smallholders (VECO, 2015). It is estimated that the global trade of the top 20 tropical tree crops exceeds US$80 billion per annum (FAO, 2010). In many cases, the markets for globally traded tree crop products are rapidly becoming more diversified, with third-party certification systems playing a key role in signalling social and environmental attributes to consumers. For example, palm oil compliant with voluntary sustainability standards accounted for 15 percent of global production in 2012, with Roundtable on Sustainable Palm Oil certification accounting for the vast majority of this (IIED, 2014). Additionally, the market for certified cocoa (Fairtrade, Rainforest Alliance and UTZ Certified) was estimated to be around 275 000 Mt in 2010, which represents a doubling of the market share captured in just two years (from 3 percent in 2009 to slightly more than 6 percent in 2010).

In recent years, extraordinary cases have arisen where once lesser-known agricultural products have rapidly emerged from obscurity to become globally known, high value crops demanded at home and abroad. Among these cases are *acai* in northeast Brazil, *quinoa* in the high Andes, *nomi* in Southeast Asia and sheanut in West Africa. In other cases, tree products remain lesser-known to the larger world, but enjoy a steady demand at the local and regional scale and thus provide important sources of income to rural households and local traders and processors. For example, lesser known products contribute to 15-37 percent of household incomes in Nigeria (De Grande *et al.*, 2006) and have an annual trade value of US$20 million in Cameroon (Ingram *et al.*, 2012). In many other cases, however, smallholders have struggled to find lucrative market outlets for their lesser-known fruits, timber and other products derived from agroforestry. This situation reflects an overall small and inconsistent supply from smallholders, limited consumer awareness or interest in the products, a debilitating political/legal environment and weak rural business organizations (such as small-scale processors and farmer associations). Where development agencies and governments have intervened to promote markets for lesser-known fruits, evidence suggests that they are likely to focus narrowly on domestication and other efforts needed to expand supply (Clement *et al.*, 2004), rather than on working with the private sector to innovate in terms of processing, packaging and marketing.

Regardless of the market context, achieving the economic benefits from agroforestry generally requires that smallholders have the capacity to invest their scarce productive assets in more intensive production systems. Yet, many smallholders in developing countries are often constrained by factors such as poor infrastructure, limited access to technical and finance services and weak institutional and policy environments. They also struggle to effectively participate in higher-value markets for agroforestry products because of a lack of critical livelihood assets (financial, human, natural, social and physical) and diversified livelihoods strategies, which may imply trade-offs between subsistence and market-oriented agriculture (Stoian *et al.*, 2012; Fan *et al.*, 2013). For example, a lack of livelihood assets limited the capacity of smallholder certified coffee farmers in Nicaragua to intensify their coffee production systems and increase their sales to certified coffee buyers, with roughly half of production being sold outside of the certified coffee value chain at significantly lower prices (Donovan and Poole, 2014). Households with relatively low asset endowments prior to engaging in certified-coffee markets were the least likely to achieve major advances in asset building. These households benefited from certified-coffee markets mainly through access to safety nets that helped reduce vulnerability to external shocks (i.e. through membership in a cooperative).

Against this background, critical questions emerge regarding how smallholders can participate in growing markets for agroforestry products and services and effectively benefit from their participation. Better addressing the complexity of market and value chain development will be critical to understanding the opportunities and constraints and identifying effective intervention strategies. Co-innovation approaches among value chain actors, providers of services and researchers have been promoted to address challenges related to production technologies, innovation in business models and the development of farmer associations and cooperatives, among other themes (Lundy and Gottret, 2007; Thiele *et al.*, 2011; Gyau *et al.*, 2014a). This recognizes that although technical innovations in production and processing of agroforestry products (e.g. post-harvest technologies and improved planting materials) are critical in enhancing efficiency and competitiveness, understanding the relevant institutional processes (e.g. collective commercialization, access to various services and inputs, intra-chain governance) are essential. These would explain how economic transactions in the value chain are coordinated and regulated in order to foster understanding of the distribution of benefits and surpluses along the value chain (van der Ven and Hargrave, 2004; Facheux *et al.*, 2012).

Land health is a key outcome

Renewed interest in increasing agricultural productivity to meet food security needs and increasing the resilience of agricultural systems in developing countries, especially in sub-Saharan Africa, makes understanding soil fertility constraints and trends ever more important (Sanchez *et al.*, 2009). Measurement and monitoring of soil quality and land health (including monitoring vegetation and water components) are fundamental to developing a sound knowledge of problems and solutions for sustainable crop production and land management, including agroforestry. Much of the current analysis on agricultural productivity is hampered by the lack of consistent, good quality data on soil health and how it is changing under past and current management. This is especially critical in the face of increased variability in weather conditions brought on by climate change.

ICRAF and partners have proposed a land health surveillance and response framework, which is modelled on scientific principles in public health surveillance, to increase rigour in land health measurement and management. The key objectives are to: (i) identify land health problems; (ii) establish quantitative objectives for land health promotion; (iii) provide information for the design and planning of land management intervention programmes and resource allocation priorities; (iv) determine the impact of specific interventions; and (v) identify research, service and training needs for different stakeholder groups (UNEP, 2012; Shepherd *et al.*, 2015).

Land health surveillance is being operationalized by combining accurate ground observations with satellite imagery to measure and monitor changes and improvements in landscape health, closely integrated with statistical methods to form a scientific basis for policy development, priority setting and management (UNEP, 2012). Soil spectroscopy is a key technology that

makes large area sampling and analysis of soil health feasible (Vågen *et al.*, 2006; Shepherd and Walsh, 2007; Vågen *et al.*, 2010; AfSIS, 2014) and has the potential to overcome the current impediments of high spatial variability of soil forming processes and high analytical costs, which are key challenges in monitoring soil health at a landscape scale (Conant *et al.*, 2011).

The approach is being applied at continental scale in sub-Saharan Africa through the Africa Soil Information Service (AfSIS, 2014), at regional (Vågen *et al.*, 2013) and national scales by the Ethiopia Soil Information System (EthioSIS, 2014) and at landscape scale (Waswa *et al.*, 2013), as well as being deployed by the Consultative Group for International Agricultural Research (CGIAR) in sustainable land management projects and sentinel landscapes. Soil monitoring using infrared spectroscopy is also being piloted in the Living Standards Measurement Study – Integrated Surveys on Agriculture (LSMS-ISA) effort of the World Bank in Ethiopia. Having samples of the soil in plots directly linked to the household panel survey of the LSMS-ISA provides an important opportunity for enhancing the understanding of trends in soil health and their impact on crop productivity among smallholders, as well as the coping mechanisms adopted by farmers faced with deteriorating soil conditions. For example, see the case study described below on the use of the land health surveillance approach in a cocoa production system in Côte d'Ivoire.

Further opportunities exist to integrate land health surveillance into impact evaluation of development initiatives at low cost. For example, soil sampling and infrared analysis can be integrated into study designs (Shepherd *et al.*, 2015) to accumulate evidence on the impact of interventions on soil health. This is especially important to accelerate reliable learning on impacts in agroforestry because of the long production cycles.

CASE STUDIES

Food trees for improved nutrition in smallholder agricultural systems

In 2010, about 104 million children under the age of five were underweight and 171 million were stunted worldwide (i.e. they show low height for their age because of chronic undernutrition), particularly in sub-Saharan Africa and Southern Asia (WHO, 2015). One of the reasons for high stunting rates is low fruit and vegetable consumption, leading to deficiencies in minerals and vitamins. However, many poor consumers cannot afford to buy sufficient amounts of fruits and vegetables as these commodities are not produced in high enough quantities or are only available seasonally, which leads to high retail prices. There is a need to find innovative ways to increase fruit and vegetable production and consumption to meet the health requirements of present and future populations, particularly in low-income countries (Siegel *et al.*, 2014).

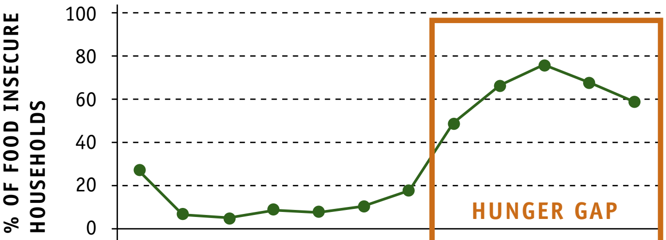
Tree-based agroforestry systems and forests provide a wide variety of nutrient-rich, traditional foods and contribute substantially to the food and nutrition security of local communities (Vinceti *et al.*, 2013). Edible tree crops, including fruits, leafy vegetables, nuts and seeds as well as starchy tree parts, complement and diversify staple-based diets as tree foods often contain high contents of micronutrients (minerals and vitamins), macronutrients (protein, fatty acids, carbohydrates) and beneficial phytochemicals (e.g. antioxidants) (Jamnadass *et al.*, 2013; Stadlmayr *et al.*, 2013; Vinceti *et al.*, 2013). Trees also have higher resilience during droughts and have different harvest times than annual crops. Thus, tree foods play an important role in overcoming hunger periods/seasons, especially when staple crops fail or before they are ready for harvest. Another benefit of tree foods is that they can provide year-round food for home consumption or income generation, if sets of species with different harvest times are available on farms or in natural habitats (Kehlenbeck *et al.*, 2013). Women are often highly involved in the production, processing and sale of food tree products, and benefit particularly with regard to nutrition, health and livelihood outcomes. ICRAF is developing and promoting location-specific ‘food tree portfolios’, which are combinations of exotic and indigenous food trees that can potentially provide year-round harvest, and can be integrated into existing farming systems to fill ‘hunger gap’ seasons and specific ‘nutrient gaps’. A study on fruit tree diversity on farms and their potential contribution to nutrition security performed by ICRAF and partners (Kehlenbeck *et al.*, unpublished data) is presented here.

In 2014, fruit tree diversity, production and consumption were studied in 300 randomly selected farms in Machakos County, Kenya, along an altitude gradient from 840 to 1 830 m above sea level. The research area has a semi-humid to transitional climate with about 700-1 000 mm of rainfall per year in two rainy seasons. The selected households were interviewed on basic socio-economic data, food insecurity periods, occurrence of fruit trees, yields, use of fruits and consumption habits. In addition, focus group discussions were performed with four groups of 10-11 farmers each to find out about the harvest times of different fruit species.

The mean farm size of the 300 surveyed farms was 1.4 ha and the average household size was five members. The respondents mentioned a total of 52 on-farm fruit tree species, including 26 indigenous and 26 exotic species. The most frequent fruit species were mango (*Mangifera indica*, occurring on 92 percent of the farms), pawpaw (*Carica papaya*, 65 percent) and avocado (*Persea americana*, 54 percent), all of exotic origin. Indigenous species occurred in less frequent numbers, on a few farms, mostly in the drier parts of the research area. The median fruit tree richness per farm was 6 species (range 1-15), including 1 indigenous species (range 0-8). While households were quite food secure during the months January to July, many reported to have problems feeding their family from August to December, with a peak in October when almost 80 percent of the respondents’ families are food insecure (Figure 3). According to the focus group discussion participants, the most import species provided a potential harvest of fresh fruits all year-round, including during the ‘hunger gap’ period (Figure 3). The fruit species mentioned in the discussions were then assessed for their vitamin C and beta carotene (a precursor of vitamin A, often deficient in the research area) contents and sorted again for their harvest periods. Seven fruits had an intermediate to very high beta carotene content, of which three species (pawpaw, water berry and chocolate berry) could potentially cover year-round supply (Figure 3). Vitamin C content was moderate to very high in nine species, of which three (pawpaw, orange/lemon and desert date) could cover year-round supply in the area. Cultivating 8-13 fruit species (including the six above mentioned species, but also guava, mango, passion fruit, white sapote, mulberry, custard apple and loquat, depending on climatic conditions) would suffice for ensuring the supply of farmers’ families in the area with fresh, nutrient-rich fruits during the whole year. Rare but important indigenous species such as desert date and chocolate berry need to be promoted

for cultivation, with provision of planting material to the communities. Indigenous fruits should be supported, in particular because of their high resilience against biotic and abiotic stresses. However, the processing and marketing of these fruits still needs to be improved and female farmers should be better integrated in the value chains for both exotic and indigenous fruits, to promote gender-sensitive income security and empowerment outcomes.

Figure 3. **Food security levels of 300 surveyed households in Machakos County, Kenya, and harvest periods of the most important exotic and indigenous fruit species according to respondents**



ENGLISH NAME	SPECIES NAME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	VIT C	VIT A
Pawpaw	**Carica papaya**	🟩	🟩	🟩	🟩	🟩	🟩				🟩	🟩	🟩	+	+++
Mango	**Mangifera indica**	🟩	🟩	🟩									🟩	+	+++
Banana	Musa x paradisiaca	🟨	🟨			🟨					🟨				
Loquat	**Eriobotrya japonica**		🟩												+++
Mulberry	**Morus alba**		🟩	🟩										(+)	
Tamarind	*Tamarindus indica*		🟨	🟨											
Waterberry	**Syzygium spp.**			🟩					🟩	🟩					+++
Custard apple	**Annona reticulata**			🟩	🟩									(+)	
Guava	**Psidium guajava**			🟩	🟩	🟩	🟩							+++	+
Pomegranate	Punica granatum				🟨										
White sapote	**Casimiroa edulis**				🟩					🟩				(+)	
Wild medlar	*Vangueria madagascariensis*				🟨	🟨	🟨								
Lemon	**Citrus limon**					🟩	🟩	🟩						+	
Orange	**Citrus sinensis**					🟩	🟩	🟩						+	
Chocolate berry	***Vitex payos***					🟩	🟩	🟩							+++
Avocado	Persea americana					🟨	🟨	🟨	🟨	🟨	🟨				
Passionfruit	**Passiflora edulis**							🟩				🟩			+
Jacket plum	*Pappea capensis*								🟨	🟨					
Desert date	***Balanites aegyptiaca***								🟩	🟩				(+)	
Bush plum	*Carissa edulis*												🟨		
NUMBER OF VITAMIN-RICH SPECIES AVAILABLE		2	4	6	4	4	5	4	2	3	1	2	2		

Indigenous fruit species are in italics. The ratings of vitamin C and beta carotene (vitamin A) contents are given as: +++ = very high; + = intermediate; and (+) = moderate. The harvest periods of fruits rich in vitamin C and A are indicated by dark green boxes and their species names are in bold.

Revitalising cocoa systems in Côte d'Ivoire

Côte d'Ivoire is the world's leading cocoa producer accounting for more than a third of the global supply. Cocoa plays a key role in the economy of the country contributing to 15 percent of its GDP, 40 percent of its exports, and supporting more than six million people (Conseil Café Cacao, 2014). In Côte d'Ivoire, cocoa was traditionally grown in agroforestry systems with permanent shade management resulting from thinning the original moist equatorial forest canopy. However, there has been an increasing move towards shade removal and monoculture practices with full sun being promoted to maximize short-term cocoa yields (Freud *et al.,* 2000). This practice has caused a loss of biodiversity and ecosystem services, pest and disease outbreaks and a reduction in long-term productivity and incomes (Assiri, 2006; Koko *et al.,* 2006; Tscharntke *et al.*, 2011). These events have left the cocoa sector in dire need for alternative, sustainable production systems (Ruf, 1991; Vaast and Somarriba, 2014).

Research in cocoa agroforestry systems has shown that integrating trees can increase and sustain cocoa productivity through eco-physiological and environmental interactions with knock-on economic impacts (Clough *et al.,* 2009). Trees, especially shade trees, enhance the efficiency of cocoa farms through various factors including soil fertility improvement (Isaac *et al.,* 2007), microclimatic amelioration (Tscharntke *et al.,* 2011), reduction in pests and diseases (Bos *et al.*, 2007) and increasing resilience to climate change (Duguma *et al.,* 2001; Franzen and Mulder, 2007). On the other hand, consumers worldwide are increasingly demanding eco-certified cocoa through which farmers receive a premium for cultivating cocoa under shade trees (Franzen and Mulder, 2007). In Côte d'Ivoire, cocoa swollen-shoot virus remains a major constraint to cocoa production and in the absence of resistant cultivars the use of barrier trees is one of the most effective approaches to reduce the spread of the disease. In addition, cocoa diversification options, including drawing on the design principles and practices of agroforestry systems, are likely to create positive synergies with cocoa intensification using various combinations of other plant species, including fruit, medicinal and timber trees. This can support rural communities and address their nutrition and food security challenges by diversifying incomes (Gyau *et al.*, 2014b; 2015), providing benefits from ecosystem services and consequently reducing the risks associated with relying solely on cocoa revenues (Cerda *et al.*, 2014).

To develop sustainable management options for cocoa, ICRAF has partnered with MARS Inc. in the Vision for Change project, to implement innovative technologies for cocoa rehabilitation with national stakeholders and through different strategies in southwest Côte d'Ivoire. In this public-private partnership initiative, *in situ* grafting on older, less productive trees was introduced as a novel technique, allowing for more rapid and economically feasible farm rehabilitation of unproductive cocoa orchards. Budwood gardens of improved cocoa clones selected by the national agricultural research institute have been developed and optimized for scaling up. In addition, a somatic embryogenesis lab was established to diversify sources of selected cocoa clones and to propagate disease free planting materials on a larger scale. A delivery mechanism involving private rural resource centres has been established to provide inputs, quality planting materials and other services to cocoa farmers. The project conducted baseline studies, which showed that 95 percent of cocoa farmers in the region wish to have companion trees on their

farms (Smith *et al.,* 2014). Currently, the cocoa land health surveillance (see the discussion above on land health as a key outcome) implemented by the project reported that tree density in cocoa farms varies from 1 to 75 trees ha^{-1}. Therefore, there is a compelling case to re-introduce trees in the cocoa farms in the project area and beyond to support a resilient cocoa production system in Côte d'Ivoire.

Agroforestry and shade trees as adaptation mechanisms in coffee systems

Worldwide, there is increasing evidence that coffee production systems are becoming more vulnerable to climate change, which is threatening the livelihoods of rural coffee producing communities. Climate change is likely to result in a shift of suitable areas for Arabica coffee production towards higher altitudes and ultimately to cause conflicts over land use by exerting further pressure from land-use change on existing upland forests (Läderach *et al.*, 2011). This is the reason why recently most collaborative research by ICRAF with national and international partners (CIAT, CIRAD, IITA, ICIPE) is undertaken on farms on high altitude and rainfall 'coffee transects' to study the drivers of change and farmers' adaptation strategies.

Arabica coffee production (accounting for 65 percent of the world's coffee production) and its quality are particularly sensitive to environmental variables, specifically rainfall patterns, extended drought periods and extreme weather events, such as the abnormally high temperatures that have become more common in many coffee producing areas throughout the world (Cannavo *et al.*, 2011). There is a general agreement that shade trees greatly reduce excessive solar irradiance and buffer large diurnal variations in air temperature and humidity that are detrimental to coffee physiology and yield (Siles *et al.*, 2010; Lin, 2011). Shade trees mimic the effects of high altitude as their presence can decrease the temperature experienced by the coffee grown underneath by up to 2-4 °C, delaying the maturation of the coffee berry pulp and hence allowing for a prolonged and better coffee bean filling, better bean biochemical composition and ultimately better cup quality (Vaast *et al.*, 2006). Shade trees also reduce flowering intensity, and hence fruit load of coffee plants, thereby reducing the alternate bearing pattern observed in monoculture, while increasing the productive life span of coffee bushes in agroforestry systems.

Pests and diseases have a major impact on Arabica coffee productivity: leaf rust, coffee berry disease and coffee berry borer can reduce production by up to 70 percent. The effects of shade trees with respect to coffee pests and diseases are rather complex and even contradictory (Mouen Bedimo *et al.*, 2012). While some pests and diseases, particularly fungal diseases such as coffee leaf rust, can be enhanced by the cooler and more humid microclimate provided by shade (especially high shade levels), impacts of others have been reduced by shade. Tree species integrated into coffee systems can either host and favour the negative impacts of pests, or decrease their incidence by favouring natural enemies. Consequently, it is often difficult to define the right shade level and composition of shade tree species in order to minimize damages from pests and diseases, while sustainably improving coffee productivity. Further, pests and diseases threatening coffee production under current climate conditions are likely to be aggravated by climate change, particularly through increased temperatures and enhanced variability in rainfall regimes (Jamarillo *et al*., 2011).

The integration of trees and other species in coffee systems presents an inexpensive option to buffer extreme climate variability for smallholders that predominate (80 percent) in coffee production regions throughout the world. Intercropping of various trees in coffee systems, such as timber, 'service trees' (e.g. fertilizer trees), fruit trees, banana and other food crops has been reported to buffer vulnerability to economic and climate shocks as well as to pests and disease outbreaks (van Asten *et al*., 2011). Trees in coffee farms and landscapes also provide a wide range of environmental services such as carbon sequestration, reduced GHG emissions, improved water yields and conservation of biodiversity (Rahn *et al*., 2014).

Agroforestry for 'greener' rubber-dominant landscapes in the Mekong

Hevea brasiliensis, the rubber tree, is the major source of natural rubber for the global annual production of more than one billion car, truck and aircraft tyres. This rapidly expanding industry is driving land-conversion of forests to rubber plantations in Southeast Asia where 97 percent of the world's natural rubber is produced. Rubber was historically cultivated in the equatorial zone between 10 degrees latitude north and south of the equator. However, China's success in developing hardy rubber clones led to an expansion of rubber in non-traditional planting areas in many parts of continental Southeast Asia. Rubber production in continental Southeast Asia has increased by almost 1 500 percent from just over 300 000 tonnes in 1961 to over 5 million tonnes in 2011. While the original expansion was driven by state agencies, the sector is now dominated by smallholders in China, Vietnam and Thailand and by large-scale economic concessions in Cambodia, Laos and Myanmar. Despite increases in income and wealth from rubber cultivation in poor areas, a number of challenges remain, including price fluctuations, narrowing of income sources, impacts on food security, increased dependency of smallholders on global markets of which they often have little knowledge of, and 'land grabbing' practices. Conversion to rubber plantations also has environmental implications such as reductions in water reserves, carbon stocks, soil productivity and biodiversity. The benefits of rubber cultivation and the costs of ecosystem service degradation are unevenly distributed, and rubber expansion has led to increased poverty and vulnerability and caused cultural disruptions in some areas. Considering the impacts on the environment, rising production costs and impacts on the poor, the monoculture rubber cultivation currently practised in the Mekong region appears to be unsustainable.

ICRAF and partners are exploring 'land sparing' approaches through establishing biological corridors and landscape restoration and 'land sharing' through agroforestry practices and developing the understory in monoculture rubber plantations. ICRAF is also investigating the potential consequences of different trajectories of rubber demand and changes in management regimes on rubber production, incomes, employment, biodiversity, GHGs and indirect land-use change in Xishuangbanna in the Yunnan province of southwest China. The intention is to apply evidence-based research results to inform discussions among key stakeholders about the most appropriate incentives and technologies for 'green rubber' and for landscape-level forest

restoration and conservation. In China the political consensus and pathways for implementing green rubber policy already exist and it is mostly Chinese markets that are driving rubber expansion throughout the region. Under pressure from both national and regional governments to address problems caused by intensive monoculture rubber cultivation, the Xishuangbanna prefectural government and the rubber industry established the Leadership Group for Environmentally Friendly Rubber (LGEFR) in 2009. LGEFR links government, research and industry stakeholders and thus provides a forum for discussing and implementing policy instruments for restoring ecosystem services, providing green growth and alleviating poverty.

However, there are important gaps in the scientific understanding of how land-use changes translate into changes in ecosystem functions and, in turn, how these changes affect the provision of ecosystem services and economic well-being. Such knowledge is essential to find the balance between services and rubber production, to ensure that benefits reach the poorest and most vulnerable groups and to design efficient governance and incentive mechanisms. An understanding of which environments rubber has spread to and whether this rubber cultivation is sustainable is vital for effective land-use planning and policy interventions. ICRAF has conducted both local and region-wide quantitative assessments of the environmental space occupied by rubber plantations (Xu *et al.*, 2014; Ahrends *et al.*, 2014) that have: (i) quantified the environmental space in which rubber occurs naturally; (ii) established the extent and trends of plantation spread into marginal environments; (iii) assessed the types of land that are being converted; (iv) used this information to predict future patterns of land-use conversion; and (v) evaluated the biodiversity and socio-economic risks of land-conversion to rubber plantations. The results showed an underestimation of the area of rubber plantation in government census data, with most new rubber plantations expanding into marginal low-productivity areas.

The project developed a spatially explicit model that simulated ecosystem services and economic returns between rubber agroforestry and monoculture systems at landscape scale in Xishuangbanna. The results showed that compared with monoculture systems, rubber agroforestry can be economically competitive when higher market value crops are intercropped, even when natural rubber dropped to its historical lowest price since 2007. Rubber agroforestry also enhances biodiversity, ecosystem services and provides more secure incomes for local smallholders from diverse crop markets. However, to keep the same amount of rubber productivity, about 25 percent more land is needed to practise this type of agroforestry. With the over-supply of natural rubber in recent years, we suggest that rubber monocultures should be replaced by rubber agroforestry systems without expanding the land area in cultivation, which would also benefit biodiversity conservation and land-use sustainability in the region provided that approaches support the development of complex, ‘nature-like’ rubber ‘analogue forests’.

CONCLUSIONS

Agroforestry offers a wide range of potential benefits. Based on a solid and growing foundation of research-based evidence, it is clear that agroforestry in its many manifestations is a scalable option for improving incomes, food and nutrition security with co-benefits for the sustainable delivery of ecosystem services. Investments in agroforestry from the public and (increasingly) from the private sector are seen as delivering viable long-term returns for the economic and ecological sustainability of agricultural systems. This is especially true where they build on stakeholder engagement and participation within a co-learning paradigm. Trees play important roles in stabilizing local livelihoods, particularly for poor farmers, by supporting a low-input resilient agricultural system. On the other hand, trees and agroforestry systems support some of the most valuable globally traded commodities. Agroforestry dominated landscapes offer better delivery of ecosystem services, including stabilizing hydrological cycles and contributing to land health. The contribution of trees, agroforestry and the agroecological approach offers opportunities and benefits beyond those mentioned in this chapter. The integration of local or traditional (ecological) knowledge further strengthens these systems. Such systems are proving to be more productive and resilient to climate variability and other hazards, thus reducing production-associated risks for smallholders, including those related to climate change. Policy support and new investments will be required in order to support what is a promising trend.

Much remains to be done: we are challenged to develop metrics to monitor increases in resilience, adaptive capacity, gender equity, food and nutrition security, and institutional/governance strength as well as elaborating strategies that support governance and market reforms, value-chain development, and the technical capacity to provide a vision beyond subsistence farming with trees. There remains a shortage of quality planting materials and distribution channels, and dissemination of agroforestry technologies and knowledge are currently inadequate for these relatively knowledge-intensive systems. Clearly, better capacity strengthening approaches and services – especially rural advisory services – are required. Nevertheless, there is clear evidence at farm and landscape levels that agroforestry embodies an approach that is realizing the potential of agroecology at scale.

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AGROECOLOGY: INTEGRATION WITH LIVESTOCK

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Abstract

Livestock systems are a large global asset contributing to food security and poverty alleviation, but livestock supply chains have major environmental impacts at global scale. The scientific literature on agroecology has not yet integrated livestock systems; only 5 percent of the indexed studies concerning agroecology deal with livestock. Following Dumont *et al.* (2013), we review five principles for integrating livestock systems within the agroecology debate: (i) adopting management practices that aim to improve animal health; (ii) decreasing the inputs needed for production; (iii) reducing emissions; (iv) enhancing diversity within animal production systems to strengthen their resilience; and (v) preserving biodiversity by adapting management practices. Through a number of case studies from different world regions, we show that the key features underpinning agroecological livestock systems are an increased use of biodiversity, the integration of crops and livestock within a diversified landscape and a recoupling of the major element cycles. For intensive landless systems, we discuss how recycling principles derived from industrial ecology could complement those from agroecology. We conclude that performance criteria far beyond annual productivity are required when assessing agroecological livestock systems.

INTRODUCTION

Livestock systems occupy approximately 35 percent of the global ice-free land area: 3.4 billion ha of grasslands and rangelands, and 350 million ha of feed crops (Foley *et al.*, 2011). These systems are a significant global asset with a value of at least US$1.4 trillion, and are also important for livelihoods. More than 800 million poor people depend on livestock farming for their survival and the sector contributes to the employment of at least 20 percent of the world's population (Herrero *et al.*, 2013). Ruminants are able to produce food on non-arable lands (because of slope, elevation and climate) and to transform resources not used for human consumption, such as grass and fodder, into edible products. However, using highly productive croplands to produce animal feed, even efficiently, reduces the potential world supply of food calories (Foley *et al.*, 2011). Keeping livestock acts as insurance and is an essential risk reduction strategy for vulnerable communities, while also providing nutrients and traction for growing crops in smallholder systems. Meat, milk and eggs provide 18 percent of calories for human consumption and close to 35 percent of essential proteins and micronutrients (e.g. vitamins, minerals, unsaturated fatty acids) (Herrero *et al.*, 2013). However, there are large differences in meat and milk consumption between rich and poor countries.

Extensive grazing systems occupy the largest fraction of the land used by livestock. Such systems help maintain ecosystem services, biodiversity and carbon stocks, but may also

contribute to land degradation, especially in dry areas. The production from grazing systems in the developing world is modest, mostly because of low productivity, low feed availability and poor quality of feed resources in predominantly arid regions (Herrero *et al.*, 2013).

Livestock plays an important role in the smallholder farming systems of sub-Saharan Africa (Vall *et al.*, 2006). Rangeland-based systems cover a large area of the continent, but mixed crop-livestock systems support the majority of rural and urban livelihoods and contribute significantly to food security. Farmers often sell livestock to buy food when crop harvests fail. In many cases livestock are kept primarily to support crop production, with milk and meat considered as useful by-products of livestock keeping. Crop residues constitute an important part of the livestock diet in mixed systems, with the remainder provided by rangelands, which are often communally managed. In industrialized countries and increasingly in developing countries, part of the demand for meat and milk products is now met through industrial systems that rely on feed markets rather than the local land base for feed inputs (Herrero *et al.*, 2013).

Drivers such as population increase, changes in diets, urbanization, changing policy and institutional contexts, and expanding markets exert a strong influence on livestock systems. While meat consumption has started to decline in some western European countries, the demand for animal products is projected to rise further in developing countries. The FAO projects a large increase in demand for both dairy products and meat products (Alexandratos and Bruinsma, 2012). Even though continuing improvements in feeding efficiency within each production system are assumed, the shift in production from developed to developing countries implies that overall animal feeding efficiencies are likely to progress at a slower pace in the future than in the past (Gerber *et al.*, 2013).

Global greenhouse gas (GHG) emissions caused by whole livestock supply chains currently account for nearly 15 percent of the total anthropogenic GHG emissions (Gerber *et al.*, 2013). Livestock production systems emit 37 percent of anthropogenic methane (CH_4), mostly from enteric fermentation by ruminants. Moreover, livestock systems cause 65 percent of anthropogenic nitrous oxide emissions, the great majority from manure, and 9 percent of global anthropogenic carbon dioxide (CO_2) emissions. The largest share (7 percent) of these CO_2 emissions are derived from land-use changes – especially deforestation caused by the expansion of pastures and arable land used for feed crops (Gerber *et al.*, 2013). Nevertheless, the global soil organic carbon sequestration potential is estimated to be 0.01-0.3 Gt C year^{-1} on 3.7 billion ha of permanent pasture (Lal, 2004). Therefore, soil carbon sequestration by the world's permanent pastures could potentially offset up to 4 percent of global GHG emissions. This could be achieved through improved grazing land management and the restoration of degraded lands. Reducing excessive nitrogen fertilization and the substitution of mineral nitrogen fertilizers by biological nitrogen fixation (BNF), as well as avoiding fire in savannahs, improving animal nutrition to reduce CH_4 from enteric fermentation and improved manure management are other factors that could also play a significant role (Lal, 2004; Gerber *et al.*, 2013).

By 2050, the global consumption of animal products could increase by up to 70 percent, leading to a further rise in livestock GHG emissions (Herrero *et al.*, 2013). Livestock-based farming systems are affected by climate change through impacts on feed quantity and quality, and through the direct effects of heat and water availability on animal production, fertility and survival. Whereas animals are generally less vulnerable to drought than crops, extreme droughts can wipe out regional herds (Morton, 2007).

As the negative externalities associated with current animal production systems are increasingly questioned, it is timely to ask what agroecology could suggest for the redesign of livestock production systems. There are an increasing (but still relatively small) number of scientific studies combining "livestock" and "agroecology" as keywords (650 indexed studies since the 1970s across all databases). Most of these studies are indexed in three research areas: agriculture, environment/ecology and veterinary sciences. In comparison, there are five times more indexed studies about livestock and environmental sustainability and this number is further multiplied by nine when counting all studies addressing environmental issues for livestock, with a substantial subset (ca. 10 000) of these studies addressing ecology and biodiversity. Therefore, despite a wealth of studies in ecology and environmental disciplines dealing with livestock, few have adopted the agroecology perspective. Likewise, only 5 percent of the indexed studies concerning agroecology include the keyword "livestock". Hence, integration with livestock has not been achieved by the scientific literature on agroecology, nor has agroecology been a mainstream paradigm in environmental studies concerning livestock.

Other approaches in the literature deemed that the optimization of livestock systems could be based on eco-efficiency (e.g. Wilkins, 2008); that is the maximization of animal products per unit of inputs or natural resources. This approach emerged through studies that aimed to reduce the consumption of energy and raw materials in the industry. However, animal production is nested into ecological and social processes, with ecosystem goods and services supporting the technological activities of husbandry. Moreover, because of their organic nature, animal products and their associated by-products are ultimately recycled in multiple loops within biogeochemical cycles such as the carbon and nitrogen cycles. Therefore, the simple paradigm of eco-efficiency (i.e. 'producing more with less') may be too linear as a concept and not sufficient to optimize ecologically grounded livestock production systems.

In his influential book on agroecology and food systems, Gliessman (2007) stated that:

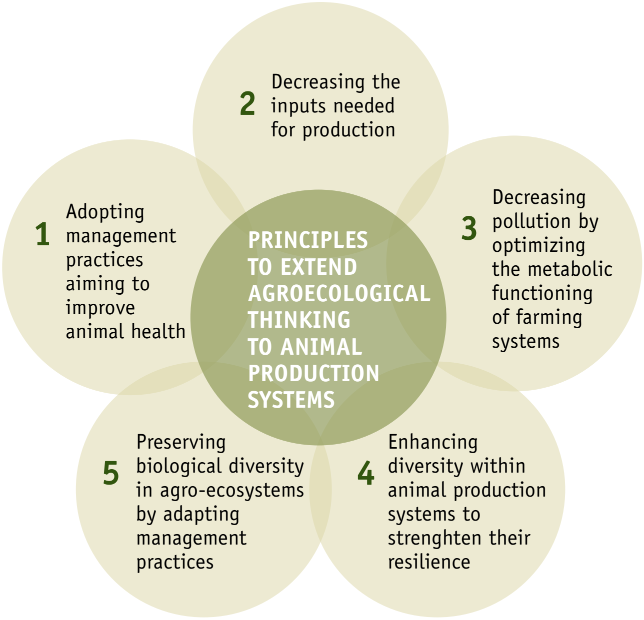
> *"the problems lie not so much with the animals themselves or their use as food as they do with the ways the animals are incorporated into today's agroecosystems and food systems. Animals can play many beneficial roles in agroecosystems, and therefore make strong contributions to sustainability."*

Numerous studies in grazing ecology, animal behaviour and farming systems have addressed the integration of farm animals in agriculturally managed ecosystems, but not through the lens of agroecology.

It is only recently that a review has addressed for the first time the prospects for agroecology in the animal production sector (Dumont *et al.*, 2013). This review covers a large diversity of livestock systems (i.e. grazing, mixed and industrial systems) and shows how agroecological principles can be applied to most, but possibly not all, systems. For intensive systems where animals are kept in farm buildings, recycling principles derived from industrial ecology could complement those from agroecology.

Dumont *et al.* (2013) have proposed five principles to be optimized in animal production systems: (i) adopting management practices that aim to improve animal health; (ii) decreasing the inputs needed for production; (iii) decreasing pollution by optimizing the biogeochemical functioning of farming systems; (iv) enhancing diversity within animal production systems to strengthen their resilience; and (v) preserving biodiversity in agro-ecosystems by adapting management practices (Figure 1). Each of these principles (or objectives) is based on ecological processes. Therefore, animal husbandry is viewed through a paradigm which is derived from ecology. In the following sections we review each of these five principles and discuss how they can be applied to animal production systems along a large intensification gradient.

Figure 1. **Five ecological principles for the redesign of animal production systems**



Source: Dumont *et al.*, 2013

INTEGRATED ANIMAL HEALTH MANAGEMENT

Applying agroecology to the question of animal health implies focusing on the causes of animal diseases in order to reduce their occurrence. Major attention will therefore be given to choosing animals adapted to their environment and using a set of management practices that favour animal adaptations and strengthen their immune systems. Animals express morphological (small body size, little hair or feathers, etc.), physiological (urea recycling, compensatory growth, etc.) or behavioural (night feeding, selection for less fibrous diets, etc.) adaptations to hot or other types of harsh environments. Local species or breeds that have been selected in tropical environments are more resistant to trypanosomes, gastrointestinal parasites and ticks.

Adapting management practices can also strengthen animal immune systems and reduce sensitivity to pathogens. This is crucial for pigs, poultry and rabbits. For instance, mixing animals has been shown to suppress, as a result of increased stress, the immune response to a viral vaccine in pigs (de Groot *et al.*, 2001), and should thus be avoided as much as possible. In poultry, susceptibility to dietary stress is genetic strain dependent, which further emphasizes the importance of choosing genotypes adapted to particular environments and production objectives. In pigs, stringent hygienic conditions altered the development of digestive microflora and stimulated inflammatory response genes (Mulder *et al.*, 2009). Removing newly borne animals from their mothers very early can weaken the development of immunity. Conversely, experiments have shown that adoption of rabbits at one-day of age by reproductive females permits the early implantation of a functional and diverse microbiota, which increases their resistance to pathogens (Gidenne *et al.*, 2010). For all these species, managing the size and genetic structure of animal groups, and the way they are housed (e.g. systems allowing sick animals to be isolated from their group), coupled with tools for the early detection of diseases will limit the need to use chemical drugs (Dumont *et al.*, 2014).

In grassland-based systems with rotational grazing, mixed farming of several species on the same farm limits the contact that each species has with its specific pathogens by clearing pastures of parasites using a non-susceptible species. An integrated health management practice in organic sheep farming systems uses a preventive anthelminthic treatment with tannin-rich plants before ewes are turned out to pasture. This system benefits from rotational grazing, as nematode larvae numbers decline in temporarily ungrazed plots. Lambs are grazed on newly-sown pastures or on highly nutritive areas of regrowth in cut meadows in order reduce the risk of nematode infestation. When no other measures are available, the targeted treatment of highly infected sheep using chemical drugs is used, based on individual indicators such as anaemia and diarrhoea (Cabaret, 2007).

Some legume species offer opportunities for improving animal health using less medication through the presence of bioactive secondary metabolites (Lüscher *et al.*, 2014). In addition to a direct antiparasitic effect, tannin-rich plants might also have some indirect effects by increasing host resistance. The observation that sick ruminants are able to consume substances that are not part of their normal diet, containing active ingredients capable of improving their health, supports the hypothesis that animals can self-medicate. Lambs infected with parasites also slightly increased their intake of a food containing tannins while experiencing a parasite burden (Villalba *et al.*, 2010). Therefore, the self-selection of plant secondary metabolites provides a potential source of alternatives to chemical drugs in pastoral systems.

In Kenya, the additional forage resources of the push-pull system, using native grasses and legumes, have been shown to contribute to the sustainability of livestock systems by improving animal health (Hassanali *et al.*, 2008). In Madagascar, essential oils are used as alternatives to antibiotics and may also repel biting insects attacking livestock (e.g. geranium oil against *Stomoxys calcitrans* and *Jatropha* spp. extracts as anthelmintic). This may help prevent the harmful effects on soil macrofauna from the use of veterinary products (Ratnadass *et al.*, 2013).

Aquaculture is quickly growing as an animal production sector. While the sector is still dominated by shellfish and herbivorous/omnivorous pond fish, either entirely or partly utilizing natural productivity, rapid growth in the production of carnivorous species such as salmon, shrimp and catfish has been driven by globalizing trade and favourable economic incentives for large-scale intensive farming. Most aquaculture systems rely on environmental goods and services that are provided freely or at a low cost (Bostock *et al.*, 2010). In aquaculture, controlling water quality is pivotal for health management. In intensive systems, an alternative to antibiotics is the use of probiotics and prebiotics for modulating gut microflora, delivered through the feed or directly into the water (Balcázar *et al.*, 2006). Probiotics and prebiotics can improve fish health, resistance to diseases, growth performance and body composition. For instance, feeding turbot larvae (*Scophthalmus maximus*) with rotifers enriched in lactic acid bacteria provided protection against a pathogenic *Vibrio* sp., and increased mean weight and survival rate compared with control turbot larvae (Gatesoupe, 1994).

REDUCED USE OF EXTERNAL INPUTS FOR FEED PRODUCTION

A high proportion of global arable land is devoted to animal feed production (including grains, oilseeds, pulses and fodder), which reached 208 million tonnes of proteins per year in 2005, that is 38 percent of global arable protein production[1]. As a comparison, grasslands contributed an estimated 300 million tonnes of proteins per year towards the nutrition of ruminants in 2005 (Soussana *et al.*, 2013). Crop feed production requires a variety of inputs including chemical fertilizers, pesticides and, in some regions, large quantities of water for irrigation. Additionally, livestock has large direct and indirect impacts on land use, primarily through the expansion of pastures and arable crops into tropical forested areas.

Thus, a major challenge is to reduce the inputs required for production and increase the efficiency of animal production systems to minimize direct and indirect environmental impacts. This can be done by increasing the feed conversion efficiency of livestock and by using feed sources (e.g. crop residues, agricultural by-products, backyard wastes, grasslands, rangelands, browsing) that do not compete with the human food supply, thereby increasing food security and reducing environmental damages.

Improving the efficiency of nutrient utilization by animals can help reduce the import of nutrients from outside the farm and decrease emissions. Research has initially focused on pigs and poultry, as these species compete directly with human food supply. The low digestibility of phosphorus in pig feeds was partly alleviated by a diet supplementation with natural microbial phytase, an enzyme solubilizing immobilized form of phosphorus (Dourmad *et al.*, 2009). Nitrogen and phosphorus excretion and GHG emissions per animal can be manipulated through diets (e.g. for mitigating CH_4 emission in ruminants) or through appropriate feeding practices

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[1] Calculated from FAOSTAT in 2012 (see: http://faostat3.fao.org/home/E).

(e.g. phase feeding for reducing nitrogen and phosphorus excretion in pigs) (Dourmad *et al.*, 2009; Martin *et al.*, 2010).

The benefits of improving the efficiency of feed utilization can be extended by applying appropriate feeding practices. For example, in laying hens, sequential feeding of wheat grain and protein–mineral concentrate can improve feed conversion, and facilitate the use of local feedstuffs introduced as whole grains, thus reducing feeding costs (Faruk *et al.*, 2010). In organic egg production systems, stimulating the hens to exercise natural foraging behaviour reduced the import of nutrients into the system. High-producing layers were able to forage on crops consisting of grass/clover, pea/vetch/oats, lupine and quinoa without negative effects on health or performance (egg weight and body weight) (Horsted and Hermansen, 2007). In another example, geese that grazed on unfertilized grass growing between tree rows in a walnut plantation increased walnut production by 26 percent and tree growth by 6 percent (Dubois *et al.*, 2008). There was no microbial contamination (e.g. *Escherichia coli*) of the fruits if geese were removed at least two months before harvesting.

Feeding systems based on natural resources and agricultural by-products enable resources to be spared for human food supply. Permanent pastures and rangelands are cheap natural resources. On the other hand, the major limitations of rangeland-based feeding systems are the large areas required to compensate for low forage productivity and quality, which increases farm work (e.g. construction of fences, shepherding), and the seasonal and year-to-year variability in the amount and quality of forage resources (Jouven *et al.*, 2010). This reduces the feeding efficiency within grazed systems, leading to high enteric CH_4 emissions per unit of meat or milk produced (Gerber *et al.*, 2013). Nevertheless, extensive grazing systems have low GHG emissions per unit of area, and emissions from livestock are partly compensated in such systems by soil carbon sequestration (Lal, 2004).

There are many examples of cheap, alternative feed resources (e.g. millet, wheat, oats, barley straws) that are used as supplemental feed for ruminants, horses and donkeys in many agro-ecosystems around the world. Food crop by-products, such as waste vegetables and fruit residues after juice extraction, can be used to supplement grazing animals or forages (Gliessman, 2007). Various tropical forages make a viable alternative to soybean meal in the diets of lambs (Archimède *et al.*, 2010) or growing pigs (Kambashi *et al.*, 2014). Close to 1 400 worldwide livestock feed sources are indexed in the open access information system *Feedipedia* jointly developed by INRA, CIRAD, AFZ (Association Française de Zootechnie[2]) and FAO.[3] This information system shows that many unconventional sources can be integrated into feeding systems, including multiple by-products from plant production and plant food processing. Because agroecology usually enhances the diversity of crop species produced and processed within the farm, it opens many options for the design of livestock feeding systems using less energy, fertilizer and irrigation water inputs. Draft animal power for land preparation and transport further reduces energy use in extensive tropical farming systems.

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[2] French Association for Animal Production

[3] Available at: www.feedipedia.org

Because of competing demands for water for drinking, hygiene and energy, it is urgent to improve water management in aquaculture. A variety of technologies have been developed to offer solutions to limited water resources and degradation of water quality. These include recirculating aquaculture systems (RAS) (Martins *et al.*, 2010), and integrated intensive aquaculture installations that can take place in coastal waters, offshore environments or in ponds, and are adaptable for various combinations of fish, shrimps, shellfish, sea urchins, plankton and seaweeds (Neori *et al.*, 2004; Gilles *et al.*, 2014). These systems serve to decrease some of the inputs needed for production (e.g. water, nutrients, land) but they are energy demanding. As pointed out by Martins *et al.* (2010), a small water exchange rate in RAS can also create problems resulting from the accumulation of growth-inhibiting factors coming from fish (e.g. cortisol), bacteria (metabolites) and feed (metals).

OPTIMIZING THE BIOGEOCHEMICAL FUNCTIONING OF FARMING SYSTEMS

Recoupling C-N-P cycles in grasslands

Within extensive grasslands, the carbon, nitrogen and phosphorus cycles are naturally coupled by plant autotrophy and by soil organic matter (SOM) stabilization. This coupling is tightly regulated through a host of biological and ecological processes including plant plasticity, plant and soil community functional diversity and root symbioses driving BNF and phosphorus mobilization. Therefore, the stoichiometry[4] of these major cycles is controlled, resulting in converging element ratios in SOM. However, ruminants tend to uncouple the carbon and nitrogen cycles by releasing digestible carbon as CO_2 and CH_4, and by returning digestible nitrogen in high concentrations as reactive nitrogen in urine patches. Phosphorus from animal excreta becomes bound to soil particles, which reduces its mobility provided that soil erosion is low. Since the 1950s, grassland intensification has mostly been based on mineral and organic nitrogen and phosphorus fertilization, controlled grazing (and mowing), and vegetation improvement through the introduction of productive and high quality grasses. Grassland intensification has led to increased pasture productivity and to an increased animal stocking density. While this may have been initially beneficial for soil carbon sequestration, it has also favoured increased enteric CH_4 and reactive nitrogen emissions.

The environmental impacts of grassland intensification are controlled by a trade-off between increased C–N coupling by vegetation and increased C–N decoupling by animals. Stimulation of vegetation productivity by the adequate application of nitrogen and phosphorus fertilizer raises carbon uptake and storage, while increasing stocking density reduces mean carbon residence time within the ecosystem (Soussana and Lemaire, 2014). Hence, a threshold level of grassland

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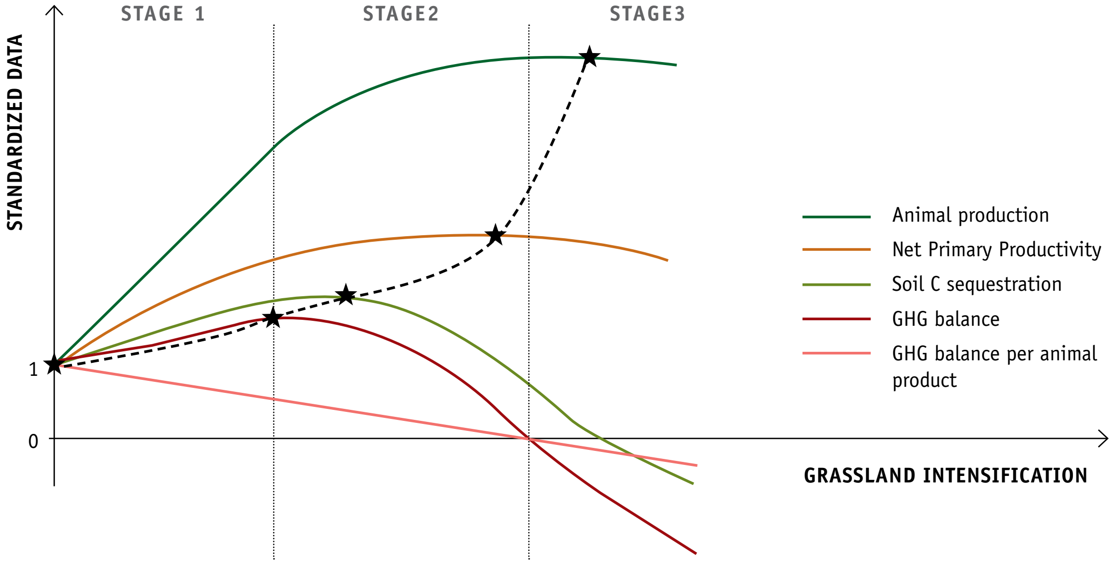
[4] Stoichiometry indicates the mass ratio in which elements involved in chemical reactions stand. This mass ratio analysis can also be used for biogeochemical cycles.

Figure 2. **Effects of grassland intensification by grazing and cutting, and N fertilizer application on animal production, net primary productivity, soil C sequestration and GHG balance per unit of land and per unit animal production**



Responses are standardized to one for an un-intensified control pastoral system prior to modernization of animal agriculture. Star symbols connected by a dashed line show the maximum value for each variable. Grassland intensification combines inorganic N fertilization and an increase in animal stocking density following a step change in management.

Source: Soussana and Lemaire, 2014

intensification can be determined above which any additional animal production would be associated with large environmental risks (Figure 2).

Agroecology provides a number of specific pathways to ensure greater environmental sustainability for pasture intensification. Agroecologically focused breeding programmes, animal nutrition initiatives and improved animal health by the means mentioned above can increase pasture productivity and herbage quality, thus raising animal protein conversion efficiencies. Replacing inorganic nitrogen fertilizer inputs by BNF and recycling efficiently the organic nitrogen from animal excreta within integrated arable-livestock systems can increase the carbon flows in animal products and soils, while recoupling the C-N-P cycles and reducing losses to the environment.

Managing grasslands with less mineral nitrogen fertilizers and with an increased reliance on BNF is a desirable objective in order to reduce the costs of inputs, avoid GHG emissions caused by the process of industrial synthesis and by the transport of mineral nitrogen fertilizers, and to increase the digestibility and protein content of the herbage (Frame, 1986). In contrast with inorganic fertilizers, BNF allows the introduction to the ecosystem of quantities of nitrogen already coupled with corresponding carbon, which reduces overall N_2O emissions (IPCC, 2006). The symbiotic interaction between legume plants and *Rhizobium* bacteria offers the unique possibility to allow the host plant access to the unlimited source of atmospheric nitrogen. Legumes have a distinct competitive advantage in nitrogen-limited systems. However, where

nitrogen is abundant, N_2 fixation is energetically costly and N_2-fixers tend to be competitively excluded by non-fixing species (Soussana and Tallec, 2010).

Legume-based grassland systems have often been shown to be difficult to manage, as the proportion of pasture legumes in sown mixtures and in permanent grasslands fluctuates both from year-to-year and within single growth periods. The benefits of legumes for ruminant systems are most effective in species-diverse mixed swards with a legume proportion of 30-50 percent, resulting in lower production costs, higher productivity and increased protein self-sufficiency (Lüscher *et al.*, 2014). Sown legumes may also contribute to the restoration of degraded pastures, providing a win-win solution combining increases in plant productivity, soil carbon stocks and animal production. Such a scheme has been successfully applied in Portugal through the use of phosphorus fertilization and species rich grass–legume mixtures.[5] Forage nitrogen-fixing trees also offer an interesting alternative (e.g. *Acacia* spp., *Faidherbia* spp., *Gliricidia* spp.) as they can be used to restore degraded pastures and to provide forage during seasonal droughts, while offering shade to herds.

The maintenance of a wide range of grazing intensities at the landscape level can be used for conserving a diversity of pasture species at this scale (McIntyre *et al.*, 2003). Managing grassland communities to obtain a desirable mix of plant traits and plant functional types helps to recouple the carbon and nitrogen cycles and to match seasonal fluctuations in feeding demands by domestic herbivores (Pontes *et al.*, 2007). Moreover, functional diversity enhances the resistance of temperate grasslands to weed invasion in both extensively and intensively managed swards (Frankow-Lindberg *et al.*, 2009). In permanent pastures, grassland diversity may reduce risks of nitrate leaching through an increased complementarity between species in nitrogen uptake and water uptake (De Deyn *et al.*, 2009).

Integrated livestock systems

An integrated farm is one in which livestock is incorporated into farm operations to achieve synergies among farm units and not just as a marketable commodity (Gliessman, 2007). These systems demonstrate complementarity in resource use when livestock are fed with crops or forages (including trees) that are being produced on-farm, while farm manures improve crop production and income from the cropping system. Through spatial and temporal interactions among farm units, livestock integration contributes to the regulation of biogeochemical cycles and environmental fluxes to the atmosphere and hydrosphere. Adding herbivores mimics further ecosystem functions, which can help increase the stability of the agro-ecosystem. Excreta from one species can even be directly used as components of formulated diets for another species. For example, West African dwarf goats can be sustained on diets including poultry excreta, resulting in improved liveweight gains, feed conversion ratios, carcass yields and ultimately better economic returns to farmers (Alikwe *et al.*, 2011). The main synergy from mixing crops and animals is derived from animal manure becoming a resource that is rich in nutrients and provides soil micro-organisms with a key source of energy. Self-sufficient, low-input dairy

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[5] For more information see: www.terraprima.pt

farms in Brittany illustrate how cost-cutting management practices (part of the arable crops are used as home-grown feeds and grass–legume mixtures are integrated in crop rotations) can lead to a win-win strategy combining good economic and environmental performances (Bonaudo *et al.*, 2014).

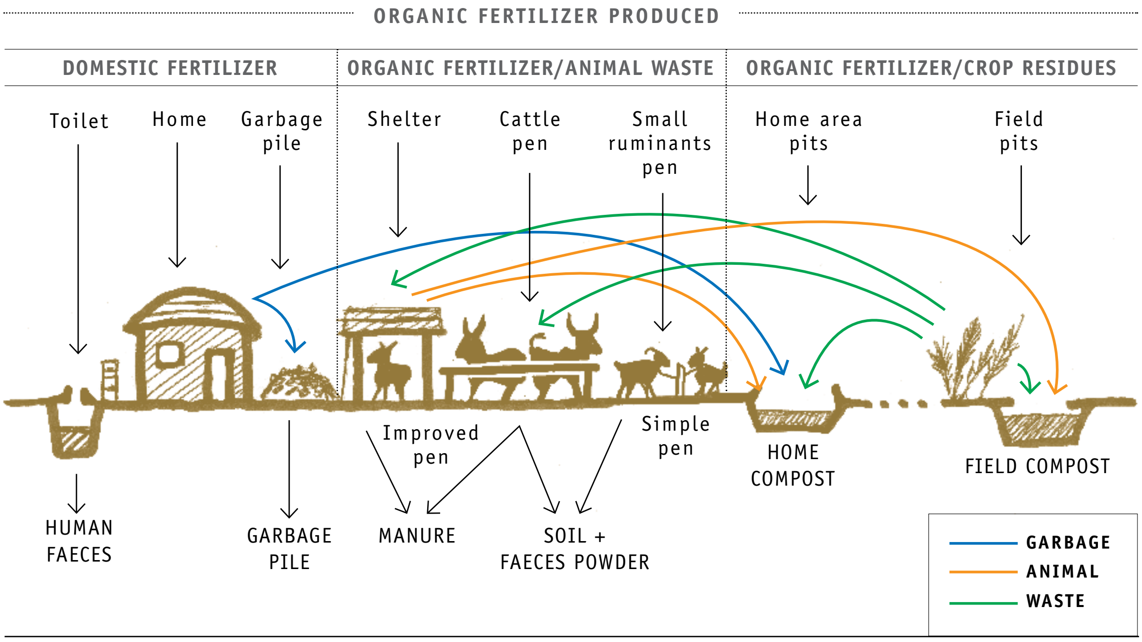
In sub-Saharan Africa, garbage piles containing domestic waste, daily sweepings and faeces from small ruminants, along with some soil, can be produced in the homestead area. Confining animals to facilitate manure collection helps produce organic fertilizer in significant amounts. Some farmers add bedding material and feed leftovers to the pen or animal shed, which further increases the quantity and nutrient content of manure, as the nutrients in urine are trapped by the litter. Household compost can be produced in pits near the homestead area combining the animal faeces, feed and crop residues, and domestic waste. Farmers may choose to irrigate the pit, turn the compost and use a cover to limit nitrogen losses and promote decomposition.

Nutrient cycling and losses associated with the management of manure have been estimated for farms with 10-75 tropical livestock units (TLU) in southern Mali (Blanchard *et al.*, 2013). Between 38 and 50 percent of animal faeces (6-40 tonnes farm^{-1} year^{-1}) are deposited during grazing on common pastures. Deposition of faeces during transhumance represents up to 25 tonnes farm^{-1} year^{-1}. This indicates that in West Africa, 46 percent of the nitrogen in crop residues and manure is returned to the soil of common pastures or areas of transhumance, whereas 13 percent is lost in gaseous form at the time of excretion (Figure 3). Organic manure produced on the farm represents 24 percent of the nitrogen in animal waste, while 17 percent is lost through leaching or in gaseous form during handling and storage of manure and compost. In this study the nitrogen-cycling efficiencies of animal waste varied between 13 and 28 percent, indicating large margins for progress in the complex agroecological management of such systems (Blanchard *et al.*, 2013).

With the rising price of mineral fertilizers and reduction in fertilizer subsidies and programmes promoting organic manure quality, there is an increasing focus on the efficient use of nutrients in livestock manure. To increase nutrient conservation, it is recommended to compost under roofs and on floors, and to limit storage time. Where improved forage is available, farmers often tend to keep animals longer in confinement. On-farm biodigesters providing energy for light and cooking are another innovation in Mali that have been used to deliver a new type of manure. In African conservation agriculture, the use of plant cover through the early mowing of *Brachiaria* spp., *Stylosanthes* spp. and *Vicia* spp. produces fodder with very high protein contents. In Burkina Faso and Madagascar, the managed grazing of crop cover and/or the making of silage or hay from part of the biomass cover adds further value to the ‘no-till cover crop’ innovation (Naudin *et al.*, 2012).

Agroforestry arrangements that combine fodder plants, such as grasses and legumes, with shrubs and trees are often used for animal nutrition. They include scattered trees in pastureland, live fences, tree-based fodder banks and cut-and-carry systems. The restoration of extensive silvopastoral systems in arid and semi-arid areas of Africa is an option that can be used to regenerate rangeland productivity once stocking density rates are well managed. In these systems, trees and shrubs have been observed to enhance carbon sequestration in soils through their root systems while also providing the benefits of bird habitat and shade (Akpo *et al.*, 1995). Moreover, in the dry season trees and shrubs increase the quality of diets for ruminants,

Figure 3. **Crop-livestock integration and diversity of organic fertilizer management in Mali**



Source: adapted from Blanchard *et al.*, 2013

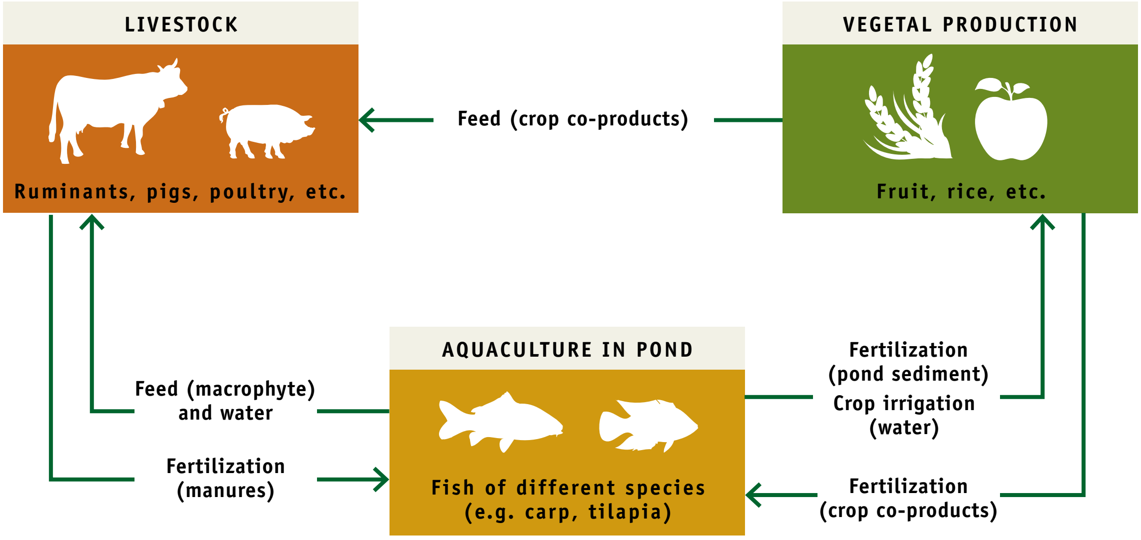
contributing up to 50 percent of dry matter intake for cattle and 80 percent for small ruminants, with protein contents at least four times that of grasses.

Intensive silvopastoral systems in Latin America can be directly grazed by livestock and also include fodder shrubs (e.g. *Leucaena* spp.) and productive pasture species. These systems produce high milk yields and can be combined at the landscape scale with connectivity corridors and protected areas (Murgueitio *et al.*, 2011). Silvopastoral systems that integrate trees, crops and pastures are becoming more common in the Brazilian savannah and have also been associated with increased soil fertility through the continuous supply of organic matter and better land management practices (e.g. avoiding erosion) (Tonucci *et al.* 2011). They also provide a large carbon sequestration potential and shading to livestock, and are likely to be more resilient to heat waves and to droughts. However, many barriers to the adoption of silvopastoral practices still exist. High initial costs, slow returns on investment, and an overall unawareness of the benefits suggest that efforts are needed on behalf of the scientific community and stakeholders towards building capacity and financing.

Integrated aquaculture

In intensively managed wetlands in Southeast Asia, farmers are adding an aquaculture component to already integrated crop-livestock systems. These integrated agriculture-aquaculture systems are based on the recycling of nutrients between farm components: livestock manure and other farm wastes fertilize fish ponds, pond sediments fertilize crops and crop co-products feed livestock (Figure 4). Different fish species and combinations of species are commonly reared in ponds (Rahman *et al.*, 2006). Not only fish yields, but also livestock growth performance, biomass production relative to inputs and economic benefits can all be substantially increased in these systems. For instance, introducing tilapia (*Oreochromis niloticus*) into existing integrated farming systems increased gross margins from US$50-150 to US$300 per household in peri-urban areas of Bangladesh (Karim *et al.*, 2011). However, fish grown under waste-fed conditions can become contaminated with pathogens from human or animal excreta, antibiotics or antibiotic-resistant bacteria. Therefore, reducing sanitary risks is a priority, as outlined in the WHO (2006) guidelines for fish farming.

Figure 4. **Simplified diagram of the interactions within integrated agriculture-aquaculture systems in Southeast Asia**



Source: Dumont *et al.*, 2013

In such aquaculture systems, pond productivity can also be increased by introducing submerged substrates in water to naturally stimulate fish productivity. This principle is based on traditional fishing methods known as *acadjas* in Africa (Bene and Obirih-Opareh, 2009), and *Samarahs* and *Katha* fisheries in Asia (Shankar *et al.*, 1998), where the periphyton – a complex assemblage of all sessile biota attached to the substratum, including associated detritus and micro-organisms – grows and can constitute a natural food for fish. Submerged substrates also offer shelter, while their associated microfauna helps to improve water quality through the trapping of suspended solids, organic matter breakdown and enhanced nitrification. The control of the C:N ratio in pond water through the addition of carbohydrates offers another alternative to enhance microbial development, protein recycling and biomass production. According to Bosma and Verdegem (2011), manipulating the C:N ratio (e.g. by adding tapioca starch) doubled protein input efficiency in ponds, while substrate addition (e.g. bagasse, molasses) increased production by two to three times.

Industrial ecology for intensive livestock systems

Compared with agroecological systems *sensu stricto*, systems based on industrial ecology have a highly controlled composition and a much looser link to the land. These systems make it possible to treat and make productive use of waste from other agricultural or non-agricultural systems (Takata *et al.*, 2012), and will add quantitatively to production, while reducing pollution and competition for land, energy and water. It is noteworthy that the first three principles that have already been discussed can also be applied to these systems. Pig farming systems provide a classic example in which most of the environmental impact is associated with the production of feed ingredients, animal housing and manure storage. An ecologically sound pig farming system optimizes metabolic functioning by using manure from sows to produce biogas for heating and, after treatment, to fertilize cereals, oilseeds and peas grown on the farm to feed the pigs. Biodigesters produce biogas from liquid and solid pig manure (and silage of intercrops), which is the most effective way to avoid environmental losses of CH_4 from liquid manure while also reducing the biological activity of drug residues (Petersen *et al.*, 2007). Biogas can be used for electricity production and heat for pig housing, thus reducing farm energy costs and decreasing piglet mortality. Marked annual variations in the price of pig meat can be strongly buffered by sales of crops produced on the farm. The system is efficient both economically and for the management of manure collection, treatment and use to increase nutrient cycling while reducing pollution. However, it requires a major initial investment for biodigester installation. This example shows that industrial systems can readily be reconnected to a land base by applying industrial ecology principles which form a subset of the broader concepts used in agroecology.

SYSTEMS DIVERSITY AND RESILIENCE

Agricultural intensification has drastically reduced diversity – that is the variety of both plant and animal species and the variety of management practices and production factors. Recent empirical evidence has underlined the potential of diversity in animal production systems for increasing resilience through mechanisms that operate at different levels (Tichit *et al.*, 2011).

At the herd level, diversity in both animal species and management practices secures pastoral systems. Rearing different animal species provides a risk-spreading strategy against drought, disease outbreaks and market price fluctuations (Tichit *et al.*, 2004). Adapting management practices to the biological characteristics of each species is also a key lever to ensure resilience (e.g. by modulating breeding practices according to female longevity and climate sensitivity). Combining several herbivore species in free-grazing systems enables higher overall vegetation use and liveweight gains (D'Alexis *et al.*, 2014). The guiding principle of these systems is the use of multiple spatial niches and feed resources that is also applied in aquaculture. For example, in the popular rohu (*Labeo rohita*) and carp (*Cyprinus carpio*) combination found in Southern Asia, while browsing the sediment for food, carp oxidize the pond bottom and suspend nutrients accumulated in sediments, leading to up to 40 percent higher rohu production and almost doubling total pond production (Rahman *et al.*, 2006).

Within a monospecific ruminant herd, there is some variability in animal traits and the diversity of lifetime performance, which is suggested to act as a buffer by stabilizing overall herd production. Managing diversity over time becomes a central issue in large herds where management strategies targeted at different herd segments are expected to increase overall performance (Lee *et al.*, 2009). Diversity in lifetime performance emerges from complex interactions between herd management practices and individual biological responses (Puillet *et al.*, 2010). These interactions generate contrasting groups of females with different production levels and feed efficiencies. The relative size of these groups in the herd is thus a key determinant of overall performance.

A diversity of forage resources also helps to secure the feeding system against seasonal and long-term climatic variability. Grazing animals take advantage of resource diversity to maintain their daily intake and performance, with contrasting effects of selective grazing occurring according to breed morphological and physiological traits. For instance, Salers beef cows with a relatively high milk yield potential maintained daily milk yield at the expense of body condition in the late season, whereas Charolais cows, which have less milk potential reduced milk yield but lost less liveweight (Farruggia *et al.*, 2008).

In agro-pastoral systems, the feeding system is based on complementarities between cultivated grasslands, which are used to secure animal performance in crucial periods such as mating or lactation, and rangelands, which are mostly grazed at times when the animals have low nutrient requirements (Jouven *et al.*, 2010). When the availability of feed resources is low or unpredictable, defining seasonal priorities between animals with high requirements or key production objectives (e.g. improving body condition), which will need to be given priority access to the best resources, and animals with low requirements or secondary production objectives, helps in the design of efficient feeding systems. The diversity of grassland types within a farm has been shown to improve farm self-sufficiency for forage in both dairy (Andrieu *et al.*, 2007) and suckler farms (Martin, 2009). Recent research has also emphasized that a diversity of grazing management practices, in terms of stocking rate and periods, can enhance production stability despite drought events (Sabatier *et al.*, 2012).

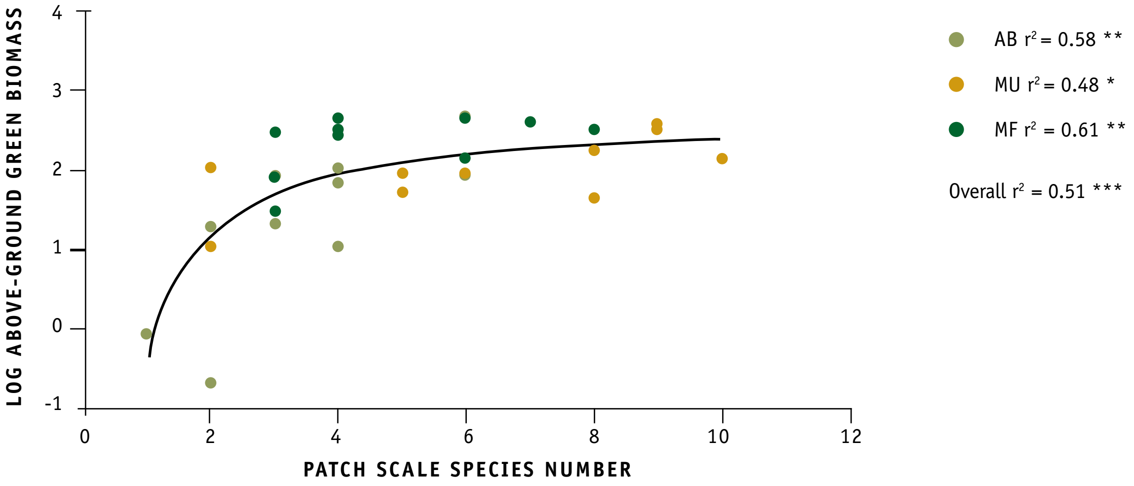
Dumont *et al.* (2014) have pointed out several unresolved challenges involved in understanding whether resilience is a manageable property of animal production systems: (i) to assess the relative weights of biological and decisional processes involved in resilience; (ii) to identify diagnosis and adaptive management indicators, and explore the operational character of early-warning indicators for the anticipation of critical thresholds or "tipping points" (Veraart *et al.*, 2012); and (iii) to understand which management strategies are used by farmers to overcome climatic events and biotic or abiotic stresses. Managing several species or breeds with contrasting adaptive capacities within the same system offers an efficient mechanism to buffer the effects of extreme climate events on herd productivity and farm income (Tichit *et al.*, 2004). The benefits of diversity have also been reported in plant assemblages and at forage system level; the next step is to combine the herd and resource components to identify which level of within-farm diversity could be deployed to benefit several farm performance criteria.

BIODIVERSITY PRESERVATION

In the past decade, concerns over biodiversity loss have spread to domestic biodiversity (i.e. animal genetic resources and local breeds) (Taberlet *et al.*, 2011). Higher performance of commercial breeds means that local breeds tend to be replaced by more productive ones, or at least outcrossed. A loss of genetic diversity has also occurred in commercial breeds via the development of artificial insemination, with only a few males being involved in reproduction schemes. Local breeds have greater abilities to survive, produce and maintain reproduction levels in harsh environments. Therefore, using local breeds is well suited to economically marginal conditions, because of reduced veterinary intervention, ease of breeding and lower feedstuff costs. Animal products from traditional breeds with a strong local identity can fetch premium prices, as consumers identify them as having superior sensory properties (e.g. taste) or nutritional quality, or are attracted by the image of a particular region or tradition. Developing niche markets could help preserve resistance or adaptation traits that would otherwise be rapidly lost and difficult to rescue.

Agricultural intensification and homogenization have been important drivers of losses in the diversity of flora and fauna in grazing lands. In temperate grasslands, plant species diversity tends to reach a maximum at intermediate disturbance and stress levels – which implies that intensively managed grasslands have reduced plant diversity. Maintaining a diversity of local plant species has been shown to increase grassland productivity (Gross *et al.*, 2009) (Figure 5). Therefore, the management of plant functional diversity is a key agroecological strategy that can be applied to grazing systems.

Figure 5. **Above-ground biomass at the patch scale as a function of the number of plant species in a grassland patch (14 x 14 cm)**



Treatment codes are as follows: AB (green circles) = 'abandonment' (no mowing or fertilization); MU (orange circles) = mown and unfertilized; and MF (dark green circles) = mown and fertilized. Regressions are linear within each land-use treatment and non-linear for the pooled data set. Levels of significance for regressions are: *$p<0.05$; **$p<0.01$; ***$p< 0.0001$

Source: Gross *et al.*, 2009

Pasture management strategies that preserve biodiversity while ensuring good economic returns to farmers can create win-win outcomes. For example, preserving legume-rich grasslands and introducing sown margin strips at the edge of arable fields favours pollinator abundance and species richness as a result of positive trophic interactions (Marshall *et al*., 2006). Likewise, manipulating the timing of grazing (through late grazing or grazing exclusion at peak flowering times) can be a powerful conservation tool for flower-visiting insects (Farruggia *et al*., 2012) and grassland birds (Durant *et al*., 2008), without impacting stocking rates. However, grazing intensity must be adapted to the livestock type and annual variation of grass growth so that grazing management can meet both production and conservation goals. Jouven and Baumont (2008) modelled grassland-based beef systems and found that meat production could be maintained by deploying biodiversity-friendly practices on up to 40 percent of the farm area. This result is similar to the recommendations of Franzén and Nilsson (2008) for late grazing in Swedish farms. The choice of specific practices that result in the optimal production-biodiversity equilibrium will depend on the particular farming context (e.g. type of grasslands, overall stocking rate, herd management).

To enhance soil biodiversity, management practices such as pasture restoration or land manure spreading contribute to the enrichment and diversification of macrofauna and microflora. Compared with the use of inorganic fertilizers, the application of organic manure in maize or cotton fields has significant positive effects on microbial biomass, the profile of existing species and, consequently, on the enzymes that circulate in the soil and its pool of organic matter (Ratnadass *et al*., 2013). These interactions promote overall soil fertility. Such changes in the soil ecosystem influence the primary production capacity and floristic biodiversity of the vegetation cover that colonizes the soil in agricultural fields and pastures. In the example of cheese production, interactions also take place between soil micro-organisms, phyllosphere microflora and the microflora used for cheese processing. On temperate mountain pastures, microbial diversity reduced the pathogenicity of *Listeria monocytogenes* in raw milk cheese (Retureau *et al*., 2010). Moreover, species-rich pastures subjected to extensive management produce a variety of secondary compounds including terpenes that are a key factor for the organoleptic diversity of dairy products (Cornu *et al*., 2005).

The management of diversity and heterogeneity has to extend beyond farm boundaries to encompass the landscape scale. Ecological processes and services like pest control or pollination are grounded at the landscape scale, stressing the need for collective landscape management among farmers and other land-users, accounting for both farmed and semi-natural elements. Recent research has demonstrated that the proportion of management practices (grazing vs cutting) and their spatial arrangement can affect the long-term dynamics of bird populations in agro-landscapes. While converting some intensive practices into extensive ones affected production, altering the spatial arrangement of practices to increase landscape heterogeneity helped to reconcile production and conservation goals (Sabatier *et al*., 2014). The selection of temporarily ungrazed plots should take into account not only the ‘habitat value’ of each plot, but also their location so that they can act as dispersal sources or ecological corridors.

Landscape features can exert multiple functions and thus play an important role in biodiversity conservation. In Latin America, high milk yields have been achieved without chemical fertilizers

in intensive silvopastoral systems with trees and palms that provide timber, fruit, green forage for livestock, and root and bark for medicinal uses (Murgueitio *et al.*, 2011). Farmers that participated in the project reported that they perceived a dramatic increase in bird abundance and diversity, including more sightings of endangered species. These systems also facilitate connectivity between tropical forest fragments, providing a further benefit to biodiversity. Farmers received a premium payment for incorporating focal native trees, palms and cacti species into their connectivity corridors – these species were selected for their particular contribution to biodiversity. As the payments did not depend on farm size or capital endowments, they were available to all farmers. Extensive fishponds are another typical example, contributing to food production ecosystems, while providing attractive landscape features and a habitat for wild bird species. In temperate fishponds with a controlled fish biomass (400 kg ha^{-1}), the presence of aquatic vegetation over 10-15 percent of the total area improved water quality, benefited fish reproduction and offered a refuge and nesting habitat for waders (Bernard, 2008). However, the interactions between the biotic and abiotic components of fishponds are complex, and depend on the specific practices used and regional conditions.

PERSPECTIVES

This chapter demonstrates how agroecological principles can be applied to systems incorporating livestock, to promote synergies (rather than trade-offs) between local agro-ecosystems and animal production. Each of the five principles is generic and can be applied to the design of a large range of livestock systems, through options that may vary considerably between agro-ecological zones and according to the social, economic and human dimensions of livestock farming. These options include: (i) the intensification of tropical livestock systems by raising yield outputs through an increased use of biodiversity; (ii) transitions to organic livestock production; and (iii) transformation of intensive systems by encouraging farmers to reduce the use of fertilizers and antibiotics. Therefore, depending on the baseline conditions, agroecological transitions with livestock systems may put more emphasis on a subset of the five principles, in order to achieve specific goals such as maximizing economic returns, conserving biodiversity, mitigating GHG emissions, increasing soil and water quality, and enhancing climatic resilience.

An increased use of both planned and unplanned biodiversity (for animal health and nature conservation purposes), a better crop-livestock integration within a diversified landscape matrix and a recoupling of the major element (C, N and P) cycles are the key features underpinning the five principles discussed in this chapter. All of these features could help balance the supply of animal products and the delivery of supporting and regulating ecosystem services.

Interestingly, the concept of eco-efficiency (the maximization of outputs per unit of inputs/natural resources used) is not promoted as a guiding principle of agroecology, although competition with other uses of land and water resources may necessitate more efficient livestock production. Moreover, the current debate on reduced CH_4 emissions from cattle and sheep per unit of animal production is not at the centre of the debate on livestock within agroecology.

This may question the degree to which agroecology can provide answers to global-scale livestock challenges. Nevertheless, agroecology can offer specific answers, such as how to enhance soil carbon sequestration in herbage-based ruminant systems.

Independently from agroecology, new technologies, such as advanced breeding and precision livestock farming, could play an important role in meeting these challenges. For instance, genomic selection, which enables prediction of the genetic merit of animals from genome-wide markers, has been adopted by dairy industries worldwide and is expected to increase genetic gains for milk production and other traits including feed conversion efficiency (Hayes *et al.*, 2013). Such techniques could evolve (e.g. by considering animal robustness in genetic indices) to become more compatible with the principles of agroecology. In addition, agroecology cannot be applied *stricto sensu* to landless industrial systems which are developing rapidly in both industrialized and developing countries. Hence, agroecology is not a silver bullet. Rather, a dual perspective is needed, grounded in the principles of agroecology and industrial ecology as complementary frameworks for improving the net effects of animal production for sustainable development.

In conclusion, agroecological principles can be applied to a large variety of livestock systems covering extended gradients of soil, climate, farm size and production intensity. Some of the bottlenecks for scaling up agroecological systems pertain to the costs of labour, a relatively weak knowledge basis compared with our detailed understanding of simpler industrial systems, and a lack of training of farmers in applied ecology and farming systems. Moreover, scaling up these systems may require broader changes in markets, industries and food systems (Francis *et al.*, 2003). As illustrated by the examples described in this chapter, it should be emphasized that the principles of agroecology point to performance criteria far beyond annual productivity and call attention to trade-offs between the economic, ecosystem and social dimensions of agriculture.

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13

HOW TO ACHIEVE FOOD SECURITY IN CHINA:

FROM FIELD-SCALE SOLUTIONS TO MILLIONS OF FARMERS

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INTRODUCTION

Although the past half-century has seen remarkable growth in food production, the challenges facing agriculture today are greater because of the need to increase global food production while also protecting environmental quality and conserving natural resources over the next 30 years. During the past 50 years, the 240 percent increase in Chinese grain production can be partly attributed to a 3 600 percent increase in nitrogen fertilization and a 9 000 percent increase in phosphorus fertilization (Zhang *et al.*, 2012). However, the environmental costs of this increased fertilizer use have been very high, resulting in severe threats to water quality through eutrophication (Ju *et al.*, 2009), threats to air quality through ammonia volatilization and greenhouse gas (GHG) emissions (Ju *et al.*, 2009; W.F. Zhang *et al.*, 2013), increased nitrogen deposition (Liu *et al.*, 2013), as well as threats to soil quality through nitrate accumulation (Ju *et al.*, 2006) and soil acidification (Guo *et al.*, 2010).

China's increasing population is projected to peak at 1 467 million in 2030. Grains are particularly important for ensuring Chinese food security to meet the increasing food demand and ensure social stability. However, compared with other commodities there are particular challenges in providing sufficient grains based on the limited farm land and resources available. To feed 1 467 million people, China will need 776 MT of grain per year, a net increase of 204.4 MT compared with its highest annual production of 571 MT in 2011 (Li *et al.*, 2014). The high projected demand for grain means that if there is no increase in land area, grain yield per unit area has to increase by 30 percent (Li *et al.*, 2014). At the same time, China must reduce the emission of pollutants associated with agriculture to achieve environmentally friendly targets by 2030, particularly for grain production with high chemical inputs.

Chinese total grain production has been increasing continuously since 2003, but the annual rate of increase has stagnated at around 1 percent, with 54 percent of the increases attributable to yield increases per unit area and an 11 percent increase in the use of chemical fertilizer inputs. Continuing business as usual will not be able to meet the expected targets for increasing grain yields and improving environmental quality. Technically, the grain yield can be increased by 30 percent through the adoption of new technologies such as integrated plant–soil system management, but this would still rely on similar inputs of chemical fertilizers to those currently used by conventional practices (Chen *et al.*, 2011; F.S. Zhang *et al.*, 2013).

To address these challenges involving grain production, resources and environment, Chinese agriculture must be transformed from the decades-long approach of concentrating solely on high yields to a new approach combining both high yields and high resource-use efficiency, i.e. 'double high sustainable agriculture' (DHA). To achieve the win-win outcome of food security and environmental sustainability we have developed an integrated technology system in which the focus is on achieving both high crop productivity and high resource-use efficiency simultaneously, termed 'double high technology' (DHT).

The key components of DHT involve: (i) significantly increased grain yields through crop management, especially optimum cropping system design and canopy management to maximize yield potentials in systems that are well adapted to the climatic conditions in a given geographical region; (ii) greatly increased nutrient-use efficiency through fine-tuning root/

rhizosphere management to optimize the nutrient supply intensity and composition in the root zone to maximize root/rhizosphere efficiency with reduced nutrient inputs; (iii) improved soil quality to ensure long-term food security by managing soil organic matter and soil fertility and eliminating soil constraints; and (iv) enhanced agricultural sustainability through integrated resource–environment management by increasing resource-use efficiency, reducing nutrient losses and GHG emissions and minimizing ecological footprints. Technologically, DHT can increase yields by 15-20 percent and reduce fertilizer nitrogen use by 30-50 percent on a field scale (Chen *et al.*, 2011; 2014). However, the key question is how these advanced management systems can be embraced by farmers. Clearly, the application of DHT relies greatly on these technologies effectively reaching the end users, namely the farmers.

STRATEGIES TO INCREASE THE YIELDS AND RESOURCE EFFICIENCY OF CHINESE CROP PRODUCTION

The strategies for integrating agricultural technology innovation, transfer and application for DHA include the following key components: (i) establishing an integrated platform for efficient interaction between the government sector (education and research, public extension, and enterprise) and farmers; (ii) developing innovative and integrated agricultural technologies that are well adapted to local farming conditions; (iii) establishing highly efficient technology application channels to transfer these technologies directly to farmers; and (iv) strengthening linkages and communication among public extension systems, scientists, enterprises and farmers, in order to provide farmers with timely and effective services to help them adopt new technologies and acquire new information.

Harnessing interactions between government and farmers to ensure that the solutions and strategies outlined above are applied on a large enough scale to achieve a significant impact transforming agriculture towards sustainable crop production with DHA has become a great challenge for Chinese society, as it is for other nations. To address these problems we have developed new communication solutions to close the 'last mile' of the gap between government and farmers through the establishment of a new platform termed 'Science and Technology Backyards' (STB) (Shen *et al.*, 2013). Based in villages or farmer's homes, STBs are organized by graduate students and their professors from universities or research institutes, working jointly with local extension experts and farmers, with the aim of achieving agricultural transformation by increasing crop productivity, resource-use efficiency, environmental sustainability and farming incomes (Shen *et al.*, 2013).

DHT has been successfully adopted, demonstrated and extended in the major agricultural regions of China through this comprehensive and open platform and it has successfully opened up effective channels of communication between government and farmers. In particular, it has fostered close links between farmers and government extension systems, scientists from research institutes or universities, commercial enterprises and other professional farmer cooperatives or associations. Agricultural scientists play a key role in STBs, especially graduates and professors from institutes or universities who are supported by central government to develop a new

graduate education system leading to a professional master's degree in which the students must complete their applied research programme in crop production with a close linkage to practical farming technology.

Internationally, many transnational corporations as well as public agricultural sectors from developed countries have started to develop and implement similar programmes to intensify the transfer of agricultural technology services directly to farmers' fields. This model is typically centred on rural villages to help farmers in a timely fashion and on-site. In these systems both students and experts need to have strong links to agricultural practices and understand adaptive research within relevant agro-ecosystems. Students and experts spend more time living and working in villages thanks to the direct '4-Zero Service', which provides zero distance, zero time lag, zero entrance charges and zero access charges for farmers to the STB platform throughout China. The STB model could be further optimized and adapted to other international environments, through government subsidies, industry-based free services for stimulating the extension of products, or other voluntary services provided by local farmers associations and cooperatives.

CONCLUSION

The optimized integration of various intellectual, information and material resources on the STB platform may help maintain the sustainable operation of the system with multi-channel support from the education and research sectors, public extension systems, enterprises and farmers. Most importantly, the system has built a higher level of trust between farmers and government bodies. As a result of the direct two-way interactions between farmers and government, the communication of information, adoption of new technologies and implementation of high standards in 'double high' farming practices for sustainable agriculture have been greatly enhanced. The STB acts as a communication bridge and plays a key role in promoting DHA in China. More than 50 STBs have been developed throughout China, and the new STB model with 'high yields, high resource efficiency and high resilience' has become an effective agricultural development path to ensure food security and improve environmental quality in China and other developing nations where there is a need to transform low-efficiency systems to achieve high yields with high resource-use efficiency.

ACKNOWLEDGEMENTS

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14

THE INFLUENCE OF FOOD SYSTEMS ON THE ADOPTION OF AGROECOLOGICAL PRACTICES:

POLITICAL-ECONOMIC FACTORS THAT HINDER OR FACILITATE CHANGE

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Abstract

Farmers' decisions about the practices they use are inevitably affected by the social, political and economic conditions that surround them, as well as the biophysical or environmental context. Increasing the adoption of agroecological practices to produce nutritious food requires efforts to address critical political-economic and market factors in food systems, which influence farmers' decisions and actions, but tend to be overlooked. This chapter will identify and explore several key factors in food systems that hinder or limit the use of agroecological approaches to meet food security needs, as well as contrasting elements that can support and expand the adoption of agroecology. The influential food system factors that are considered here include market conditions (such as the roles of food retailers, buyers and brokers in shaping food demand), farm input suppliers and related food policies. Relationships between peers and organizations in food systems are also briefly discussed. The concentration and globalization of commodity markets in food systems are significant factors that prevent farmers from adopting sustainable agroecological practices that meet their food security needs. The chapter will conclude with some comments on the policy and political-economic implications, such as the importance of addressing market power in food systems, supporting social movements that help scale up agroecological practices, as well as developing policies to support more sustainable, diverse, healthy and just food systems.

INTRODUCTION: UNDERSTANDING THE ADOPTION OF AGROECOLOGY IN THE CONTEXT OF FOOD SYSTEMS

Growing attention is being given to agroecology as an important approach for increasing sustainability and food security in agriculture worldwide. There is growing evidence about the ecological, economic and social advantages of using agroecological approaches, including advantages for achieving food sovereignty and improving the livelihoods of small-scale farmers at regional and local levels (Cohn *et al.*, 2006; Altieri *et al.*, 2011; Thiemann, 2015).[1] Efforts to support agroecological practices through national policies and programmes have been increasing

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[1] As discussed by Wezel *et al.* (2009), the term agroecology has been used to refer to a science, a movement and a practice. Commonly, agroecology refers to a scientific discipline that defines, classifies and studies agricultural systems from an ecological and socio-economic perspective. Agroecology is also often considered a basis for authentic organic agriculture, although agroecology is not associated with certification and/or policy programmes that are connected to the term organic.

in a few countries, particularly in Brazil and Bolivia. Cuba is also a prominent example of nation-wide efforts to promote agroecological approaches in agriculture (Rosset and Benjamin, 1994; Rosset *et al.*, 2011; FAO, 2014; AUSC, 2015). Some international organizations such as FAO and major foundations have also been paying increased attention to agroecology in some of their programmes.[2] These efforts by countries and international organizations have created tangible increases in the adoption of agroecological practices (Hernández and Hernández, 2010; Mckay and Nehring, 2014; Parmentier, 2014).

Scientists and advocates promoting agroecology generally focus efforts on building sustainable opportunities for small-scale farmers, who have been increasingly marginalized and impoverished in the Global South (Murphy, 2012). Renowned analysts and practitioners in this field usually view smallholder farmers as the greatest potential beneficiaries of agroecology; and likewise, they usually agree that agroecology is best suited to meet the needs of low-income smallholder farmers in order to help them develop greater sustainability in agriculture and achieve food justice (Altieri, 1995; Gliessman, 2007).

However, the adoption of agroecological practices, even among smallholder farmers, is still greatly limited worldwide and their application on a large scale is geographically isolated. Although there is a lack of quantitative data on the level of adoption, there appear to be significant barriers and challenges in scaling up agroecology. There is a lack of incentives and policy support for agroecological practices in many contexts. Even though many indigenous and traditional farming methods are based on agroecological principles, these methods have often become displaced and marginalized as conventional industrial practices have become more predominant in the global context. It is critical to understand *why* this is happening, by identifying and addressing the deeper political-economic causes, in order to achieve further progress in disseminating and scaling up agroecology. Policy-makers, organizations and scientists in this field need to understand the role of ***food systems*** and food supply chains that influence farmers' adoption of agroecology or other farming methods. Farmers' choices are directly influenced by the political and economic systems in which they are embedded (Boardman *et al.,* 2003; Government Office for Science, 2011).

This chapter focused on two key questions:

- What are the important political-economic factors in food systems that commonly constrain or limit the adoption of agroecological practices?
- What factors (or strategies) in food systems can foster greater adoption of agroecological practices?

As used here, the term "food systems" refers to *an array of activities, processes and infrastructure involved in providing food to society – ranging from input distribution through on-farm production and marketing, to processing, consumption and disposal; A food system operates within and is influenced by political, economic, social and environmental contexts* (adapted from Ericksen, 2006). Figure 1 provides a simple visual representation of food systems. Related to this

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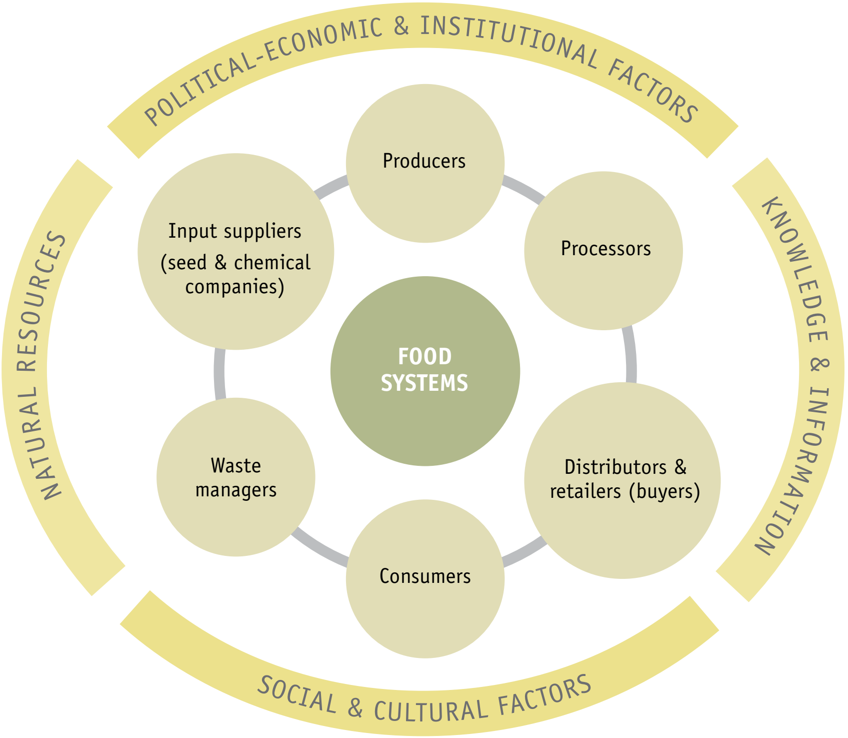
[2] Examples include the FAO International Symposium on Agroecology for Food Security and Nutrition (www.fao.org/about/meetings/afns/en/), the United Kingdom All-Party Parliamentary Group on Agroecology (http://agroecology-appg.org/), and many others.

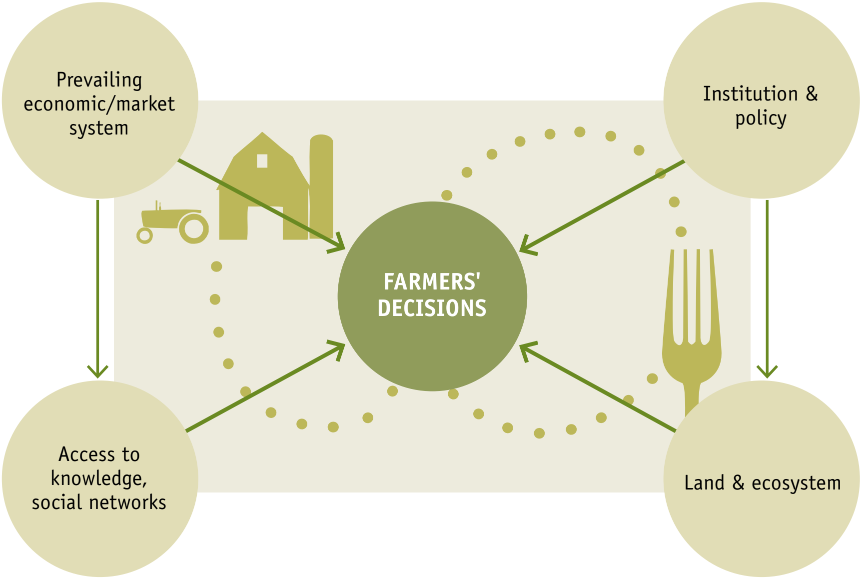
is the important influence of food supply value chains within food systems, sometimes called 'food chains', referring to the links between stages or actors in the system that add or extract value, from production to consumption. The roles of food distribution, sales, marketing and market supply chain relationships are often left out of analysts' considerations of agroecology and sustainable agriculture, but must be addressed in any attempt to scale up or broaden the adoption of agroecological practices.

Figure 1. **Visual representation of food systems**



This analysis uses a 'political ecology' framework, which focuses on understanding producers' perspectives at the field level, and identifying the reasons underlying their decisions and behaviours. This approach traces the chain of causation to the broader political and economic factors indicated in Figure 2. This framework recognizes that producers' decisions are affected by institutional and policy factors at the national and regional levels, by environmental factors that affect their specific local conditions and, more importantly, by economic forces and market pressures that are generally outside of their control. This perspective is informed by previous research and case studies of farming practices and farmers' perspectives in Central and South America (mainly Guatemala, Costa Rica, Ecuador and Peru) and in Africa (in Kenya and Ghana), and hands-on direct experience working on farms and with farmers in research on agri-food system change (e.g. Thrupp *et al.*, 1995; Thrupp *et al.*, 1998; Desta *et al.*, 2000; Thrupp, 2002; Boardman *et al.*, 2003; McCullough *et al.*, 2008).

Figure 2. **Chains of causation for political and economic factors affecting food producers' decisions**



Decisions are affected by broader food systems, including inequitable structures, and are often influenced by global market forces.

MARKET INFLUENCES AND CONSTRAINTS

Market supply chains and farmers' relationships to their product buyers must be considered in order to understand farmers' decisions to adopt or not adopt agroecological practices. The summary of trends in this section is very general and may be oversimplified, as specific situations vary considerably; but the general trends pertain to common patterns that have been documented and demonstrated worldwide.

Although there is a lack of global generalized data on the percentage of farmers connected to markets, there is a growing movement to strengthen existing connections and build new market opportunities (Wiggins and Sharada, 2013). There is great variation in the kinds of market integration, from local informal markets to formal conventional global/export markets. However, even smallholder farmers, who are often featured in agroecology analyses, usually sell some portion of their crops, even if their land holdings are primarily used to produce food for their own subsistence. The large majority of farmers in the Global South sell to informal markets, such as farmers' markets, street vendors or in other non-formalized exchanges (IFAD, 2003; Louw *et al.*, 2008). For example, 70 percent of fruit and vegetables grown in Chile by smallholders are sold to street vendors (Arias *et al.*, 2013). In the North/industrial countries, nearly all farmers are integrated into formal markets, and subsistence farming has nearly disappeared (McCullough *et al.*, 2008).

Integration into formal markets is supported by development agencies as well as global food companies, and is generally considered a positive strategy for economic development. These market development efforts are generally aimed to overcome constraints to smallholders' participation in formal markets, such as minimum volumes of produce set by retailers, or the need for investment in on-farm technology (McCullough *et al.,* 2008). When such constraints are alleviated, farmers and their families may increase and diversify income and assets, expand their operations and/or hire employees, and supply food to growing populations that are landless or have no access to land for food production. Hundreds of economic and rural development projects, policies and investment practices over many decades have been aimed towards increasing market integration, and many of these projects and policies are also tied to efforts to introduce new technologies and practices to increase production and yields for market purposes (Ronchi, 2006; Emran and Shilpi, 2008; Lloyd *et al.,* 2009; FAO, 2009; Wiggins and Sharada, 2013).

As farmers in the Global South transition from subsistence-based production to selling their products in local markets, whether formal or informal, they often need to alter their production practices to some extent to meet the demands, needs and preferences of other people who are buyers or potential buyers. They may need to change the focus of production towards more valuable commodities such as horticultural crops or livestock (McCullough *et al.,* 2008). Alternatively, they may start selecting specific crop varieties and methods, such as trying ways to increase production of particular crops that buyers want, and/or storing crops post-harvest, allowing sales over a longer time period or at strategic times when prices are higher. They will also be responsible for meeting stricter quality and safety requirements to comply with local and, increasingly, international standards (McCullough *et al.,* 2008). In some cases farmers can plan together so that varieties are not all produced at the same time, swamping markets and lowering prices. Of course, market links often require transport and infrastructure changes as well, which may be much harder to implement and outside the capacity of individual producers. But generally, making successful changes in practices can allow farmers to succeed in market contexts and gain income/value from selling their goods.

As farmers in both the Global South and the North become integrated into more formal food supply chains, as suppliers for larger commercial markets or distributors, brokers or retailers based in cities, and/or global markets, they can gain even greater opportunities for earning more sustainable and sufficient incomes. At the same time, the involvement in more formal markets means that farmers are generally required to make more significant changes in production practices, harvest, transport and delivery and other details in order to meet the demands of buyers. This formalization in the supply chain often entails contractual relationships and financial commitments for farmers who sell their goods to buyers who need regular supplies of goods that meet specific customer preferences. These kinds of market supply chain relationships can contribute to economic and technological advances for farmers, although these market changes have also been associated with some challenges, especially for smallholder farmers who often lack the capacity to compete as effectively and have often been subject to unfairly low prices in market economies, with distributors and retailers gaining higher values (Thrupp *et al.,* 1995; Conroy *et al.,* 1996).

As globalization and international trade relations have rapidly expanded, a growing number of farmers have become linked to international global markets, through export/import relationships and growing investments of transnational food corporations worldwide. The globalization of food systems has also been accompanied by a consolidation and concentration of the agriculture industry, as documented in many studies and reports (UNCTAD, 2006; Howard, 2009; De Schutter, 2011; Econexus, 2013). A small number of global corporations have become highly influential in the concentration and vertical integration of food and agricultural markets, increasingly controlling supply chains at the global level (Howard, 2009; Econexus, 2013; Constance *et al.,* 2014;). As one example, just four major corporations account for 75 percent of the market share of trade in grain and soy globally (Econexus, 2013).

This trend of consolidation has been associated with the displacement of small and medium farmers. Although 85 percent of the world's approximately 450 million farms are small scale – producing around half of all food – these farmers are disappearing (UNCTAD, 2006). An estimated 450 million labourers work on industrial plantations and farms. These large-scale farms are increasingly held by banks or other big companies, which provide credit to farmers for seeds, agrochemicals, young animals, and feed (Econexus, 2013). However, they do not always provide sustainable livelihoods for farmers or use agroecological practices.

Even if farmers do not directly sell to export markets, they are often affected by international trade policies and competition, and trends in food markets, which influence local marketing, sales and pricing of food products. Such trends have resulted in benefits to major food corporations and to large farmers who can compete effectively in the system, and have contributed to the growth of agro-industries and other ancillary economic businesses involved in transport and infrastructure. They have also brought benefits to consumers of food products that are marketed both locally and globally, through worldwide exports. Rural populations, including farming families, have been actively engaged in these changes, often by becoming labourers in farming operations or food industries, or by supplying specific products that are demanded by the food companies and processors that are buyers in the supply chain. However, these changes have seldom brought sustained benefits to smallholder and low-income farmers or landless rural people. Evidence shows that smallholder farmers have become increasingly marginalized and displaced or impoverished in these situations where commercial markets have become prevalent (Fan *et al.,* 2013). These prevailing market trends have frequently exacerbated inequalities, especially when social support systems or policies to assist smallholder producers do not exist.

Studies and empirical evidence show that the growing integration into formal global food systems/markets create increasingly rigorous and specific requirement and obligations for producers' production practices, as well as growing competition among producers to meet such demands. Producers are generally obligated by contracts or formal agreements. These requirements include the following:

- Crop variety (including specified seeds) and volume of crops in specified time periods;
- Detailed standards for crop yields and quality (including size, shape and other specific cosmetic characteristics), safety aspects and more;

- Timing of production, harvesting, handling and/or storage practices;
- Delivery/transport and packing method;
- Specific practices and inputs to meet desired yields (fertilizers, pesticides and other inputs).

In their relationships with buyers, producers must conform to these marketing requirements in order to receive payments for their crops, and to continue to be contracted as suppliers over time. At the same time, producers rarely have bargaining power to establish prices for their products. They often become subject to unfair pricing, and receive very low payments and gain little or no profit in comparison with buyers or other actors in the supply chain. Many farmers in these situations also become dependent on buyers for their income. In many cases, they are obligated to take loans and credit from their suppliers, or from banks that are linked to the buyers, in order to purchase the specific seeds, pesticides, fertilizers or other technologies that are required for the production of the crops required for commercial markets.

In addition, the companies that manufacture and sell the seeds, pesticides, and fertilizers generally work closely with the food buyers and extension agents to give instructions to farmers on the practices and inputs that must be used (Thrupp *et al.,* 1995; Conroy *et al.,* 1996). These initiatives that aim to increase export market opportunities are also directly linked with the policies and programmes of development agencies and are tied to the commercial interests of companies in Northern countries. For example, USAID has heavily supported policies and programmes in Latin America for 'non-traditional' exports, which refers to high-value specialty crops such as fruits and vegetables, rather than traditional exports of coffee, bananas and sugar cane (Thrupp *et al.,* 1995; Conroy *et al.,* 1996). The development agencies associated with these agro-export programmes generally have technical experts who also prescribe and endorse practices and standards that comply with the demands of importers and globalized commodity markets.

If producers do not meet the market demands of buyers in the supply chain, they seldom compete and retain their livelihoods in this competitive market. Farmers face penalties or lose contracts if specific practices are not used and qualities and demands are not achieved.

How do these trends pertain to agroecology and/or the use of other 'sustainable' farming practices? Many of the trends associated with commercial global market integration create constraints or barriers to farmers' adoption of agroecological principles and practices, because farmers must meet the market requirements of their buyers to:

- Use particular crop varieties/seeds that generally require monocultures, and rarely allow diverse varieties;
- Use prescribed inputs of particular pesticides and fertilizers that are required by buyers who want to assure the desired production outcomes (but are generally contrary to agroecology).

These obligations contradict with the basic principles of agroecology that emphasize diversity in crop varieties and farming systems, adaptation of crops to local geographical and ecological conditions, and the elimination (or major reduction) of chemical pesticides and fertilizers, in order to avoid ecological and economic problems in farming systems.

In these situations, farmers often become dependent on the use of pesticides and fertilizers that are expensive and often obligate them to take loans and become indebted, although they seldom receive training or adequate equipment for the use of these chemicals. Moreover, the agrochemicals often do not provide long-term effectiveness in pest control and can exacerbate

problems, because of inadequate application methods, resistance and resurgence of pests, residues that are found in the produce, and/or health and safety risks. In addition, the continual use of chemical fertilizers has contributed to long-term social and environmental costs from runoff and water contamination problems in some contexts.

These marketed commodity crops are also subject to high levels of competition, market instability, uncertainty of contracts, price volatility, vulnerability to price or demand fluctuations and specific requirements set by target markets (e.g. quality requirements of produce imported in the European Union). Such challenges are particularly evident in cases involving export production, as illustrated in the cases of snow peas in Guatemala and pineapples in Ghana (Thrupp *et al.,* 1998; Takane, 2004; Whitfield, 2010). In addition, the conditions and requirements surrounding these food production systems in formal markets have resulted in significant inequalities; smallholders and workers rarely secure lasting benefits. Moreover, as farmers become heavily reliant on the market demands and obligations required by their buyers, they typically lose control over their decisions and their livelihoods. As some farmers in Brazil have stated, they feel as though they are “hostages” or victims of the supply chain in which they are obligated to function (Vavra, 2009).

These challenges have been illustrated in global export markets for vegetables, fruits and more. From Guatemala to Peru to Ghana (snow peas to potatoes to pineapples), market demands required growers to use high-input conventional approaches (Thrupp *et al.*, 1995; Thrupp *et al.*, 1998). In cases in the United States of America, mainstream commodity markets for both major grain crops and specialty crops (e.g. wine grapes, almonds and fruits) typically pressure farmers to use standardized industrial practices and rarely allow for alternative crop varieties, practices and qualities. Some exceptions to these trends are evident in so-called ‘alternative agro-food system’ supply chains, including for example organic, ‘sustainably’ or ‘locally grown’ products, which are described in the section below.

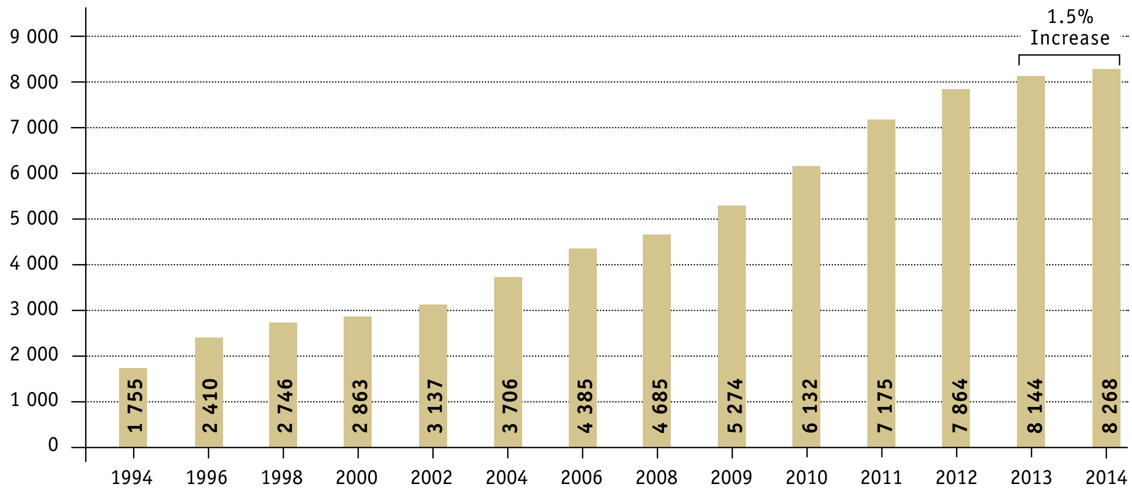
ALTERNATIVES: INNOVATIVE MARKET OPPORTUNITIES AND POLICY CHANGES

The growing efforts to introduce and support agroecological approaches in food systems are generally associated with NGOs, the activities of small-farmers groups, and some scientists working on alternative approaches. In a few cases, agroecology programmes are associated with international organizations or foundations, for example, CIPAV in Colombia (Murgueitio *et al.*, 2015), Naturaleza Viva in Argentina (Vénica and Kleiner, 2015), Songhai in Benin (Nzamujo, 2015) and ActionAid in Nepal (Marcatto and Tiwari, 2015). Many of these efforts are relatively small, isolated and lack cohesion (although this is changing with the increasing involvement of social movements), and are rarely connected to market demands or conditions. They often face barriers for wider adoption, and in fact, may be thwarted by the mainstream and predominant market pressures and consolidation trends, as described above.

At the same time, some efforts have attempted to address these challenges through market changes, such as developing alternative food system markets that aim to support ecologically and socially responsible production practices, through direct marketing and shortening supply chains for farmers, especially among smaller-scale landholders. These initiatives often aim to connect producers more directly to buyers and consumers. They also generally encourage the reduction of chemical inputs in the production stage and promote more diversity in farming systems (Goodman, 2004). Such approaches are more likely to be supportive of agroecological practices, including their ecological, social and political components (Goodman, 1999). There has been growing interest and demand from consumers for agricultural produce that has particular quality characteristics – and some suggest that among the most sought after are an indication that the product has been produced locally or fairly traded (Goodman, 2004; Roseland and Soots, 2007).

Several examples exist of efforts to shorten the food chain and directly link producers to consumers. Farmers' markets, where agricultural producers coming from surrounding areas gather to sell their produce, often highlight the diversity of products and provide fresher and more nutritious food to local communities. While the trade of food from farms to nearby urban areas is a long-standing practice, the phenomenon has been growing in recent years (see Figure 3). Community supported agriculture schemes offer farmers the possibility of linking to the local community for mutual support[3]. Similarly, food aggregation hubs allow smaller producers to group together and gain access to resources (e.g. processing and distribution infrastructure) that would not be available to single individuals (USDA, 2012).

Figure 3. **National count of farmers' markets directory listings in the United States of America**



Farmers' market information is voluntary and self-reported to USDA.

Source: USDA, 2014

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[3] See: www.nal.usda.gov/afsic/pubs/csa/csadef.shtml

There has also been a great increase in urban agriculture efforts worldwide (FAO, 2015). Many of these programmes involve agroecological approaches, and are located in lower-income urban areas, involving diverse groups in an effort to respond to food access and justice needs. One of the most notable examples of a country where urban agroecological farming is practised on a large scale is Cuba, where for several decades food production in urban and peri-urban areas has been carried out according to agroecological principles, including soil organic matter management and composting, integrated pest management techniques for pest control and water saving drip irrigation practices (FAO, 2014; Colozza and Choptiany, 2015). Several other examples exist of agroecological practices applied in urban and peri-urban areas worldwide as documented in Africa (FAO, 2012), and Latin America and the Caribbean (FAO, 2014).

In addition, there are many alternative agriculture certification programmes that have been introduced into the supply chain in recent years, generally aiming to encourage ecologically and/or socially responsible approaches in food production and markets. The most renowned and widespread approach to set standards to food products through certification schemes is Organic Agriculture[4] – a method of production based on the four principles of health, ecology, fairness and care (IFOAM, 2015). In the last 20 years, Organic Agriculture has been formalized in food systems globally, under standards that are usually defined by government bodies[5] (Bruinsma, 2003). There are other newer certification programmes related to sustainability in farming, which can be defined in different ways. Some of these programmes include agroecological elements. Some certification programmes have been designed for specific products, such as bananas, coffee, cacao and wine, and have been developed by corporations or corporate groups. Examples include the Food Alliance[6], Rain Forest Alliance[7], Bird Friendly Coffee[8] and Coffee and Farmer Equity (C.A.F.E.)[9]. These certification schemes are often designed by buyers and aim to meet the demands of consumers who want to promote alternative production practices that are more environmentally responsible. Other certification programmes, such as various fair trade certifications[10], or the Equitable Food Initiative (EFI)[11], also address social responsibility

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[4] For a definition of Organic Agriculture see the standard used by the International Federation of Organic Agriculture Movements (IFOAM): www.ifoam.bio/en/organic-landmarks/definition-organic-agriculture

[5] For example, see the National Organic Program managed by the United States Department of Agriculture (www.ams.usda.gov/AMSv1.0/nop) and the organic certification standards set by the European Union (www.ec.europa.eu/agriculture/organic/).

[6] See: http://foodalliance.org/

[7] See: www.rainforest-alliance.org/

[8] See: http://nationalzoo.si.edu/scbi/migratorybirds/coffee/

[9] See: www.starbucks.co.uk/responsibility/sourcing/coffee

[10] Such as the scheme promoted by Fair Trade International (www.fairtrade.net/) to certify specific products (e.g. coffee, bananas); and the scheme promoted by the World Fair Trade Organization (www.wfto.com) that certifies organizations that work in agricultural and non-agricultural sectors respecting specific fair trade standards.

[11] See: www.equitablefood.org

aspects, ranging from fairness in pricing for producers to adequate wages, safety and health of labourers in the food system (Mohan, 2010). Many of these schemes also include efforts to provide higher prices for farmers who use practices that are beneficial (or at least less degrading) for the environment and human resources.

While certifications and standards for agricultural products may have direct benefits for smallholders, there is a rising concern that, as they grow in scale, many of these alternative agri-food networks start following the path of industrial agricultural systems. In the case of organic agriculture, for example, the growing demand for certified products has promoted the expansion of large-scale monocultures that, while employing smaller quantities of chemical inputs, at times largely resemble conventional intensive monocropping systems in terms of ecosystem diversity (Kremen *et al.,* 2012).

In light of this, promoting agroecological approaches that extend beyond certification systems and take into account social and economic dynamics alongside ecological considerations could represent a further step towards scaling up sustainable agricultural practices and linking these to markets. Efforts that work towards this goal and that can help confront the pressures of the predominant food market systems that are already in place, including for example, cooperative strategies and agroecological movements among smallholder farmers. La Via Campesina and other farmers networks are among those that have helped to build momentum to defend the livelihoods and rights of smallholder farmers (Pimbert, 2009). These organizations and networks are attempting to defend themselves against the imposition of globalized market standards that seldom meet their interests.

Such efforts need to be strengthened in order to gain more value in the overall food system. Current programmes related to agroecology generally oppose or avoid engagement with market considerations, and largely rely on NGOs and support from foundations and/or international agencies. Although this is understandable, because markets have seldom served their interests, these issues regarding global supply chains and market power simply cannot be ignored, dismissed or avoided if alternative sustainable, agroecological and equitable alternatives are to be achieved.

CONCLUSION

While attention to agroecological practices is increasing at both the policy level and in practical implementation, for the movement to grow in scale and be able to increase its impact, several points still need to be addressed and reinforced. Alternative market systems, including organic and locally produced food supply chains that benefit smallholders by linking them more directly to markets, while contributing to food security, should be further strengthened. On the other hand, support to chemical-intensive agriculture should be reduced, and resources gathered this way should be redirected to promoting sustainable, agroecologically sound farming systems, alternative supply chains and markets, and participatory farmer-centred approaches to research and development on agroecology. Credit and insurance systems should be reshaped in order to recognize the value of agroecological approaches.

On the policy side, it is also important for groups working on agroecological approaches to gain strength through partnerships and strategic collaboration across regions and national borders. The movement for change can potentially be empowered through collaborations and cooperation. This also includes alliances with organizations and efforts that are aiming to increase economic opportunities and equity for smallholder farmers in general. This is already happening to some extent through La Via Campesina and other networks that are organizing and advocating for change among smallholders. While there are still thousands of farmers and landless people, including farm workers, who are not yet involved in efforts for change, these people constitute key stakeholders for building alliances and efforts that can effectively reshape food systems through greater support to agroecology and justice in food systems.

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15

AGROECOLOGY:
DESIGNING CLIMATE CHANGE RESILIENT SMALL FARMING SYSTEMS IN THE DEVELOPING WORLD

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Abstract

It is anticipated that climate change will have various impacts on agricultural production, through an increase in global surface temperatures, with subsequent consequences on precipitation frequency and amounts. Small farmers are expected to be the most affected by climate change, suffering significant agricultural production losses. Adaptation is considered a key factor that will shape the future severity of climate change impacts on food production. Fortunately, many traditional farming systems still persist in the developing world and these constitute repositories of a wealth of principles and measures that if effectively disseminated, can help thousands of small farmers become more resilient to climatic extremes. Understanding the agroecological features that underlie the resilience of traditional agro-ecosystems is critical, as these can serve as the foundation for the design of adapted agricultural systems. Agroecological strategies used by traditional farmers that reduce vulnerabilities to climate variability include: crop diversification, maintaining local genetic diversity, animal integration, soil organic management, water conservation and harvesting, etc. Observations of agricultural performance after extreme climatic events (hurricanes and droughts) in the last two decades have revealed that resiliency to climate disasters is closely linked to farms with increased levels of biodiversity. Field surveys and results reported in the literature suggest that agro-ecosystems are more resilient when they form part of a complex landscape matrix, featuring adapted local germplasm deployed in diversified cropping systems, managed with soils rich in organic matter, and water conservation and harvesting techniques. The identification of systems that have withstood climatic events recently or in the past, and understanding the agroecological features that allowed these systems to persist and/or recover from extreme events is an urgent step. The resiliency principles and practices that underlie successful farms can be disseminated to thousands of farmers via *campesino-a-campesino* (farmer-to-farmer) networks to scale up agroecological practices that enhance the resiliency of agro-ecosystems. Even biodiverse agro-ecosystems may be threatened in the long run by climate change if they are not undergoing a constant adaptation – or even transformation – process. Therefore, adapting local agrobiodiversity, managed with agroecological practices, will be required on a continual basis to confront the threat of future climatic changes.

INTRODUCTION

Most scientists agree that climate change and variability will impact food and fibre production around the world because of the effects on plant growth and yield caused by elevated CO_2, higher temperatures, altered precipitation and transpiration regimes, increased frequency of extreme events, and modified weed, pest and pathogen pressure (IPPC, 2014). Many modelling studies suggest that an increased frequency of crop loss among small farmers in the developing world will occur because of climatic variability and the increased frequency of extreme events such as droughts and floods, or changes in precipitation and temperature variance (see Figure 1) (Rosenzweig and Hillel, 2008). Although it is true that extreme climatic events can severely impact small farmers, the available data only provides a gross approximation that lumps all small farmers together. This ignores the heterogeneity of small-scale agriculture and does not disaggregate on the basis of those applying agroecological practices versus those applying conventional practices. Perhaps the most relevant aspect of the relationships between climate change and peasant agriculture is the realization that many small farmers cope with and even prepare for climate change, minimizing crop failure through increased use of drought tolerant local varieties, water harvesting, mixed cropping, agroforestry, soil conservation practices and a series of other traditional techniques (Altieri and Koohafkan, 2008).

Observations of agricultural performance after extreme climatic events in the last two decades have revealed that resiliency to climate disasters is closely linked to the level of crop and genetic diversity used by farmers. Managing risk exposure is an important preoccupation of

Figure 1. **Droughts will severely affect the production of dry farmed crops, such as this maize (*maíz de temporal*) in the Mixteca Region of Mexico**

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agricultural households in marginal environments; it is the only insurance mechanism available to these farmers, derived from the use of inventive self-reliance, experiential knowledge, and locally available resources including on-farm biodiversity (Altieri, 2002). Many traditional farmers achieve durable benefits by using agroecological measures including the diversification of agro-ecosystems in the form of polycultures, agroforestry systems and mixed crop-livestock systems accompanied by organic soil management, water conservation and harvesting, and the general enhancement of agrobiodiversity. In this chapter we contend that understanding the agroecological features that underlie the resilience of traditional agro-ecosystems is an urgent matter, as these can serve as the foundation for the design of adapted agricultural systems. What is needed is an agroecological transformation of small farms by favouring field diversity and landscape heterogeneity – a strategy that represents a robust path to increasing the productivity, sustainability and resilience of agricultural production while reducing the undesirable socio-economic and environmental impacts of climate change (Altieri, 2002; De Schutter, 2010).

TRADITIONAL FARMING SYSTEMS AS MODELS OF RESILIENCE

Many traditional farming systems, which still persist in many developing countries, offer a wide array of management options and designs that enhance functional biodiversity in crop fields, and consequently support the resilience of agro-ecosystems (Toledo and Barrera-Bassols, 2008; Koohafkan and Altieri, 2010). In continuously coping with extreme weather events and climatic variability for centuries, farmers living in harsh environments in Africa, Asia and Latin America have developed and/or inherited complex farming systems managed in ingenious ways. These systems have allowed small farming families to meet their subsistence needs in the midst of environmental variability without depending on modern agricultural technologies (Denevan, 1995). The continued existence of millions of hectares under traditional farming is living proof of a successful indigenous agricultural strategy, which is a tribute to the “creativity” of small farmers throughout the developing world (Wilken, 1987).

One manifestation of this creativity is the thousands of hectares of raised bed cultivation systems on seasonally flooded lands in savannahs and in highland basins of Surinam, Venezuela, Colombia, Ecuador, Peru and Bolivia. The origin and use of these systems has traditionally been associated with water management issues, either by providing opportunities to reduce the adverse impact of excess water on crop production, or to actively harvest excess water and irrigate crops in times of rainfall scarcity. Another example is the instances of farming in wetlands subjected to temporal flooding, known as the *chinampas* in the Valley of Mexico (Armillas, 1971) and the *waru warus* found near Lake Titicaca in Peru and Bolivia (Erickson and Chandler, 1989).

Today, well into the twenty-first century, millions of smallholders, family farmers and indigenous people continue to practise resource-conserving farming. This is testament to the remarkable resilience of agro-ecosystems to continuous environmental and economic change, while contributing substantially to agrobiodiversity conservation and food security at local, regional and national levels (Netting, 1993). A review of 172 case studies and project reports from around the world shows that agricultural biodiversity as used by traditional farmers contributes to resilience through a number of, often combined, strategies: the protection and restoration of ecosystems, the sustainable use of soil and water resources, agroforestry, diversification of farming systems, various adjustments in cultivation practices, and the use of stress-tolerant crops and crop improvement (Mijatović *et al.*, 2013).

Despite the resilience of traditional agriculture, climate change poses serious challenges to about 370 million of the poorest farmers, who live in areas often located in arid or semi-arid zones, and in ecologically vulnerable mountains and hills (Thornton, 2003). In many countries, more and more people, particularly those at lower income levels, are now forced to live in marginal areas (i.e. floodplains, exposed hillsides, arid or semi-arid lands), where they are at risk from the negative impacts of climate variability. Even minor changes in climate can have disastrous impacts on the lives and livelihoods of these vulnerable groups. The implications for food security could be very profound, especially for subsistence farmers living in remote and fragile environments that traditionally produce very low yields. These farmers depend on crops that could be dramatically affected, such as maize, beans, potatoes and rice, and have little room to adapt to even lower yields.

Despite the serious implications of model predictions, these data represent a broad brush approximation of the effects of climate change on small-scale agriculture; in many cases ignoring the adaptive capacity of small farmers who use several agroecological strategies and socially mediated solidarity networks to cope with and even prepare for extreme climatic variability (Altieri and Koohafkan, 2008). Data reporting the predicted impacts of extreme weather on small farmers lumps all small farmers together and does not disaggregate on the basis of those applying agroecological practices versus those using conventional methods. Many researchers have found that despite their high exposure sensitivity, indigenous peoples and local communities are actively responding to changing climatic conditions and have demonstrated their resourcefulness and resilience in the face of climate change. Strategies such as maintaining genetic and species diversity in fields and herds provide a low-risk buffer in uncertain weather environments (Altieri and Nicholls, 2013). By creating diversity temporally as well as spatially, traditional farmers add even greater functional diversity and resilience to systems with sensitivity to temporal fluctuations in climate (Perfecto *et al.*, 2009).

A multi-country study that explored resilience of African smallholder farming systems to climate variability and change between 2007 and 2010, revealed farmers priorities for strategies to adapt to climate change: (i) improving soil fertility with green manures and organic residues; (ii) conserving water and soil; (iii) developing mechanisms for establishment and sustenance of local strategic food reserves; (iv) supporting traditional social safety nets to safeguard vulnerable social groups; (v) conservation of indigenous fruit trees and other locally adapted crop varieties; (vi) use of alternative fallow and tillage practices to address climate change-related moisture and nutrient deficiencies; and (vii) changing land topography to address the moisture deficiencies associated with climate change and reduce the risk of farm land degradation (Mapfumo *et al.*, 2013).

BIODIVERSITY AND RESILIENCY IN AGRO-ECOSYSTEMS

In agricultural systems, the level of existing biodiversity can make the difference between the system being stressed or resilient when confronting a biotic or abiotic perturbation. In all agro-ecosystems a diversity of organisms are required for ecosystem function and to provide ecosystem services (Altieri and Nicholls, 2004). When agro-ecosystems are simplified, whole functional groups of species are removed, shifting the balance of the system from a desired to a less desired state, affecting the capacity to respond to changes and to generate ecosystem services (Folke, 2006). Two categories of diversity can be distinguished in agro-ecosystems: functional and response diversity. Functional diversity refers to the variety of organisms and the ecosystem services they provide for the system to continue performing (Loreau *et al.*, 2001). Response diversity is the diversity of responses to environmental change among species that contribute to the same ecosystem function. An agro-ecosystem that contains a high degree of response diversity will be more resilient against various types and degrees of shocks (Cabell and Oelofse, 2012).

Biodiversity enhances ecosystem function because different species or genotypes perform slightly different functions and therefore have different niches (Vandermeer *et al.*, 1998). In general there are many more species than there are functions and thus redundancy is built into the agro-ecosystem. Therefore, biodiversity enhances ecosystem function because those components that appear redundant at one point in time become important when some environmental change occurs. The key is that when environmental change occurs, the redundancies of the system allow for continued ecosystem functioning and provisioning of ecosystem services. On the other hand, a diversity of species acts as a buffer against failure caused by environmental fluctuations by enhancing the compensation capacity of the agro-ecosystem. If one species fails, others can play their role, thus leading to more predictable aggregate community responses or ecosystem properties (Lin, 2011).

Given the positive role of biodiversity in providing stability to agro-ecosystems, many researchers have argued that enhancing crop diversity will be even more important in a future exhibiting dramatic climatic swings. Greater agro-ecosystem diversity may buffer against shifting rainfall and temperature patterns and possibly reverse downward trends in yields over the long term as a range of crops and varieties respond differently to such shocks (Altieri and Koohafkan, 2013).

ENHANCING AGROBIODIVERSITY TO REDUCE VULNERABILITY

For decades agroecologists have advocated that a key strategy in designing a sustainable agriculture is to reincorporate diversity into agricultural fields and surrounding landscapes and manage it more effectively (Altieri and Nicholls, 2004). Diversification occurs in many forms: genetic variety and species diversity (e.g. variety mixtures and polycultures), and over different scales at field and landscape level (agroforestry, crop-livestock integration, hedgerows, corridors, etc.), giving farmers a wide variety of options and combinations for the implementation of this strategy. Emergent ecological properties develop in diversified agro-ecosystems that allow the system to function in ways that maintain soil fertility, crop production and pest regulation. There are many agroecological management practices that increase agro-ecosystem diversity and complexity as the foundation for soil quality, plant health and crop productivity. Many entomologists and plant pathologists contend that inter- (species) and intra- (genetic) specific diversity reduces crop vulnerability to specific diseases and insect pests. There is a vast body of literature documenting the pattern that in diverse cropping systems (variety mixtures, polycultures, agroforestry systems, etc.) there is less insect pest incidence and lower rates of disease development, leading to less crop damage and higher yields in mixed crops as compared with corresponding monocultures (Francis, 1986; Altieri, 2002).

Swiderska *et al.* (2011) found that maintenance of diverse traditional crop varieties (maize, potatoes, rice) and access to seeds was essential for the adaptation and survival of poor farmers in China, Bolivia and Kenya. Even when planted alongside modern crops, traditional crop varieties are still conserved, providing a contingency when conditions are not favourable (Figure 2). For example, in China, when farmers from fifteen different townships grew four different mixtures of rice varieties over 3 000 ha, their crops suffered 44 percent less blast incidence and exhibited 89 percent greater yield than homogeneous fields, without the need to use fungicides (Zhu *et al.*, 2000). Maintaining species diversity in fields acts as a buffer against insect pests and also against uncertain weather. In Kenya, scientists at the International Centre of Insect Physiology and Ecology (ICIPE) developed a push-pull system using two kinds of

Figure 2. **Maintenance and deployment of traditional varieties managed with traditional technologies buffers against climatic risk**

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Many farmers in the Mixteca Alta of Mexico still use the *maíz de cajete*, which is more resistant to drought events than *maíz de temporal*. This maize is planted at a certain soil depth that exhibits enough moisture for the maize to emerge without rainfall and produce reasonable subsistence yields (Rogé *et al.*, 2014).

crops that are planted together with maize: a plant that repels borer pests (‘push’) and another that attracts (‘pull’) them away from the crop (Khan *et al.*, 1998). Two of the most useful trap crops are Napier grass and Sudan grass (planted in a border around the maize). These plants attract the borers’ natural enemies such as the parasitic wasp (*Cotesia sesamiae*), and are also important sources of fodder. Two excellent borer-repelling crops (planted between the rows of maize) are molasses grass, which also repels ticks, and the leguminous silverleaf desmodium (*Desmodium uncinatum*), which also increases suppression of the parasitic weed *Striga* by a factor of 40 compared with maize monocrop. The nitrogen-fixing ability of *Desmodium* spp. increases soil fertility leading to a 15-20 percent increase in maize yield. It is also an excellent source of forage (Khan *et al.*, 1998).

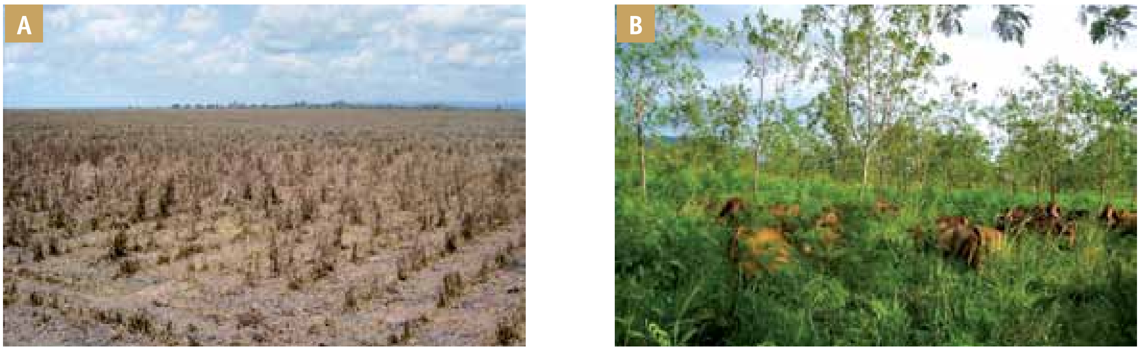
Plant diversity and resiliency

Diversified farming systems such as agroforestry, silvopastoral and polycultural systems provide a variety of examples of how complex agro-ecosystems are able to adapt and resist the effects of climate change. Agroforestry systems are examples of agricultural systems with high structural complexity that have been shown to buffer crops from large fluctuations in temperature, thereby keeping the crop closer to its optimum conditions (Lin, 2011). More shaded coffee systems have been shown to protect crops from decreasing precipitation and reduced soil water availability as the overstory tree cover is able to reduce soil evaporation and increase soil water infiltration (Lin, 2007).

Intercropping enables farmers to produce various crops simultaneously and minimize risk (Vandermeer, 1989). Polycultures exhibit greater yield stability and lower productivity declines during drought than in the case of monocultures. Natarajan and Willey (1986) examined the effects of drought on yields in polycultures by manipulating water stress on intercrops of sorghum and peanut, millet and peanut, and sorghum and millet. All of the intercrops over-yielded consistently at five levels of moisture availability, ranging from 297 to 584 mm of water applied over the cropping season. Quite interestingly, the rate of over-yielding actually increased with water stress, and the relative differences in productivity between monocultures and polycultures became more accentuated as stress increased (Natarajan and Willey, 1986).

Intensive silvopastoral systems (iSPS) are a sustainable form of agroforestry for livestock production that combines fodder shrubs planted at high densities, trees and palms, and improved pastures. High stocking and the natural production of milk and meat in these systems are achieved through rotational grazing with electric fencing and a permanent supply of water for the cattle. At the El Hatico farm in the Valle del Cauca, Colombia, a five story iSPS composed of a layer of grasses, *Leucaena* shrubs, medium-sized trees and a canopy of large trees have enabled increases in stocking rates to 4.3 dairy cows ha^{-1} and increased milk production by 130 percent, alongside the complete elimination of the use of chemical fertilizers over the last 18 years. 2009 was the driest year in El Hatico’s 40-year record with 44 percent less precipitation compared with the historical average. Despite a reduction of 25 percent in pasture biomass, the fodder production of trees and shrubs remained constant throughout the year, neutralizing the negative effects of drought on the whole system. In response to the extreme weather, the farm had to adjust its stocking rates and increase energy supplementation. In spite of this, the farm's milk production for 2009 was the highest on record with a surprising 10 percent increase compared with the previous four years. Meanwhile, farmers in other parts of the country reported severe animal weight loss and high mortality rates because of starvation and thirst (Figure 3). The productive performance of El Hatico during the exceptionally hot and dry period of the El Niño Southern Oscillation illustrates the huge potential of iSPS as a sustainable intensification strategy for climate change adaptation and mitigation (Murgueitio *et al.*, 2011). The combined benefits of a favourable microclimate, and enhanced water regulation, biodiversity and carbon stocks in these diversified farming systems not only provide environmental goods and services for producers but also greater resilience to climate change.

Figure 3. **Response of tropical pastoral systems to drought in Colombia**



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(A) Highly productive pastures in the tropics require water and nitrogen; therefore they are highly vulnerable to droughts as shown in this example from the Llanos Orientales in Colombia.

(B) In contrast, intensive silvopastoral systems with an overstory of shrubs and trees are resilient allowing for continual fodder availability for cows, which maintain stable levels of milk production despite low rainfall.

Performance of biodiverse agro-ecosystems under extreme climatic events

A survey conducted in Central American hillsides after Hurricane Mitch showed that farmers using diversification practices such as cover crops, intercropping and agroforestry suffered less damage than their neighbours cultivating conventional monocultures (Figure 4). The survey, spearheaded by the *campesino-a-campesino* movement, mobilized 100 farmer-technician teams to carry out paired observations of specific agroecological indicators on 1 804 neighbouring sustainable and conventional farms. The study spanned 360 communities and 24 departments in Nicaragua, Honduras and Guatemala. It was found that sustainable plots had 20-40 percent more topsoil, greater soil moisture and less erosion, and experienced lower economic losses than their conventional neighbours (Holt-Giménez, 2002). Similarly, in Soconusco, Chiapas, coffee systems exhibiting high levels of vegetational complexity and plant diversity suffered less damage from Hurricane Stan than more simplified coffee systems (Philpott *et al.,* 2009). Forty days after Hurricane Ike hit Cuba in 2008, researchers conducted a farm survey in the Provinces of Holguin and Las Tunas and found that diversified farms exhibited losses of 50 percent compared with neighbouring monocultures that experienced 90 or even 100 percent losses (Figure 5). Likewise, agroecologically managed farms showed a faster productive recovery (80-90 percent recovery 40 days after the hurricane) than monoculture farms (Rosset *et al.*, 2011).

All the above studies emphasize the importance of enhancing plant diversity and complexity in farming systems to reduce vulnerability to extreme climatic events. These observations have bolstered a new recognition that biodiversity is integral to the maintenance of ecosystem functioning and point to the utility of crop diversification strategies used by traditional farmers as an important resilience strategy for agro-ecosystems (Altieri and Nicholls, 2013). By the

Figure 4. **Response of monocultures compared with biodiverse farms to hurricane damage in Honduras**

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(**A**) After Hurricane Mitch in Central America, Honduran farms under monoculture exhibited higher levels of damage in the form of mudslides; (**B**) Compared with neighbouring biodiverse farms featuring agroforestry systems, contour farming, cover crops, etc.

Figure 5. **A diversified farm in Sancti Spíritus, Cuba exhibiting crop–pasture rotations and a complex matrix of multiple purpose windbreaks and hedgerows that protect against the effects of hurricanes**

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end of the century, if global warming is not halted, even biodiverse agro-ecosystems may be threatened by climate change if they are not undergoing a continuous process of adaptation – or even transformation. In the long term, continual selection and adaptation of agrobiodiversity managed with agroecological methods will be required to confront future climatic conditions. Crop species used by farmers must be exposed to the environment, considering the wide agroecological variation in the different farming regions. Resistance of plants to environmental stress (e.g. drought tolerance) is mostly a multi-genetic characteristic best developed by *in situ* exposure to it. On the other hand, a careful analysis of future climate conditions is required when selecting crop or tree species to be used in diversified farming systems as some of the current species might not be adapted in the future and new varieties or even species may need to be introduced (Kotschi, 2007).

SOIL MANAGEMENT AND RESILIENCY

Enhancing soil organic matter

Many traditional and small organic farmers add large quantities of organic materials on a regular basis via animal manures, composts, tree leaves, cover crops and rotational crops that leave large amounts of residue, etc. This is a key strategy used to enhance soil quality. Soil organic matter (SOM) and its management are at the heart of creating healthy soils with high biological activity and good physical and chemical characteristics. Of utmost importance for resiliency is that SOM improves the soil's water retention capacity, enhancing the drought tolerance of crops, improving infiltration and diminishing runoff, so that soil particles are not transported with water during intense rains. SOM also improves surface soil aggregation, holding soil particles more securely during rain or windstorms; stable soil aggregates resist movement by wind or water (Magdoff and Weil, 2004).

Organically rich soils usually contain symbiotic mycorrhizal fungi, such as arbuscular mycorrhizal fungi (AMF), which form a key component of the microbial populations influencing plant growth and soil productivity. AMF are important in sustainable agriculture because they improve plant water relations and thus increase the drought resistance of host plants (Garg and Chandel, 2010). The abilities of specific fungus–plant associations to tolerate drought are of great interest in areas affected by water deficits as AMF infection has been reported to increase nutrient uptake in water-stressed plants, and to enable plants to use water more efficiently and to increase root hydraulic conductivity.

Crop productivity under dry land conditions is largely limited by soil water availability. SOM content (% SOM) is a reliable index of crop productivity in semi-arid regions because SOM aids the growth of crops by improving the soil's ability to store and transmit air and water, increasing the soil's water retention capacity, and thus enhancing the crop's drought resistance. In a study of the semi-arid Pampas of Argentina, researchers found that wheat yields were related to both soil water retention and total organic carbon contents in the top layers (0-20 cm) in years with low moisture availability. Dependence of wheat yields on soil water retention and on total organic carbon contents under water deficit conditions was related to the positive effect of these soil components on plant-available water. Losses of 1 Kg of SOM ha^{-1} were associated with a decrease in wheat yields of approximately 40 kg ha^{-1}. These results demonstrate the importance of using cultural practices that enhance SOM and thus minimize losses of soil organic carbon in semi-arid environments (Diaz-Zorita *et al.*, 1999).

Managing soil cover

Protecting the soil from erosion and drying up, and improving soil moisture levels and water circulation is also a fundamental strategy to enhance the resiliency of agro-ecosystems. Cover crop mulching and green manures offer great agroecological potential as such practices conserve soil, improve the soil ecology, stabilize and increase crop yields, and enhance water conservation. Stubble mulching disrupts the soil drying process by protecting the soil surface with residues. Mulching reduces the wind speed by up to 99 percent and, therefore, losses through evaporation are significantly reduced. In addition, cover crop and weed residues can improve water penetration and decrease water runoff losses by a factor of 2-6 times. The *fríjol tapado* or covered bean system is an ancient slash/mulch system common in the hillsides of Central America (Buckles *et al.*, 1998). This system of migratory agriculture allows 3-5 months of bean production in one year, taking advantage of the high precipitation and the residual moisture maintained by the slash/mulch after the rains. *Fríjol tapado* management consists of first selecting appropriate land and then slashing paths through the vegetation to create access for subsequent planting. This is followed by broadcasting at high rates (25-40 kg of seed ha^{-1}) and slashing of fallow vegetation over the bean seeds. *Fríjol tapado* is usually grown on hill sides, preferably facing the morning sun so that leaves and pods of the bean plants dry quickly in the morning (they are susceptible to rot diseases) and the plants receive maximum sunlight, as mornings are often sunny and rain usually falls in the afternoon. Farmers look for land with a cover of tall herbs or low shrubs; there must be enough plant material to provide a mulch which can completely cover the soil. Areas dominated by grasses are avoided as they regrow quickly and compete strongly with the beans. The fields are then left untouched until harvest. Typically, the mulch is not too thick – as this would result in low bean germination and survival, and therefore low yields – while still maintaining soil moisture and protecting the soil against erosion. The absence of burning and cultivation, and the presence of thick mulch, prevents the germination and growth of weeds. The fallow period reduces the pathogens in the soil, and the mulch protects the bean plants from soil particle splash during rains. The system is adapted to fragile slope ecosystems. The soil is not disturbed by cultivation and the mulch protects it from erosion. Moreover, the natural root system is left intact and the vegetation's fast regrowth further reduces the risk of erosion and restores soil fertility (Buckles *et al.*, 1998).

In an effort to emulate and improve the *fríjol tapado* system throughout Central America, several NGOs have promoted the use of grain legumes for green manure, as an inexpensive source of organic fertilizer to build up organic matter (Altieri, 1999). Hundreds of farmers in the northern coast region of Honduras are using velvet bean (*Mucuna pruriens*) with excellent results, including corn yields of about 3 000 kg ha^{-1}, more than double the national average, along with the additional benefits of erosion control, weed suppression and reduced land preparation costs. Velvet beans produce nearly 30 tonnes ha^{-1} of biomass per year, or about 90-100 kg N ha^{-1} $year^{-1}$

(Flores, 1989). The system diminishes drought stress because the mulch layer left by *Mucuna* helps conserve water in the soil profile, making nutrients readily available in synchrony with periods of major crop uptake (Bunch, 1990).

Taking advantage of well-established farmer-to-farmer networks such as the *campesino-a-campesino* movement in Nicaragua and elsewhere, the spread of this simple technology has occurred rapidly. In just one year, more than 1 000 peasants recovered degraded land in the Nicaraguan San Juan watershed (Holt-Giménez, 1996). In Cantarranas, Honduras, the massive adoption of velvet bean tripled maize yields to 2 500 kg ha^{-1}, while labour requirements for weeding were cut by 75 percent. In Central America and Mexico, an estimated 200 000 farmers are using some 14 different species of green manure and cover crops (Bunch, 1990).

Today, well over 125 000 farmers are using green manure and cover crops in Santa Catarina, Brazil. Hillside family farmers modified the conventional no-till system by initially leaving plant residues on the soil surface. They first observed reductions in soil erosion and lower fluctuations in soil moisture and temperature, and later, that repeated applications of fresh biomass improved soil quality, minimized erosion and weed growth, and improved crop performance. These novel systems rely on mixtures for both summer and winter cover cropping, leaving a thick residue mulch layer on the soil. After the cover crops are rolled, traditional grain crops (corn, beans, wheat, onions, tomatoes, etc.) are directly sowed or planted in the mulch, suffering very little weed interference during the growing season and reaching agronomically acceptable yield levels (Petersen *et al.*, 1999). During the 2008-2009 agricultural cycle, which experienced a severe drought, conventional maize producers exhibited an average yield loss of 50 percent, reaching productivity levels of 4 500 kg ha^{-1}. However, the producers who had switched to no-till agroecological practices experienced smaller losses of around 20 percent, confirming the greater resilience of these systems compared with those using agrochemicals (Altieri *et al.*, 2011).

WATER HARVESTING

In many parts of the world, such as in sub-Saharan Africa, 40 percent of the farmland is located in semi-arid and dry sub-humid savannahs that are increasingly subjected to frequent occurrences of water scarcity. In most years there is more than enough water to potentially produce crops. The problem is that rainfall is concentrated in 2-3 months of the year and/or large volumes of water are lost through surface runoff, soil evaporation and deep percolation. The challenge is how to capture that water, store it in the soil and make it available to crops during times of scarcity. A variety of rainwater harvesting and floodwater harvesting techniques have been recorded in much of the developing world (Reij *et al.*, 1996; Barrow, 1999).

An old water harvesting system known as *zaï* is being revived in Mali and Burkina Faso. The *zaï* are pits that farmers dig in often rock-hard barren land, into which water otherwise could not penetrate. The holes are typically 10-15 cm deep and 20-30 cm in diameter and are filled with organic matter (Zougmoré *et al.*, 2004). The application of manure in the pits further enhances growing conditions and simultaneously attracts soil-improving termites, which dig channels and thus improve soil structure so that more water can infiltrate and be held in the soil. By digesting the organic matter, the termites make nutrients more easily available to plants. In most cases farmers grow millet or sorghum or both in the *zaï*. At times the farmers sow trees directly together with the cereals in the same *zaï*. Farmers use anywhere from 9 000 to 18 000 pits ha^{-1}, with compost applications ranging from 5.6 to 11 tonnes ha^{-1} (Critchley *et al.*, 2004).

Over the years, thousands of farmers in the Yatenga region of Burkina Faso have used this locally improved technique to reclaim hundreds of hectares of degraded lands. Farmers have become increasingly interested in the *zaï* as they observe that the pits efficiently collect and concentrate runoff water and function with small quantities of manure and compost. The use of *zaï* allows farmers to expand their resource base and to increase household security (Reij, 1991). Yields obtained on fields managed with *zaï* are consistently higher (ranging from 870 to 1 590 kg ha^{-1}) than those obtained on fields without *zaï* (averaging 500-800 kg ha^{-1}).

In Niger, traditional planting pits were improved by making them into water collecting reservoirs imitating part of a soil improvement technology traditionally used in other parts of the country and in Burkina Faso. It has been reported that villages in Burkina Faso that adopted land reclamation techniques, such as this approach of pitting through crusted soils and then filling the pits with manure and water, have seen crop yields rise by 60 percent. In contrast, villages that did not adopt these techniques realized much smaller gains in crop yields under rainfall increases (Critchley, 1989). In north Nigeria, small pits in sandy soil are filled with manure for keeping transplanted tree seedlings wet after the first rains.

A CONCEPTUAL FRAMEWORK TO ASSESS THE RESILIENCY OF FARMING SYSTEMS

Resilience is defined as the ability of a social or ecological system to absorb disturbances while retaining its organizational structure and productivity, the capacity for self-organization, and the ability to adapt to stress and change following a perturbation (Cabell and Oelofse, 2012). Resilience is a product of the dynamics of a social-ecological system, whose constituent parts are integrated and interdependent (Adger, 2000). Resilience can be understood as the propensity of a system to retain its organizational structure and productivity following a perturbation. Thus, a ‘resilient’ agro-ecosystem would be capable of providing food production when challenged by severe drought or by excess rainfall. Conversely, vulnerability can be defined as the possibility of loss of biodiversity, soil, water or productivity by an agro-ecosystem when confronted with an external perturbation or shock. Vulnerability refers to the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate variability and extremes. It denotes a state of susceptibility to harm from exposure to stresses associated with environmental change and from the absence of the capacity to adapt (Folke, 2006).

Thus, the resulting risk is derived from threat, vulnerability and response capacity as described in the following equation (Nicholls and Altieri, 2013):

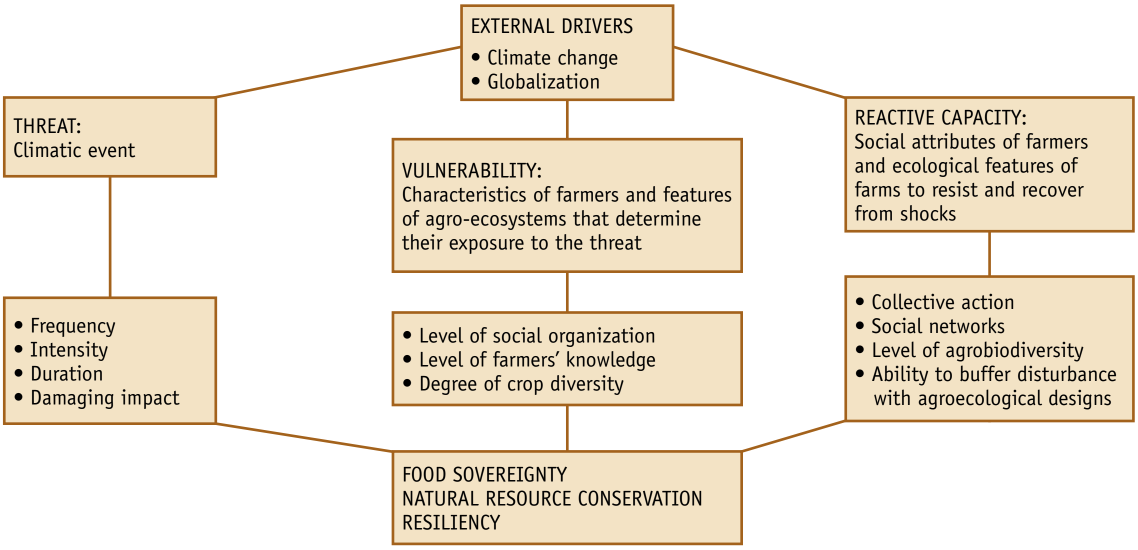
$$\textbf{Risk} = \frac{\textbf{Vulnerability * Threat}}{\textbf{Response capacity}}$$

- ***Risk*** is understood as the probability of experiencing a certain level of (negative) impact by a climatic phenomenon by the system being considered.

- ***Vulnerability*** is determined by biophysical features of the farm and socio-economic conditions the farmers that enhance or reduce the exposure to the threat.
- ***Threat*** is the climatic event's intensity, frequency, duration and level of impact (i.e. yield losses caused by storm or drought).
- ***Response capacity*** is the ability (or lack of) of farming systems and farmers to resist and recover from the threat depending on the level of social organization and the agroecological features (i.e. crop diversity) of the farms.

In summary, for an event to be considered a risk, depends on whether in a particular region there is a community that is vulnerable to it. In order for the event to become a threat, there should be a high probability that it will occur in that region, and for the threat to be devastating will depend on the magnitude of the event and the level of exposure and vulnerability of the community. Such vulnerability can be reduced by the 'response capacity', defined as the agroecological features of the farms and the management strategies used by farmers to reduce climatic risks and to resist and recover from such events. Therefore, adaptation refers to the adjustments made by farmers to reduce risks. The capacity of farmers to adapt is based on the individual or collective reserves of human and social capital that include attributes such as traditional knowledge and skills, levels of social organization and safety networks, etc. As observed in Figure 6, the level of vulnerability of a farm is determined by its type of agroecological infrastructure (level of landscape, crop and genetic diversity, soil quality and cover, etc.) and social traits of the family or community (levels of organization and networking, food self-sufficiency, etc.). The vulnerability can be reduced by the capacity of response of the farmers and their farms, which in turn determines their ability to resist events and recover function and infrastructure.

Figure 6. **Socio-ecological features that determine the vulnerability and reactive capacity of farmers to enhance the resiliency of their systems and communities**



Source: Nicholls *et al.*, 2013

METHODOLOGICAL ATTEMPTS TO ASSESS RESILIENCY

In 2011, a group of Latin American agroecologists associated with REDAGRES (Red Iberoamericana de Agroecología para el desarrollo de Sistemas Agrícolas Resilientes al Cambio Climático)[1] engaged in a two-year survey of small farming systems in selected regions of seven countries in order to identify systems that have withstood climatic events recently or in the past and to understand the agroecological features of these systems that allowed them to resist and/or recover from droughts, storms, floods or hurricanes. Identified principles and mechanisms that underlie resiliency were then transmitted to other farmers in the region via field days where farmers can visit the resilient farms and discuss among themselves the features of the farms that have enhanced resilience and how to replicate them in other farms. Cross visits were also organized where resilient farmers could visit other communities in other regions and share their experiences, management systems and socio-ecological resiliency strategies. Researchers and a group of selected farmers elaborated a manual containing two main sections: (i) a simple methodology with indicators that allows farmers to assess whether their farms can withstand a major climatic event (drought or hurricane) and what to do to enhance the resiliency on the farm; and (ii) a description of the main socio-ecological principles and practices that farming families can use individually or collectively (at the community level) to enhance the adaptability of the farming systems to climate change (Nicholls *et al.*, 2013).

Using the conceptual resiliency framework described above, the teams engaged in socio-ecological research in the selected farming systems in each country, and developed a methodology to understand the agroecological features of the farming systems and the social strategies used by farmers that allowed them to resist and/or recover from droughts, storms, floods or hurricanes (Nicholls and Altieri, 2013). To illustrate the application of the methodologies, data is presented from two case studies conducted in: (i) Carmen del Viboral, Antioquia, Colombia; and (ii) Mixteca Alta, Oaxaca, Mexico.

Carmen del Viboral

In this study researchers assessed the resiliency of six farms (three conventionally managed with agrochemicals and without soil conservation practices, and three agroecological, diversified farms with soil conservation practices) exhibiting similar slope and exposure conditions (Henao, 2013).

The team developed six indicators to estimate vulnerability (e.g. slope, landscape diversity, soil's susceptibility to erosion) and capacity of response (e.g. soil conservation practices, water management practices, crop diversity levels, food self-sufficiency) estimated on the three agroecological farms and the three conventional farms. By actually giving values (from 1 to 5, with values closer to 1 expressing a higher level of vulnerability) to these indicators it was possible to compare the farms in an amoeba diagram (Figure 7). Clearly, the agroecological farms (green) were less vulnerable than the conventional ones (red). The team also applied

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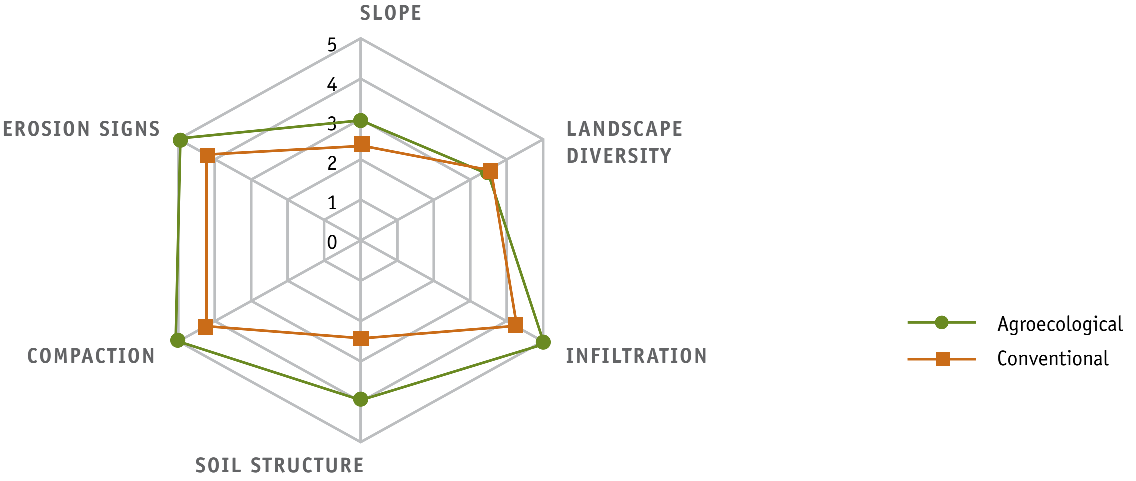
[1] http://www.redagres.org/

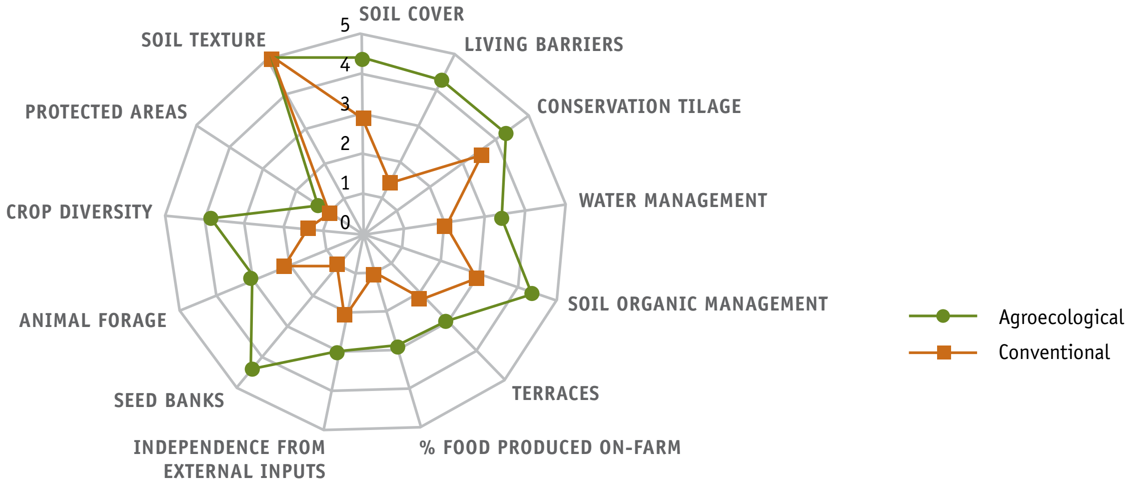
13 indicators to assess the capacity of response exhibited by the farmers, and again the agroecological farms (green) clearly exhibited higher response capacity than the conventional ones (red) (Figure 8). Applying the methodology and placing the risk values in a triangle, it is apparent that the agroecological farms (green dots in Figure 9) exhibited low vulnerability because of their high response capacity in relation to the conventional farms (orange dots in Figure 9), which exhibited higher vulnerability, and a lower response capacity.

Figure 7. **'Vulnerability' values of conventional (red) versus agroecological (green) farms in Antioquia, Colombia**



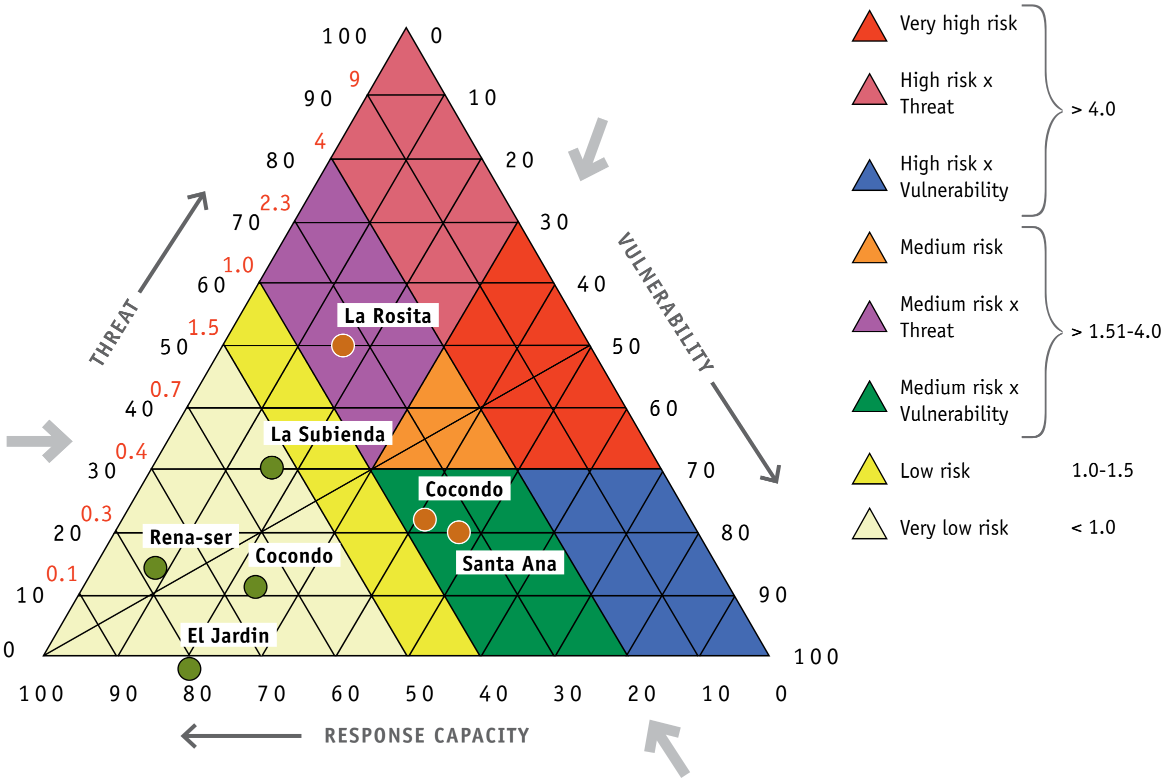
Source: Henao, 2013

Figure 8. **'Capacity of response' values of farmers managing conventional (red) versus agroecological (green) farms in Antioquia, Colombia**



Source: Henao, 2013

Figure 9. **A risk triangle showing the vulnerability and response capacity of agroecological (green dots) and conventional (orange dots) farms in Antioquia, Colombia**



Source: Henao, 2013

Mixteca Alta

This study conducted in Oaxaca, Mexico, describes how small farmers adapted to and prepared for past climate challenges, and also what are they doing to deal with recent increases in temperature and rainfall intensity, and later rainfall onset (Rogé *et al.*, 2014). Farmers identified 14 indicators to evaluate the adaptive capacity of four agro-ecosystems located in the Zaragoza and El Rosario communities using the template shown in Figure 10. Researchers pooled the agro-ecosystem evaluations within each community by assigning numerical scores of 0 for marginal, 1 for acceptable, and 2 for optimal. Farmers analysed outcomes by drawing bar plots of the pooled scores for their community. Farmers were prompted to analyse the results of their evaluations as a group by the following questions:

- How to obtain more happy faces (i.e. the optimal condition) in the landscape, farmer management, and soil quality categories?
- How to maintain the happy faces (i.e. optimal condition) that you already have in the landscape, farmer management, and soil quality categories?

At the landscape scale, Zaragoza farmers observed that vegetated borders and perennial vegetation with multiple uses mitigated exposure to extreme climatic events. Similarly, Coxcaltepec farmers recognized that heterogeneous and forested landscapes protected fields by bringing rain, retaining groundwater, accumulating soil organic matter and controlling insect pests. El Rosario participants observed that contour ditches capture soil and water, and that a slight slope to the contour ditches avoids flooding and breaching during heavy rainfall events.

Figure 10. **Forms used by farmers to evaluate four agro-ecosystems in each community of Zaragoza and El Rosario, based on the 14 locally derived indicators**

TEAM:________________________________ **COMMUNITY:**____________________________

PRODUCTION SYSTEM:____

CATEGORY	INDICATOR	MARGINAL	ACCEPTABLE	OPTIMAL
Landscape	Territorial composition			
	Windbreaks			
	Field location			
	Soil conservation			
Farmer management	Crop rotation			
	Crop varieties			
	Polyculture			
	Soil amendments			
	Soil cultivation			
Soil quality	Spontaneous plants			
	Soil productivity			
	Soil organic matter			
	Soil depth			
	Soil texture			

Source: Rogé *et al.*, 2014

Indicators of farmer management at the field scale included the importance of crop genetic and species diversity for stabilizing overall yields given the variation in crop performance from year-to-year. The indicator of “soil amendments” was derived from farmer testimonies that synthetic fertilizer only improved crop yields when rainfall was favourable; in drought years, synthetic fertilizer was ineffective and even “burned crops”. Coxcaltepec participants recommended substituting synthetic fertilizers with various locally derived soil amendments, including animal manures, worm castings, forest humus and human urine.

Soil quality was also observed by farmers to affect the impact of climatic variability on agro-ecosystems. The three communities associated soil moisture retention with soil texture and depth. Generally, clayey soils were described as the most productive in drought years, but also difficult to cultivate in wet years. In contrast, farmers described sandy soils as the easiest to cultivate in wet years but also the least productive. Farmers considered deep soils, measured by how far the Egyptian plough entered the soil, to be the most productive soils in both wet and dry years.

The resiliency evaluations conducted so far by the REDAGRES group suggest that agroecological strategies that enhance the ecological resiliency of farming systems are a necessary but not sufficient condition to achieve sustainability. The ability of groups or communities to adapt in the face of environmental stresses – which determines their social resilience – must go hand in hand with ecological resiliency. Although the REDAGRES studies have focused mainly on biophysical parameters, the group realizes that to be resilient, rural societies must generally demonstrate the ability to buffer disturbance with agroecological methods adopted and disseminated through self-organization and collective action. Reducing social vulnerability through the extension and consolidation of social networks, both locally and at regional scales, can contribute to increases in agro-ecosystem resilience. As expressed in the risk formula, the vulnerability of farming communities depends on how well-developed natural and social capital are, which in turn makes farmers and their systems more or less vulnerable to climatic shocks. Adaptive capacity refers to the set of social and agroecological preconditions that enable individuals or groups and their farms to respond to climate change in a resilient manner. The capacity to respond to changes in environmental conditions exists within communities to different degrees but it is not the case that all responses are sustainable. The challenge is to identify the ones that are sustainability, in order to scale these up so that vulnerability can be reduced. One effective way to enhance the reactive capacity of communities is to create mechanisms for the dissemination and deployment of agroecological practices that allow farmers to resist and recover from climatic events. Social organization strategies (solidarity networks, exchange of food, etc.) used collectively by farmers in order to cope with difficult circumstances imposed by such events are thus a key component of resiliency.

CONCLUSIONS

With certainty, some degree of climate change will have to be confronted by agricultural sectors across all countries, thereby rendering adaptation imperative. It is essential that steps are taken to support farmers and households engaged in agriculture to cope with both the threat of climate variability as well as the challenges that climate change will pose on future livelihood opportunities.

The launching of the Global Alliance for Climate Smart Agriculture[2] at the recent Climate Summit, held in New York during September 2014, recognizes the imperative of adaptation. However, the specific adaptation measures to be targeted remain unclear, and many messages from this process focus on sustainable improvements in productivity and building resilience through innovations such as identification and development of climate smart genes for crop improvement, with little attention to traditional farming or agroecologically based approaches.

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[2] http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/09/AGRICULTURE-Action-Plan.pdf

This is unfortunate given that traditional farming systems are repositories of a wealth of knowledge, including a range of principles and measures that can help modern agricultural systems become more resilient to climatic extremes (Altieri and Toledo, 2011). Many of these agroecological strategies (listed in Table 1) can be implemented at the farm level to reduce vulnerabilities to climate variability. The literature suggests that agro-ecosystems will be more resilient when inserted into a complex landscape matrix, featuring genetically heterogeneous and diversified cropping systems, managed with soils rich in organic matter and using water conservation techniques.

Table 1. **Agroecological practices and their potential to enhance resiliency to climatic stresses through various effects on soil quality and water conservation**

	SOIL ORGANIC BUILDUP	NUTRIENT CYCLING	INCREASE SOIL COVER	REDUCE EVAPO-TRANSPIRATION	RUN OFF REDUCTION	INCREASE WATER HOLDING CAPACITY	INCREASE INFILTRATION	MICROCLIMATIC AMELIORATON	REDUCE SOIL COMPACTION	REDUCE SOIL EROSION	INCREASE HYDROLOGICAL REGULATION	INCREASE WATER-USE EFFICIENCY	INCREASE MYCORRHIZAL NETWORK
DIVERSIFICATION													
Mixed or intecropping			✓	✓	✓			✓	✓	✓		✓	
Agroforestry	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Intensive silvopastoral systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Crop rotation	✓	✓	✓		✓		✓		✓	✓		✓	
Local variety mixtures			✓									✓	
SOIL MANAGEMENT													
Cover cropping	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Green manures	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓
Mulching													
Compost applications	✓					✓							✓
Conservation agriculture (organic no-till)			✓	✓	✓		✓		✓	✓		✓	
SOIL CONSERVATION													
Contour farming					✓		✓		✓	✓	✓		
Grass striping/ living barriers			✓		✓		✓			✓	✓		
Terracing					✓		✓			✓	✓		
Check dams along gullies					✓		✓			✓	✓		

Given the resilience of diversified small farming systems, understanding the agroecological features of traditional agro-ecosystems is an urgent matter, as they can serve as the foundation for the design of agricultural systems that are resilient to climate change (Swiderska *et al.*, 2011). A first key step is to understand the agroecological features of traditional and other agroecological farming systems that have stood the test of time (Dewalt, 1994). The key question to address is what are the principles and mechanisms have allowed these systems to resist and/or recover from droughts, storms, floods or hurricanes. These mechanisms can be deciphered using the methodologies described in this chapter that assess the socio-ecological resiliency of farming systems.

The second step is to disseminate, with increased urgency, the derived resiliency principles and practices used by successful farmers to other farmers in need of reducing their vulnerability, via farmer-to-farmer networks. It will also be important to spread results from scientific studies that document the effectiveness of agroecological practices in enhancing the resiliency of agro-ecosystems to extreme climatic events (droughts, hurricanes, etc.). The effective diffusion of agroecological technologies will largely determine how and how well farmers adapt to climate change. Dissemination to farmers in neighbouring communities and others in nearby regions can be achieved via field days, cross-visits, short seminars and courses that focus on methods that explain how to assess the level of resiliency of each farm and what to do to enhance resistance to both drought and strong storms. The *campesino-a-campesino* methodology used by thousands of farmers in Mesoamerica and Cuba consists of a horizontal mechanism of transfer and exchange of information, and is perhaps the most viable strategy to scale up agroecologically based adaptive strategies (Holt-Giménez, 1996; Rosset *et al.*, 2011).

Most research focuses on the ecological resiliency of agro-ecosystems, but little has been written about the social resilience of the rural communities that manage such agro-ecosystems. The ability of groups or communities to adapt in the face of external social, political, or environmental stresses must go hand in hand with ecological resiliency. To be resilient, rural societies must generally demonstrate the ability to buffer disturbance with agroecological methods adopted and disseminated through self-organization and collective action (Tompkins and Adger, 2004). Reducing social vulnerability through the extension and consolidation of social networks, both locally and at regional scales, can contribute to increases in agro-ecosystem resilience. The vulnerability of farming communities depends on how well developed their natural and social capital are, which in turn makes farmers and their systems more or less vulnerable to climatic shocks (Nicholls *et al.*, 2013). Most traditional communities still maintain a set of social and agroecological preconditions that enable their farms to respond to climate change in a resilient manner.

By pursuing adaptation through the frameworks of agroecology and food sovereignty, the livelihoods of more than 1.5 billion smallholders will not only continue to endure; many of their systems will persist and serve as examples of sustainability from which the world must urgently learn.

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SOCIAL ORGANIZATION AND PROCESS IN BRINGING AGROECOLOGY TO SCALE

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Abstract

Numerous scientific studies and empirical experiences around the world have shown that peasant and family farm-based agroecological approaches are superior to industrial agriculture in terms of: production of healthy food for local populations (food sovereignty), enhancement of rural livelihoods and cultures, resilience to climate change and other shocks, fewer greenhouse gas (GHG) emissions, lower production costs, stewardship of productive resources and rural biodiversity ('Mother Earth'), relative autonomy and lower external dependence for farming families, etc. Yet the challenge remains of how to bring agroecology to scale, so that it is practised by ever more families, over ever larger territories.

The experience of rural social movements, and farmer and peasant organizations, indicates that the degree of organization (called 'organicity' by social movements), and the extent to which horizontal social methodologies based on peasant and farmer protagonism are employed to collectively construct social processes, are key factors in 'massifying' and bringing agroecology to scale. *Campesino-a-campesino* ('farmer-to-farmer') processes and peasant agroecology schools run by peasant organizations themselves are useful examples of these principles.

While most agroecology research to date has emphasized natural science, the results presented in this chapter point to the need to prioritize social science approaches and self-study by rural movements, to draw systematic lessons from their successful experiences. This can produce the information and principles needed to design new collective processes.

These points are illustrated with reference to emblematic cases selected from the experience of La Via Campesina (LVC), arguably the world's largest social movement, and a key venue for expanding agroecological experience through its global, regional and national agroecology and peasant seed processes.

INTRODUCTION: THE ADVANTAGES OF AGROECOLOGY

The starting point for this chapter is that peasant and family farm-based agroecological farming has significant advantages over industrial agriculture, both for people and for the planet (IAASTD, 2008; De Schutter, 2011). It is not the intention to conduct an exhaustive review of the evidence here, though it is worthwhile to mention several of the more important advantages:

» **Production of sufficient and healthy food for local people (food sovereignty):** Despite the common misconception that the industrial farming systems of agribusiness are the most productive, many studies have shown in recent years that: small farms are more productive than large farms (Rosset, 1999); and 'agroecological', 'sustainable' and/or 'organic' systems are as productive, and in many cases more productive, than chemical-dependent monocultures (Badgley *et al*., 2007; Pretty and Hine, 2001; Pretty *et al*., 2003; De Schutter, 2011). The most productive systems per unit area are highly integrated agroecological systems on small farms (Rosset *et al*., 2011; Machín Sosa *et al*., 2013).

- **Rural livelihoods and cultures:** When rural people have access to land and other production factors, and they are favoured as food producers for local and national markets, their livelihoods are preserved and strengthened and rural culture is conserved and enhanced (Rosset, 1999).
- **Resilience to climate and other shocks:** Diversified agroecological farming systems are far more resistant and resilient when faced with climate and other shocks (Rosset *et al*., 2011; Altieri and Koohafkan, 2008).
- **Lower greenhouse gas emissions:** A more localized food system, based on agroecological small farms producing for local and national markets, would significantly reduce GHG emissions (Vandermeer *et al*., 2009; LVC, 2009).
- **Lower production costs, less indebtedness:** Agroecological systems that utilize on-farm inputs and the synergies available in integrated systems can significantly reduce production costs and farmer indebtedness (Rosset *et al*., 2011; Rosset and Martínez-Torres, 2012).
- **Better stewardship of productive resources and biodiversity:** Small farmers, especially those that practice traditional or agroecological farming, are much better stewards of productive resources (Rosset, 1999) and of functional biodiversity like crop genetic resources (Jarvis *et al*., 2011).
- **Greater autonomy and less external dependence:** A common challenge of peasants and family farmers is the search for relative autonomy from the credit, input and global output markets that operate on unfavourable terms for them (van der Ploeg, 2008; 2010). They can build relative autonomy from these markets through agroecology (Rosset and Martínez-Torres, 2012).

Therefore, there are a number of arguments in favour of the agroecological transformation of farming systems. Yet the challenge remains of how to bring agroecology to scale, so that it is practised by ever more families, over ever larger territories.

BRINGING AGROECOLOGY TO SCALE REQUIRES SOCIAL PROCESS AND ORGANIZATION

The question of how to scale up agroecology is under debate in the literature (von der Weid, 2000; Holt-Giménez, 2001; 2006; Altieri and Nicholls, 2008; Rosset *et al*., 2011; Parmentier, 2014). Various authors argue that social process methodologies, social organization, and rural social movements hold the key (Rosset *et al*., 2011; Rosset and Martínez-Torres, 2012; McCune *et al*., 2014; McCune, 2014).

While conventional top-down agricultural research and extension has shown a negligible ability to develop and achieve broad adoption of the practices of agroecological diversified farming, social movements and methodologies that build on social dynamics appear to have significant advantages (Rosset *et al.*, 2011). Social movements incorporate large numbers of people – in this case large numbers of peasant families – in self-organized processes that can dramatically increase the rate of innovation and the spread and adoption of innovations.

The fact that agroecology is based on applying principles in ways that depend on local realities means that the local knowledge and ingenuity of farmers must necessarily take a front seat, as farmers cannot blindly follow pesticide and fertilizer recommendations prescribed on a recipe basis by extension agents or salesmen. Methods in which the extensionist or agronomist is the key actor and farmers are passive are limited to the number of peasant families that can be effectively attended to by each technician. This is because there is little or no self-catalysed dynamic among farmers themselves to carry innovations beyond the last visit of the technician. Consequently, these cases are limited by the budgetary constraints of how many technicians can be hired. Many project-based rural development NGOs face a similar problem. When the project funding cycle comes to an end, virtually everything reverts to the pre-project state, with little lasting effect (Rosset *et al.*, 2011).

The most successful methodology for promoting farmer innovation and horizontal sharing and learning is the *campesino-a-campesino* ('farmer-to-farmer' or 'peasant-to-peasant') methodology (CAC). While innovation and sharing between farmers goes back to time immemorial, the more contemporary and more formalized version was developed locally in Guatemala and spread through Mesoamerica, beginning in the 1970s (Holt-Giménez, 2006). CAC is a Freirian horizontal communication methodology (*sensu* Freire, 1970; 1973), or social process methodology. It is based on farmer-promoters who have innovated new solutions to problems that are common among many farmers or have recovered/rediscovered older traditional solutions, and who use a 'popular education' methodology to share them with their peers, using their own farms as classrooms. A fundamental tenet of CAC is that farmers are more likely to believe and emulate a fellow farmer who is successfully using a given alternative on their own farm than they are to take the word of an agronomist of possibly urban extraction. This is even more the case when they can visit the farm of their peer and see the alternative functioning with their own eyes. For instance, in Cuba farmers say, "seeing is believing" (Rosset *et al.*, 2011).

Whereas conventional extension can be demobilizing for farmers, CAC is mobilizing, as farmers themselves become the protagonists in the process of generating and sharing technologies. CAC is a participatory method based on local peasant needs, culture and environmental conditions, that unleashes knowledge, enthusiasm and leadership as a way of discovering, recognizing, taking advantage of, and socializing the rich pool of family and community agricultural knowledge, which is linked to their specific historical conditions and identities. In conventional extension, the objective of technical experts all too often has been to replace peasant knowledge with purchased chemical inputs, seeds and machinery, in a top-down process where education is more like domestication (Freire, 1973; Rosset *et al.*, 2011). Holt-Giménez (2006) has extensively documented the experiences of Mesoamerican social movements using CAC as a methodology for promoting agroecological farming practices, which he calls "peasant pedagogy".

Cuba is where the CAC social methodology achieved its greatest impact, when the National Association of Small Farmers (ANAP), a member of LVC, adopted the approach along with a conscious and explicit goal of building a grassroots movement for agroecology inside the national organization (as extensively detailed in Machín Sosa *et al.*, 2013 and Rosset *et al.*, 2011). In less than ten years, the process of transforming systems of production into agroecological integrated and diversified farming systems had spread to more than one-third of all peasant families in Cuba – a remarkable rate of growth. During the same time period when peasants became agroecological, the total contribution of peasant production to national production jumped dramatically, with other advantages in reduced use of farm chemical and purchased off-farm inputs (more autonomy), and greater resiliency to climate shocks (Machín Sosa *et al.*, 2013).

The experience of rural social movements, and farmer and peasant organizations, indicates that the degree of organization (called 'organicity' by social movements), and the extent to which horizontal social methodologies based on peasant and farmer protagonism are employed to collectively construct social processes, are key factors in 'massifying' and bringing agroecology to scale. CAC processes and peasant agroecology schools run by peasant organizations themselves are useful examples of these principles (Rosset and Martínez-Torres, 2012; McCune *et al.*, 2014).

These points can be illustrated with reference to emblematic cases selected from the experience of LVC, arguably the world's largest social movement, and a key venue for expanding agroecological experience through its global, regional and national agroecology and peasant seed processes (Rosset and Martínez-Torres, 2012; LVC, 2013; Martínez-Torres *et al.*, 2014).

In recent years, LVC and its members have set up CAC agroecology programmes in many countries in the Americas, Asia and Africa, as well as producing agroecology training materials, and sponsoring seed fairs and seed saving and exchange networks in a number of regions and countries. One enormously successful national programme has been developed in Cuba, under which farmers breed and select their own varieties, with smaller-scale programmes in other countries. LVC has not only organized national and international exchanges so that farmers can see for themselves ('seeing is believing') and learn from the best cases, but it has also recently begun to identify, self-study, document, analyse, and horizontally share the lessons of the best cases of farmer-led, climate-robust agroecology and food sovereignty experience. LVC has opened regional agroecology training schools and/or peasant universities in Venezuela, Paraguay, Brazil, Nicaragua, Indonesia and India, with others planned for Mozambique, Zimbabwe, Niger and Mali (in addition to dozens of national and sub-national level schools).

LVC has also created political leadership training academies in many countries and several regions to prepare peasant leaders to pressure governments to adopt the necessary policy changes. It has taken steps to engage in an on-going, critical but constructive way with 'peasant friendly' policy-makers in local, provincial and national governments in diverse countries, and with selected programmes and functionaries in international agencies, to promote the implementation of alternative public policies that are more agroecology, climate, farmer and consumer friendly. In countries with less-receptive governments and policy-makers, member organizations have organized massive mobilizations of political pressure to encourage them to consider the alternatives more seriously.

In Southern India, a grassroots agroecological movement has grown rapidly. The movement cuts across the bases of some member organizations of LVC, which is now facilitating exchanges with farmers from other countries across Asia (Rosset and Martínez-Torres, 2012). The Zero Budget Natural Farming (ZNBF) movement is partially a response to the acute indebtedness in which many Indian peasants now find themselves. The debt is from the high production costs of conventional Green Revolution-style farming, as translated into budgets for bank credit, and is the underlying cause of the well-known epidemic of farmer suicides in that country (Vasavi, 2012; Mohanty, 2005). The idea of ZBNF is to use agroecological practices based totally on resources found on the farm, like mulching, organic amendments and diversification, to break the stranglehold of debt on farming households by purchasing zero off-farm inputs. According to LVC farmer leaders in Southern Asia, several hundred thousand peasant families have joined the movement.

The Zimbabwe Organic Smallholder Farmers Forum (ZIMSOFF) is a recent member of LVC (Rosset and Martínez-Torres, 2012). The current president of ZIMSOFF is an agroecology promoter from Shashe in the Masvingo agrarian reform cluster. Shashe is an intentional community or collective created by formerly landless peasants who engaged in a two-year land occupation before being awarded the land by the government land reform programme. A cluster of families in the community are committed to practising and promoting diversified agroecological farming; through ZIMSOFF they are making a national impact and through LVC, an international impact. When Shashe hosted a regional agroecology encounter of LVC organizations from Southern, Central and Eastern Africa in 2011, the participants noted in their final declaration that:

> *We have been meeting at the Shashe Endogenous Development Training Centre in Masvingo Province, Zimbabwe to plan how to promote agroecology in our Region (Southern, Eastern & Central Africa). Here we have been privileged to witness first hand the successful combination of agrarian reform with organic farming and agroecology carried out by local small-holder farming families. In what were once large cattle ranches owned by three large farmers who owned 800 head of cattle and produced no grain or anything else, there are now more than 365 small holder peasant farming families with more than 3,400 head of cattle, who also produce a yearly average of 1 to 2 tonnes of grain per family plus vegetables and other products, in many cases using agroecological methods and local peasant seeds. This experience strengthens our commitment to and belief in agroecology and agrarian reform as fundamental pillars in the construction of Food Sovereignty (LVC, 2011).*

They also decided to establish an international agroecology training school in Shashe, to train peasant activists from LVC organizations in the region as agroecology promoters using the CAC method.

These examples illustrate the burgeoning agroecology process in LVC and its member organizations (Rosset and Martínez-Torres, 2012; La Via Campesina, 2013; Martínez-Torres *et al.*, 2014). Part of the process has consisted of holding regional and continental 'Encounters of Agroecology Trainers'. These have been held in the Americas (2009 and 2011), Asia (2010), Southern, Central and Eastern Africa (2011), West Africa (2011) and Europe (2012), as well as a first Global Encounter of Peasant Seed Farmers, held in Bali (2011).

This process has served several important purposes. One has been to help LVC itself to collectively realize the sheer quantity of on-going agroecology organizing processes that are currently underway inside member organizations at the national and regional levels. The vast majority of organizations either already have some sort of internal programme to promote agroecology, or they are currently discussing how to create one. Another purpose that the encounters are serving is to elaborate detailed work plans to support these on-going processes designed to bring agroecology to scale, and to link them with one another in a horizontal exchange and learning process. The encounters have created a space to collectively construct a shared vision of what agroecology means to LVC; in other words, the philosophy, political content and rationale that links organizations in this work (Rosset and Martínez-Torres, 2012; LVC, 2013; Martínez-Torres *et al.*, 2014).

FACTORS IN BRINGING AGROECOLOGY TO SCALE

In 2014, El Colegio de la Frontera Sur (ECOSUR) in Mexico, launched an interdisciplinary research group to study the 'Massification' (scaling up) of agroecology.[1] By examining successful cases of scaling up of agroecology from around the world (including, but not limited to, cases from LVC), the programme hopes to elucidate reproducible factors that contribute to success. The programme is only in its initial stages, but already has a preliminary list of factors that seem to play important roles, to a greater or lesser extent, in different success stories.[2] These factors are:

- **Social organization–social movements:** As explained above, rural social movements, and their ability to strengthen social organization and construct social processes, appear to be very important. Social organization is the culture medium on which agroecology grows, and upon which it can be scaled out (Rosset and Martínez-Torres, 2012; McCune, 2014).
- **Horizontal social process methodology and pedagogy:** As the case of Cuba illustrates, the use of a social process methodology like CAC, based on a 'peasant pedagogy', is often a critical element in the acceleration of an agroecology process (Rosset *et al.*, 2011; Machín Sosa *et al.*, 2013; Holt-Giménez, 2006).
- **Peasant protagonism:** Preliminary evidence suggests that when peasants or farmers themselves lead the innovation process, it moves much faster than when technical staff or extensionists are in the lead (Rosset *et al.*, 2011; Machín Sosa *et al.*, 2013; Holt-Giménez, 2006; Kolmans, 2006).
- **Farming practices that work:** Agroecology cannot spread based solely on social process. Any process must be based on agroecological farming practices that provide farmers with good results and solutions to the problems or obstacles that they face (Rosset *et al.*, 2011; Machín

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[1] The group is financed by CONACYT and coordinated by Dr Helda Morales.

[2] This list is substantially based on the work of Ashlesha Khadse, a graduate student at the ECOSUR Advanced Studies Institute.

Sosa *et al.*, 2013; Holt-Giménez, 2006; Kolmans, 2006). These solutions or practices do not necessarily need to be the product of formal research institutions. In fact, they are just as likely, or more likely, to come from peasant or farmer innovation, once the social process has unleashed farmer/peasant creativity and interest in recovering ancestral practices.

- **Motivating discourse and framing:** Rosset and Martínez-Torres (2012) distinguish between "agroecology as *farming*" and "agroecology as *framing*". While agroecology must of course 'work' as farming, the social process of dissemination and adoption is often driven just as much by the ability of an organization or movement to develop and use a motivating and mobilizing discourse that makes people actually want to transform their farms.
- **Political opportunity, external allies, charismatic leaders, local champions, etc.:** Like any other form of social movement, agroecology movements can be energized or take advantage of political opportunities and external allies (Fox, 1996; Morris, 2000), charismatic leaders (Morris and Staggenborg, 2004) and local champions (Bagdonis *et al.*, 2009). This can take the form of a food scare, a government official willing to have training materials printed, a public figure, artist or religious figure who champions the movement, or charismatic leadership from within.
- **Favourable markets:** The demand for agroecological products, and opportunities for farmers to sell ecologically grown produce at a profit, can be key driving forces in successful cases of bringing agroecology to scale (Brown and Miller, 2008). Conversely, failure to pay attention to the market can result in the failure of a process.
- **Favourable public policies:** Public policies play a key role in whether agroecology processes can achieve scale. Machín Sosa *et al.* (2013) examine how policies in Cuba have favoured agroecology, while Nehring and McKay (2014) do the same for Brazil. Governments can and should use government procurement, credit, education, research, extension and other policy instruments to favour agroecological transformation.

CONCLUSIONS

While all of these factors may play important roles in bringing agroecology to scale, the roles of social organization, social process methodology and social movements are emphasized throughout this chapter. It is my assertion that the experience of rural social movements, and farmer and peasant organizations, indicates that the degree of organization and the extent to which horizontal social methodologies based on peasant and farmer protagonism are employed to collectively construct social processes, are key factors in 'massifying' and bringing agroecology to scale. CAC processes and peasant agroecology schools run by peasant organizations themselves are useful examples of these principles.

While most agroecology research to date has emphasized natural science, these results point to the need to prioritize social science approaches and self-study by rural movements, in order to draw systematic lessons from their successful experiences. This can produce the information and principles needed to design new collective processes.

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AGROECOLOGY AND THE ECONOMICS OF ECOSYSTEMS AND BIODIVERSITY:

THE DEVIL IS IN THE DETAIL

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Abstract

The Economics of Ecosystems and Biodiversity (TEEB) project has recently launched a study focusing on the agri-eco-food system. The TEEB approach categorizes and makes visible the dependencies that agricultural systems have on inputs from nature as well as the provisioning of benefits from the agri-eco-food system to humans. In both cases there are 'invisibilities' – positive and negative externalities. Making these externalities visible to decision-makers and then proffering policy options to capture these values is central to the TEEBAgFood study. There is a strong link between TEEBAgFood and the agroecology discourse. On the 'input' side, the agroecology movement has focused on, *inter alia*, soil fertility, genetic diversity and system resilience, all of which underpin production and yet are relatively invisible. On the 'outputs' side, agroecology considers benefits beyond providing calorific intake such as the nutritional benefits of local varieties and the community cohesion stimulated by just, fair and sustainable production. TEEBAgFood seeks to include these aspects in a holistic economic framework. This presents particular challenges. The framework, challenges and potential ways forward in TEEBAgFood development are set out in this chapter, with a particular focus on rice systems.

THE (ENVIRONMENTAL) CHALLENGES OF AGRICULTURE AND FOOD SYSTEMS

While recognizing the centrality of agriculture to human well-being and sustainable development, essentially every statement on the future of agriculture acknowledges that a transformation is needed in the way the sector is conducted and how it impacts on the environment, even if and while production is increased to meet food security needs (IAASTD, 2009; Royal Society London, 2009; Godfray *et al.*, 2010; Foley *et al.*, 2011). Concerns over the sustainability of agriculture and the growing ecological footprint of conventional farming systems have grown exponentially over the last 25 years. To many, particularly those in the nature conservation and biodiversity realm, agriculture looms as the major global threat; as noted in the recent Global Biodiversity Outlook 4 (CBD, 2014), agriculture is thought to be the driver for around 70 percent of the projected loss of terrestrial biodiversity.

Equally important, among the ever-growing community of actors concerned with climate change, agriculture is increasingly perceived as a major contributor to greenhouse gas (GHG) emissions, estimated at quite variable ranges, from the official IPCC estimates of 10-12 percent of total global anthropogenic emissions of GHGs to the UNCTAD assessment of 40-45 percent of global totals (Hoffman, 2013). Because agriculture contributes a relatively minor share to global GDP, the sector is then identified as being highly 'GHG intensive', emitting a large share of pollutants throughout the production to consumption chain that is not commensurate with its economic contribution. This overall analysis, of course, has many problematic aspects, ignoring the strong livelihood dependence of local communities on agriculture, the importance of agriculture for food and nutrition security, and the reality of globally volatile prices for agricultural goods. Nonetheless, multiple initiatives to mitigate the environmental costs of agriculture are emerging from the climate change discussions (e.g. UNFCCC, 2009).

BUILDING A REGENERATIVE AGRICULTURAL SYSTEM

The opposite side of the challenges facing current agricultural systems is that in many parts of the developing world, conventional high-input agriculture has not – and has little chance – to take hold. In such regions, resource-poor farmers contend with issues of marginal high-risk environments, and experience poor yields just where food security is the most vulnerable. The agricultural research establishment has only recently begun to focus increasingly on these sites, and to recognize that highly site-specific resource management systems are needed to sustain productivity under these conditions (Altieri, 2002). For example, there has been considerable success in incorporating indigenous leguminous fodder species that lose their leaves during the crop growing season into agricultural fields in the Sahel area of West Africa to increase soil fertility, provide fodder for livestock and soil protection year-round (Dixon and Garrity, 2014).

The approaches that can address both the heavy negative externalities of conventional production systems and the challenges of resource-poor farmers have a central common thread: the recognition that agriculture and food systems are complex biological and social systems. They can be designed to build upon and harness the forces of biodiversity and ecosystem services so that the processes that underpin agricultural production (e.g. soil fertility, natural pest control, pollination, water retention) are optimized and encouraged. Farming systems can be regenerative, building on and adding to natural capital, rather than being increasingly dependent upon external inputs that the system cannot absorb and more often than not end up as negative externalities. Farming has traditionally never been a solitary operation; it has been carried out over millennia by communities of people. An ecosystem perspective recognizes that the regenerative aspects of agriculture occur at the level of the whole farming system, at the watershed, and/or landscape or community level, with the traditional knowledge and experience of farmers and empowerment of communities at its base. As such, it also contributes to building and strengthening the social capital underlying agriculture, while harnessing all forms of appropriate technologies to enable ecological and equitable farming systems.

THE ECONOMICS OF ECOSYSTEMS AND BIODIVERSITY (TEEB) IN AGRICULTURE AND FOOD

TEEB is a global initiative focused on drawing attention to the economic benefits of biodiversity including the growing cost of biodiversity loss and ecosystem degradation. TEEB recognizes that essentially all productive sectors depend upon the benefits provided by biodiversity and ecosystem services (including cultural services) that are collectively referred to as natural capital. It is important to note that TEEB does not conflate valuation with monetization or commodification.

The fundamental aim of the TEEB approach is to help decision-makers recognize, demonstrate and capture the values of ecosystem services and biodiversity, and help us to rethink our relationship with the natural environment and alert us to the impacts of our choices and behaviours on distant places and people. In the TEEB approach, scenario analysis is carried out to assess the provisioning of ecosystem services with a policy change *versus* business as usual (BAU). Ecosystem services are the benefits that nature provides us. Thus, if we assess changes in ecosystem services (first in biophysical terms and then using valuation approaches) we can recognize and demonstrate the trade-offs that policy-makers face in electing to support the proposed policy as compared with the BAU counter-factual scenario. Capturing these values is a further step that requires an assessment of institutional capacities, the needs of key stakeholders and governance regimes. The best way of capturing value might be a market-based reform, regulatory intervention, information provision or some combination of these.

The TEEB initiative is currently exploring a number of productive sectors in order to look at the links between a sector's impacts on both ecological and human well-being on the one hand, and its dependence upon ecosystem services on the other. In each case it is important to look beyond direct impacts and dependence, to also consider the indirect links. For instance, policies in a forestry department might have significant impacts on downstream, irrigated crop production.

The UNEP TEEB Office has recently begun to undertake a study on 'TEEB for Agriculture and Food' (henceforth TEEBAgFood). This study is designed to provide a comprehensive economic evaluation of the 'eco-agri-food systems' complex, and demonstrate that the economic environment in which farmers operate is distorted by significant externalities, both negative and positive and a lack of awareness of the dependency on natural capital. A 'double-whammy' of economic invisibility of impacts from both ecosystems and agricultural and food systems is a root cause of increased fragility and lower resilience to shocks in both ecological and human systems.

In order to build the evidence base for the main technical reports, a number of pilot studies have been commissioned on rice, livestock, palm oil, agroforestry, inland fisheries and maize. The TEEB Office has been working with a diverse set of research teams, including FAO to coordinate the rice pilot study. Within this chapter, written halfway through the pilot study, it is possible to highlight certain strengths and challenges of applying the TEEB approach to agriculture and food systems in an agroecological context, using the case study of rice production systems.

AGROECOLOGICAL APPROACHES TO AGRICULTURAL SUSTAINABILITY

The predominant model of conventional agriculture needs to urgently find a new basis that does not degrade and deplete the natural resource base upon which productivity is sustained. In response to this, a number of new 'paradigms' have been proposed in recent years. Of all the (now many) initiatives and approaches to agricultural sustainability, agroecology distinguishes itself in not presenting single technological solutions or sets of practices, but rather an overall framework that recognizes the complexity of agro-ecosystems, and the value of this complexity, or multifunctionality. Agroecology takes many forms; it refers to a scientific discipline, specific sets of agricultural practices, and a political or social movement (Wezel *et al.*, 2009).

Agroecology has been defined as the use of **ecological principles** for the design and management of sustainable food systems (Gliessman, 2007). Among all the different models and paradigms being proposed for sustainable agriculture, it is perhaps the most well-articulated and elaborated concept, dating as a scientific discipline back to the 1920s (Wezel *et al.*, 2009).

Agroecology has a broad focus, based on a set of **robust basic principles**:

1. Recycling;
2. Efficiency;
3. Diversity;
4. Biological regulation/interactions;
5. Synergies.

Tittonell (2015) has distilled these principles from the classical works on agroecology (e.g. Altieri, 1995; Gliessman, 2007). As he notes: "The choice of management practices and technologies to achieve these principles is always location specific, shaped by a given social-ecological context".

POINTS OF CONVERGENCE AND CHALLENGES BETWEEN THE TEEB FOUNDATIONS FRAMEWORK AND AGROECOLOGICAL PRINCIPLES

Objectives of the production system

Agroecology confronts current production systems with their singular focus on commodity yields, rather than a broader appreciation and support for the multiple goods and services produced by agriculture. Benefits from agricultural production, in most analyses, have been traditionally measured through crop yields and financial returns, with little or no attention to overall resource efficiency, diversity of outputs, risk reduction and non-commodity outputs (Silici, 2014).

TEEB seeks to establish a framework to link the biophysical aspects of ecosystems with human benefits through the notion of ecosystem services, in order to assess the trade-offs

(ecological, socio-cultural, economic and monetary) involved in the loss and degradation of ecosystems and biodiversity in a clear and consistent manner. In this sense, singular production objectives such as yields (in rice for example) should be assessed against such services as water quality regulation. This provides a valuable context for bringing in an assessment of the negative externalities as 'invisible' costs to production. Each of these can be assigned a value, be it monetary or non-monetary, thus identifying the 'true costs' of a production system.

Furthermore, a *system assessment* is required. Other than pure monocultures, the system will produce a range of tangible commodities for either direct (subsistence) consumption or trade/sale in the market. Even pure monocultures produce (and rely on) the full gamut of ecosystem services. Thus, although it is a useful shorthand to consider the direct one-on-one trade-off between (for instance) food production and water quality regulation, the end goal of the application of the TEEB approach is a scenario analysis comparing agricultural system A versus system B, including both a biophysical assessment of ecosystem service provision and a valuation thereof. Thus, for the TEEB approach – and of paramount importance to an agroecological approach – a more holistic analysis is needed.

The TEEB study on *Ecological and Economic Foundations* recognizes that "ecosystem assessments should be set within the context of contrasting scenarios – recognizing that both the values of ecosystem services and the costs of actions can be best measured as a function of changes between alternative options" (de Groot *et al.*, 2010). However, the economic modalities for comparing, in a genuinely holistic sense, between two systems of production, rather than the outcomes of two practices (such as use of pesticides versus reduction or non-use of pesticides) is a methodology that is in need of development.

Reasons for this are discussed in more detail below. Yet, the need for this facility is extremely relevant for TEEBAgFood. In rice production systems, for example, the ability to provision not just rice yields, but other 'goods' such as fish and aquatic organisms, may be a critical attribute, and one that justifies other practices such as reducing or eliminating pesticide applications. The interactions then, between rice, fish, pesticides, pests and water quality are more complex than simple, linear trade-offs or synergies. Multiple objectives also apply of course to social and cultural objectives, yet these do not fit neatly into an economic framework that focuses on making all costs and benefits commensurable in dollar terms and one that assumes that non-linearities and tipping points do not apply.

TEEB is not associated with any such economic framework that commodifies nature; TEEB recognizes that multifunctionality can lead to a higher overall productivity of the system, if multiple goods and services are included in the evaluation.

One solution to addressing the practical limitations of a standard economic analysis would be the use of a dynamic systems approach. This could lend a number of strengths, including a time dimension, as practices and interventions may not result in impacts immediately, but rather have crucial implications over time. The time dimension is already a feature of standard economic analysis, but the process of discounting (the converse of compound interest) means that impacts that occur in the future (be they positive benefits or negative costs) are not as valuable in economic terms as would be the case were the same impacts to occur today or the near future.

In addition, a dynamic systems approach can handle non-linear relationships, given that the marginal impact of a given activity on ecosystem services are unlikely to be constant. Agricultural ecosystems can react non-linearly to interventions. For example, an orchard could balance small disturbances such as localized pest outbreaks, be gradually affected by years of drought, and – with no change in pest pressure, be unable to regrow and recover from losses to pests.

It is not that economic analysis cannot deal with non-linearity; it can. But a better understanding of critical tipping points and how natural capital can serve as a critical constraint is needed to build adequate economic models of the role of ecosystem services and biodiversity in agricultural production.

Nesting practices within systems

A dilemma immediately facing anyone trying to analyse and compare sustainable agriculture is whether it is justified to focus on specific practices, sets of practices, or overall agricultural systems.

From an agroecological perspective, practices or sets of practices are not the operational focus; practices are measures that are adapted and modified in locally context-specific ways to optimize interactions in agroecological systems, comprising both biological and social aspects. Proponents of agroecology state quite clearly that it is a set of principles that take technological forms depending on the socio-cultural, economic and environmental realities of each community or situation. Thus, ‘diversity’ as a principle may be actualized in many forms such as intercropping or agroforestry; each of these are ways to optimize interactions between crops, shade, pests, soil organisms, etc. Many practices may also entail social elements such as increasing social interaction, learning and empowerment as part of the system.

It is evident in the literature that most research focuses on specific practices in the scientific approach of introducing one intervention while holding all other factors constant. Even if studies report on a particular ‘system’, the set of practices, and degree of their optimization, is quite variable. Where specific management systems have a number of key practices or principles (such as Systems of Rice Intensification), research studies often focus on only one or two of these, rather than comparing the implementation of all practices against the absence of all. Additionally, different definitions of practices and systems are used within specific contexts and cannot easily be simplified or homogenized in light of the peculiarities of each context.

In an earlier assessment of the multiple goods and services generated by Asian rice production systems, we assembled evidence comparing agroecologically optimized management systems and traditional farming systems against conventional baselines (Garbach *et al.*, 2014), with interesting results. This was possible as long as we remained on the level of a broad biophysical assessment, without documenting costs, benefits and values. The TEEBAgFood framework requires the assessment of impacts and dependencies of agriculture on ecosystem services and human well-being; in this framework, we have found that at the sector level, we can only compile sufficiently accurate evidence on practices, not integrated or optimized into cohesive systems. This undoubtedly has risks. A new methodology being applied to assess the socio-economic value of pollinator-friendly practices, using the compound indicator of ‘number of agroecological practices’ (Garibaldi and Dondo, in draft), may provide some solutions.

The benefits of agriculture – valuing the ecosystem services and biodiversity that sustain production

Much of the focus on environmental full-cost accounting, also called full-cost (e.g. FAO, 2014) or true-cost accounting (e.g. Sustainable Food Trust, 2013) for agriculture points to the fact that present agricultural systems are based on practices that are untenable and have major environmental and health costs, borne by common citizens, rather than by the polluters. It is recognized that many alternative farming systems have the ability to deliver multiple, cost-saving benefits – such as building soil fertility, sequestering atmospheric carbon into the soil, building resilience to weather and climate variability or delivering health and social outcomes. Yet, the 'alternative' producers are often obliged to pay higher costs in the form of certification (e.g. certified organic agriculture), increased labour in production and marketing, or higher capacity requirements (given that alternative agriculture is highly knowledge intensive) in order to deliver these public benefits, and as a consequence they might *initially* be less economically competitive.

Both capacity and labour requirements tend to be higher in agroecological systems when first implemented; however these may decrease with time once the system is established. In a recent interview, Miguel Altieri, Professor of Agroecology at the University of California, stated that "instead of high input and less land, the core strategy should be to deal with incorrect practices and rural flight (migration)" (Bringsken, 2013). Indeed, experience has shown that the provision of greater (and possibly more secure) employment opportunities in the form of farm labour might reasonably be considered an important benefit to society (although it is a private cost to the farmer) especially as such employment opportunities reduce uncontrolled, unplanned urbanization with its attendant impacts on social and physical infrastructure.

An effective TEEB analysis should and does seek to focus on these 'benefits' as much as the costs of agricultural production. It is also important to assess if there may be a 'lock-in' to conventional systems, i.e. higher costs persist. Take certification for example: markets are characterized by asymmetric and incomplete information wherein the producer has a better assessment of its ecosystem impacts than consumers, allowing both genuinely sustainable producers *and unsustainable 'cheats'* to co-exist in the market and both claim eco-friendly credentials. This is a case where there is a sound economic rationale for intervention in the market, but it does not routinely occur owing to a lack of will and vested interests, and also because it is so difficult to define and measure farm sustainability, i.e. to identify the 'cheats'.

There are, however, hidden *private* benefits to the application of agroecological principles that serve the interests of the individual farmer, but that may not be realized owing to habit-formation, culture or a lack of knowledge. In the example of biological pest control, benefits are provided in the form of avoided costs, as the need for (costly, fossil fuel-intensive) pesticide application is reduced, along with its attendant impacts. While there are some methodologies to evaluate the benefits of carbon sequestration and biodiversity conservation, not all the elements of 'invisibility' in the TEEB framework can be valued at present, even in non-monetary terms. Although the TEEBAgFood framework is designed to be comprehensive, at this stage in the project the valuation element (in particular) is limited. This has a strong impact on being able to capture and assess agroecological approaches based on the ecosystem services that sustain production.

This is perhaps best illustrated by the example of rice production as rice under conventional production may use high inputs of both pesticides and fertilizers. Use of pesticides over time will have negative impacts on the natural enemy community that can provide natural forms of pest control. In a TEEB analysis as currently constructed, the loss of natural pest control services will appear only as a cost applied to water quality instead of cost incurred by the biophysical 'infrastructure' underpinning production.

This lack of direct accounting for certain ecosystem services relates to their current conceptualization within the TEEB framework. In the current conceptualization, the underpinning biophysical processes that provide ecosystem resilience are not final services – they are intermediate services. There is a concern that if such intermediate ecosystem services are assigned values, there may be a double-counting of the benefits that nature provides. Nevertheless, as described below, the effort and human inputs into building a biophysical 'infrastructure' – requiring investment both over time and space – is a substantial input that needs reckoning in a TEEB approach. This point is illustrated by the following concrete example.

Under agroecological approaches to rice production, perhaps best described in the work of Settle *et al.* (1996), ecosystem services come into play in critical and nuanced ways, contributing to a mechanism that supports high levels of natural biological control. If organic matter is increased early in the growing season, abundant populations of detritus-feeding and plankton-feeding insects will be fostered, usually peaking and declining in the first third of the season. These insects have no direct (positive or negative) impact on rice yields, but their populations provide natural enemies of rice pests with a 'head start', to build up their populations early in the season so as to be able to strongly suppress the pest populations that enter the paddy field in mid-season. Pesticides early in the season will prevent the strong buildup of natural enemies, killing both them and their early-season food source. Minimal application of organic material into paddy field soils, and a greater dependence on inorganic fertilizers will similarly impact the early-season buildup of natural enemies. Moreover, the process of building a strong ecological community is a multi-year process that nonetheless could be reversed in one year of high applications of agricultural chemicals.

The process described above – only part of complex rice ecosystems – is precisely the kind of 'dependence upon biodiversity' that TEEB seeks to make visible. Yet, for lack of tools and methods, it is not clear at this point how numbers and values can be assigned to 'internal' ecosystem functions such as natural pest control and natural fertility maintenance, as their value goes well beyond the avoided cost of polluting water. These values may or may not be accurately reflected in the benefit of yields, but the additional benefits of building natural capital also need to be reflected (see Box 1).

A recent study begins to identify these valuation methodologies, as applied in New Zealand and extrapolated to peas, beans, barley and wheat in temperate regions worldwide (Sandhu *et al.*, 2015). While the extrapolations were only examples of the potential extent of ecosystem

services in agriculture, they serve to highlight the importance of regulating ecosystem services in food production. The economic values from this estimation should be used with caution, however, as data stems from New Zealand, and cannot be readily applied to other regions of the world.

In brief, the analysis points to high economic values for the ‘internal’ ecosystem services of biological (natural) pest control and nitrogen mineralization (soil fertility), under organic conditions as a proxy for agroecological systems. To illustrate the potential magnitude of these ecosystem services, the authors extrapolated the experimentally derived values to the global temperate area of the selected crops. The extrapolation suggests that the net value of these two ecosystem services could exceed the total direct costs (not including externalities) of pesticides and fertilizers, even if utilized on only 10 percent of the global arable area. Although the economic values obtained through extrapolation involve a wide range of uncertainty, they highlight an important dimension of the role of ecosystem services in global agriculture. The results point to an urgent need to develop and improve similar methodologies in TEEB studies and adapt them to a wider range of agricultural contexts.

Box 1. **Issues faced in The Economics of Ecosystems and Biodiversity in Agriculture and Food (TEEBAgFood) in assessing the biophysical functioning of agro-ecosystems**

The valuation of a multi-season crop that is building on a strong ecological community is one that is problematic for TEEB (and the economics discipline more generally) to capture. Not only is it methodologically challenging to value the state of an ecosystem in terms of its resilience or long-term sustainability, but it is also necessary (in terms of standard TEEB/economic assessment) to isolate the marginal, incremental change in this state arising from the application of a particular production practice in a specific agroecological and socio-cultural context. Ecological community-building is non-linear. Even if we were to be able to quantify and value the marginal change over three years, we could not attribute this proportionally across the three years.

In the TEEBAgFood analysis on rice, we evaluate the ecosystem service and biodiversity trade-offs in shifting between agricultural systems/practices. Consider the switch from an agroecological system to a conventional monoculture; the switch must account for the loss of ecological community-building – potentially a sudden shift. But if we switch this scenario around (monoculture to agroecological system), there are multiple seasons required (and attendant costs) in order to reconstruct this ecological community, and these costs depend on highly farm-specific characteristics.

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In short, it is essential that TEEBAgFood assesses the value of agroecological approaches while recognizing that: (i) there are issues of intermediate versus final ecosystem services; (ii) valuation methodologies are underdeveloped; (iii) marginal change is difficult to assess owing to non-linearities; and (iv) the dynamics of any shift must be reconciled with the limitations of economic modelling. These are all issues that have been revealed as an outcome of the process of producing pilot studies for the rice project, i.e. what we know and do not know, the boundaries of our analysis given current methodologies, and what we possibly might do in subsequent TEEBAgFood reports to integrate ecological-economic modelling to extend our understanding.

DATA LIMITATIONS

Within the rice pilot study that FAO has carried out as a contribution to the TEEBAgFood, the problem of very limited data has emerged, even with a well-researched commodity such as rice. There are surprisingly few comparative studies that document impacts on multiple ecosystem services (even as simple as, for instance, crop yield and water quality) from different management practices.

Related to this are issues of data quality; a considerable amount of data and observation on agroecology has been published in ‘grey literature’ as opposed to the conventional peer-review process. Innovations in agroecology have generally come from farmer groups or practitioners and have been shared through lateral, farmer-to-farmer routes rather than conventional agricultural research and extension channels. A good case in point is Systems of Rice Intensification, which was developed in 1983 by a Jesuit priest in Madagascar. The system has been shared and elaborated by many farmer groups around the world. The initial documentation of its success in the scientific literature was undertaken by Dr Norman Uphoff at Cornell University, although proponents and critics of the system continue to disagree (Uphoff, 2003; Surridge, 2004; Uphoff and Kassim, 2011). Yet, even critics of the system acknowledge its wide and impressive rate of uptake among farming communities. There is a growing recognition that the system delivers not just good yields, but also healthier soils and other additional benefits. Thus, the reality on-the-ground has only recently, and partially, been reflected in peer-reviewed scientific literature. The debate brings an interesting light on how agroecological methods might better be evaluated in the literature (Glover, 2011). One key point is that smallholder farming practices rarely (if ever) conform to an abstract norm as farmers adapt recommendations to their needs and conditions; thus, a criteria of ‘performance’ that is understood more widely than yields alone should be considered.

HOW TO REFLECT AGROECOLOGY IN NATIONAL ASSESSMENTS?

Given that agro-ecosystems are as diverse as human and natural ecosystems – and so is agricultural management – a question facing TEEBAgFood studies is: how much detailed information does one need to collect to reflect the uniqueness of each agro-ecosystem and its underlying processes? How much is too much, when trying to scale up the results? To what extent, and at what level of detail, could and should a robust TEEB study of a commodity or geographic region provide useful insights to policy-makers?

Different points of time and scale

Dependencies and impacts are measured at different scales within the TEEBAgFood pilot studies. The rice study, for example, measures these different parameters at the **local level** as the focus of this specific project is to analyse the positive and negative impacts of different farm management practices and management systems on the agro-ecosystem itself, the neighbouring environment and human well-being.

Other farm related parameters, however, go far beyond the local level. Measuring of water-use efficiency should be done at multiple scales, for example, and based on sound water accounting. If there is not a sound water accounting framework that takes different scales into account, a number of trade-offs will be missed, for instance that greater water efficiency means less storage benefits and less groundwater recharge. It also may detract from of a number of ecosystem services linked to biodiversity, microclimate, connected wetlands, and part of the landscape feeding off 'water losses' (such as the very productive wooded areas/trees). Water saving regimes will increase the weed biomass as flood irrigation is practised to suppress weeds; a critical issue as weed pressure is a major constraint for rice yields. Therefore, it is important to highlight the critical need for a sound water accounting framework at multiple scales, far beyond the local level. However, scientifically sound studies that take this into account – *studies that fully capture all agroecology processes at different points of time and scale* – are very rare or non-existent.

Hence the question is: can we simplify the analysis of agroecological processes without losing too much detail and by how much? Or is complexity key to a sound national and global valuation framework? Can natural capital accounting deal with 'the devil in the detail'? Biophysical ecosystem valuation techniques mostly focus on the local level, while ecosystem accounting techniques aim to aggregate information for national statistics.

Scales: from the local scale to global food systems

Agroecology has been progressively defined from, originally, the design of sustainable agricultural systems to the design of sustainable food systems, and indeed it increasingly focuses on the need to transform the entire food system, from producers to consumers. Thus, it will be important to consider an agroecological perspective on food systems, and consider how this can enter into the TEEBAgFood framework. At issue is what are the appropriate concepts and perspectives on aggregation, summing the findings at a farm, field or plot scale to landscapes, watersheds, regions and countries?

One approach to country level would be national assessments, as suggested by IAASTD (2009). Such assessments, now under discussion at the Committee on Food Security in response to a call from the Rio+20 outcomes, would provide the baseline data needed to inform the analysis of the present situation and support the development of prospective systems models to develop new strategies and policies, to meet the targets of the upcoming Sustainable Development Goals (http://unsdsn.org/resources/goals-and-targets/) relating to agriculture and food systems among other objectives.

Aggregating ecological dependency and impact data for its use at the national level seems challenging, however. For example, Miyazaki (2006) argues for aggregate environmental indices that facilitate management decisions at higher levels by simplifying complexity. Yet, he also laments that such aggregated ecological figures with a common unit are very difficult to find, especially when an appropriate ecological accounting framework does not exist. Inevitably, aggregation at a national level requires abstracting details from the functioning of specific ecosystems, and consequently some part of the inherent dynamics will be lost. Thus, the processes nees to be conducted with considerable knowledge and attention to an appropriate balance of detail and generality.

If the level of analysis is taken at the resolution of entire food systems, the need to consider the many decision points and impacts within a food system becomes important. Clearly trends are toward a greater homogeneity in the world's food supplies (Khoury *et al.*, 2014), with risks to both food security and nutrition. From both a TEEB and an agroecological standpoint, more diverse diets would promote and be supported by diverse farming systems, with additional benefits from increasing resilience, reducing risks from single crop failures, and increasing incomes and health (Kremen *et al.*, 2012; Gliessman, 2015; Nicholls and Altieri, 2015; Tittonell, 2015). Thus, the TEEBAgFood framework should and will consider how production systems are linked to and driven by consumption patterns in the second phase of the project.

Points of contention with other frameworks

Within an agroecological food system perspective, there are likely to be serious points of contention with other frameworks. For example, discrepancies have been pointed out in calculations of GHG emissions based on differing modes of environmental accounting. Some studies report CO_2 emission equivalents calculated through life cycle assessments (LCAs) by unit of product and others by unit of area (Tuomisto *et al.*, 2012). High-input intensive or conventional agriculture performs measurably better when emission equivalents are expressed per kg of produce (e.g. per kg of meat or cereal). Yet, as pointed out by Tittonell (2015), "what causes global warming is the total net emission of CO_2 and related gases per area, irrespective of the yields obtained". Clearly the definition of system boundaries needs to be made explicit, and from an agroecological standpoint, it should focus on localized units.

CONCLUSIONS

In this review, we start from the problems that agriculture – both conventional high-input and resource-poor systems – faces, while recognizing the potential of agroecological approaches to provide viable, holistic solutions. TEEB for Agriculture and Food has the potential to help us better understand the costs and benefits associated with different types of agricultural production systems. Yet, the holistic, system-based approach of agroecology presents a number of conceptual and methodological challenges. This could and should be met by analytical methods that allow for non-linearity and feedback loops. For example, the use of modern modelling and simulation tools will help in understanding the present situation and to visualize a number of alternatives for the transformation of agriculture and food systems. The TEEB study can and will effectively address these challenges and arrive at an overall analysis that makes strides *vis-à-vis* reflecting the value in agriculture's complexity. While agriculture surely faces many problems, it also has the potential to be a solution; through supporting sustainable farming, livelihoods and food systems by – among other measures – restoring ecosystem services in agricultural landscapes, benefits to both people and biodiversity can be secured.

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REDISCOVERING OUR LOST "FARMACY": WHAT PROTECTIVE HEALTH FACTORS ARE LOST WHEN MOVING FROM AN AGROECOLOGICAL TO AN INDUSTRIAL MODEL OF AGRICULTURE?

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Abstract

It is well documented that populations experience a sharp increase in the prevalence of most chronic diseases – including cardiovascular disease, diabetes, obesity, autoimmune diseases, cancer and depression – when they abandon a traditional lifestyle in favour of a more industrial one. While many environmental and behavioural factors are responsible for this phenomenon, research shows that the nutrition transition is an independent and significant contributor. To better understand this dietary transition, most investigations have focused on identifying the aspects of the Western diet that are potential promoters of disease such as ready access to fast food or processed food. By contrast, this chapter focuses on understanding the agricultural systems underlying the nutrition transition and exploring what protective dietary factors are lost when individuals are no longer connected to a traditional way of farming based on agroecological principles. The protective benefits of agroecology will be discussed in four domains: (i) dietary diversity; (ii) microbial diversity; (iii) medicinal foods; and (iv) dietary behaviours.

INTRODUCTION

In low- and high-income countries worldwide, excessive calorie intake has begun to overshadow caloric deficiency as the major cause of malnutrition and micronutrient deficiency. This trend is largely responsible for the increasing prevalence of obesity-associated, non-communicable diseases including cardiovascular disease, diabetes, cancer and depression. In the 2015 report on *The State of Food Insecurity in the World*, FAO estimates that while 795 million people still suffer from undernourishment, 500 million adults are now obese (FAO, 2015). Given current trends, more than 1 billion adults are projected to be obese by 2030. In addition, many countries face the double-burden of obesity and undernutrition persisting at the same time (Kelly *et al.*, 2008).

While many lifestyle changes are responsible for this shift, epidemiological data consistently points to a 'nutrition transition' – the change in food composition and related dietary factors that occurs when abandoning a traditional way of living in favour of a more Westernized one – as a major contributing factor (Misra *et al.*, 2011). To date, most public health efforts to reverse this obesity epidemic have focused on mitigating the effects of a modern lifestyle by levying taxes and promoting initiatives to increase physical activity and curb the consumption of high-calorie, nutritionally sparse foods (e.g. fast foods and sugar sweetened beverages) (McPherson, 2014). By contrast, with the exception of studies that examine the toxicological impact of industrial agriculture or the nutritional advantages of organic versus conventional agriculture, there has been little attention given to understanding how the farming systems that underlie this nutrition transition might promote or prevent chronic disease.

This chapter proposes that examining what is lost in the shift from a diversified, resource-conserving, local farm system (subsequently referred to as an agroecological system) to a more centralized and industrialized food system, offers a new framework for understanding our modern health epidemic. Unfortunately, due to a longstanding divide between the fields of public health and agriculture, there is very little research establishing a direct link between agricultural practices and health outcomes. Nonetheless, using case studies and observational research we can begin to understand the protective benefits of agroecology in four interrelated domains: (i) dietary diversity; (ii) microbial diversity; (iii) medicinal foods; and (iv) dietary behaviours.

DIETARY DIVERSITY

A number of leading authoritative reviews have shown that dietary diversity is linked to improved health outcomes, and that a monotonous diet, even with biofortification, is associated with nutritional deficiencies and higher rates of chronic disease (Bélanger and Johns, 2008; Burlingame, 2014). Dietary diversity contributes to health by offering a better portfolio of the estimated 50+ micronutrients needed for optimal well-being and by enhancing the positive interactions between food types (e.g. ascorbic acid increases the uptake of iron through the intestinal wall). In addition, dietary diversity is associated with a higher intake of locally grown foods whose seeds are generally selected for taste and nutritional quality over yield (Allen *et al.*, 2014).

Agroecological systems are characterized by species and genetic diversity. By contrast, the hallmark of industrial agriculture is a radical reduction in diversity, with this system focused on producing the three main crops (rice, wheat and maize) that account for more than 55 percent of human energy intake in most urban settings. By reconnecting communities with a more agroecological food system, there is the potential to boost dietary diversity and therefore generate improvements in nutrition and human health (Burlingame, 2014).

Case study: diversifying diets in Micronesia

In the Federated States of Micronesia, the prevailing diet 40 years ago included over one hundred varieties of breadfruit and a rich diversity of banana, taro, yam, pandanus (tropical fruit), coconut, seafood and fruit. However, in the intervening years there has been a transition to nutrient-poor imported processed foods, such as refined white rice, flour, sugar and fatty meats. In tandem with this transition, the area has seen a sharp increase in non-infectious chronic disease related to nutrient deficiency. For example, over 12 percent of children now have night blindness (the eye relies on a complex complement of nutrients and vision issues are generally regarded as an early sign of poor nutrition), while over 32 percent of adults have diet-related diabetes.

To reverse this trend, a two-year, food-based intervention in one community promoted local food production and consumption using a variety of approaches from agricultural retraining, to changing food distribution patterns, to launching a "Go Local" media campaign. The programme

reintroduced a traditional orange-fleshed banana with 50 times more beta-carotene than the widely available commercial white-fleshed banana, and promoted other traditional varieties of fruits, vegetables and starches with superior nutrient and fibre content. A random sample of households (n=47) was used to measure the health impact of the intervention and results showed increased (110 percent) provitamin A carotenoid intake; increased frequency of consumption of local banana (53 percent), giant swamp taro (475 percent), and local vegetables (130 percent); and increased dietary diversity (Englberger *et al.*, 2011). In this study, post-intervention disease outcomes (such as rates of night blindness or blood sugar levels) have yet to be reported but these measurements would be instrumental in fully assessing the health impacts of a diversified diet programme.

MICROBIAL DIVERSITY

A second feature of an agroecological system is its reliance on soil micro- and macro-organisms, along with recycled nutrients from local resources, to maintain the health of the soil. This is in contrast to an industrial model that generally uses external inputs of soil supplements and fertilizer to achieve this same goal. Both diversity and quantity of soil biology have been shown to correspond to a higher nutrient concentration in food, even when controlling for seed type and other farm characteristics (Reganold *et al.*, 2010). A likely mechanism for this microbe-nutrient link is that specific organisms scavenge a unique complement of nutrients for specific plants (Antunes *et al.*, 2013).

In addition to boosting the nutrient concentration in food, there is preliminary data that a healthier profile of soil microbes might help promote a healthier gut microbiome in individuals connected to that farming system. Ecological studies looking at the gut biota of subsistence farmers in traditional agrarian communities in Europe and Africa have shown that an agroecological lifestyle is linked to a healthier gut microbial composition and lower rates of diseases such as allergic, autoimmune disorders and inflammatory bowel disease, both in adults and in children. One emerging explanation for this phenomenon is that direct contact with a diversity of soil bacteria is important for immunoregulation (von Hertzen and Haahtela, 2006; Haahtela *et al.*, 2013).

Case study: microbial diversity from European agroecological farms

A multicentre, cross-sectional, European research initiative focused on children living on agroecologically managed farms and found that, when compared with urban children, the rural children had lower rates of asthma and allergy. Analysis of the rural and urban microbial environments revealed that the type and quantity of micro-organisms on the farms (many of which originate from soil) were associated with the lower prevalence of allergic diseases (Ege *et al.*, 2011).

MEDICINAL FOODS

Agroecological systems incorporate indigenous cultivated and foraged plants, many of which serve a dual function as medicine and nutrition for the local community. While much more attention has been paid to the curative – versus preventive – role for wild plants, there is preliminary ethnobotanical data suggesting that the bioactive compounds and nutrient profiles of these local food/medicine resources may play a role in preventing chronic disease (Johns and Eyzaguirre, 2007).

Protective benefits of wild plants amongst Pima Indians

The much lower prevalence of type 2 diabetes and obesity in the Pima Indians in Mexico compared with Pima in the United States of America (2.6 vs 38 percent), suggests that even in populations with a genetic predisposition to these conditions, dietary factors can play a significant role in preventing or promoting disease (Schulz *et al.*, 2006). While whole, fibre-rich staple foods, and limited processed sugars and oils within the Mexican Pima diet are certainly a major contributor to their low rates of diabetes, there is a separate pool of data suggesting that the abundance of non-crop wild plants might also offer a similarly protective benefit. In one report, ethnobotanists identified over 306 species of native plants, many of them occurring in the northern regions settled by the Mexican Pima, which have hypoglycaemic (blood sugar-lowering) properties (Andrade-Cetto and Heinrich, 2005).

DIETARY CUSTOMS

The traditional dietary customs associated with an agroecological lifestyle are also linked to a variety of eating habits and dietary patterns that promote well-being. This includes family meals, afternoon siestas, nutritionally dense breakfasts and traditional religious fasts. One study in Spain showed that subjects who ate a nutrient-dense breakfast, an earlier lunch and a lighter dinner – an eating pattern typically associated with an agrarian Mediterranean lifestyle – had a lower body mass than those who ate later and skipped breakfast (Garaulet *et al.*, 2013). To date, very little research has been dedicated to understanding the connections between food production systems, eating patterns and community health, but one study suggests that within rural communities, group cohesion and reciprocity (two forms of social capital) can mediate positive health outcomes (Motohashi *et al.*, 2013).

Periodic religious fasting in rural Greece

Greek elders who maintain a traditional rural lifestyle are much more likely to adhere to the fasts of the Greek Orthodox region than their urban counterparts. Several studies comparing fasters and non-fasters show that periodic religious fasts produce a statistically significant improvement in lipid profiles and a reduction in body mass that extends beyond the fasting periods (Sarri *et al.*, 2003; Stathakos *et al.*, 2005).

CONCLUSION AND NEXT STEPS

Most public health efforts to reverse the obesity and chronic disease epidemic have focused on mitigating the effects of a modern lifestyle. With the exception of studies that examine the toxicological impact of industrial agriculture or the nutritional advantages of organic versus conventional agriculture, there has been limited focus on understanding how the underlying systems of agriculture might play a role in disease occurrence and/or prevention. While case studies, ecological studies and small sample case control studies suggest that agroecological farming systems might offer important protective medicine, there is an urgent need for transdisciplinary research in agriculture, ecology and public health in order to explore these connections and to develop novel interventions for addressing our most pressing public health problems.

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AGROECOLOGICAL SOCIO-ECONOMICS: AGROECOLOGY'S CONTRIBUTION TO FARM INCOMES, LABOUR AND OTHER SOCIO-ECONOMIC DIMENSIONS OF FOOD SYSTEMS

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Note: Gaëtan Vanloqueren (University of Louvain, BE) apologizes for not being able to produce a chapter for these Proceedings. This chapter builds upon the presentation he gave at the International Symposium, in particular the conclusion on the need to increase research on the social and economic impacts of agroecology. It is shared in the Proceedings with his full agreement.

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Abstract

What do we know about the relationship between agroecology and its effects on the socio-economic aspects of farmers' livelihoods? Do we have evidence that agroecology leads to positive impacts such as creating jobs, and increasing incomes and social well-being? This chapter will provide preliminary, indicative evidence that agroecology has positive social and economic impacts, which deserve consideration when seeking to design policies and programmes that improve food security and nutrition. We will also highlight that a pure economic lens is not adequate for agroecology; rather the wider socio-economic effects of agroecology must be taken into account. Far from a narrow 'agronomical' concept that is only meaningful at the crop or farmer level, agroecology takes a fresh look at many levels of food systems: how they are organized, and how they could be improved to enhance food and nutrition security.

INTRODUCTION

In the past decade, a number of reports and scientific studies have highlighted the significant positive impact of agroecological practices on agricultural yields (Pretty *et al.*, 2006; Uphoff, 2008; Wezel and Soldat, 2009; Ponisio *et al.*, 2015). Other analyses have found the reverse effect. De Ponti *et al.* (2012) show that the yield gap between organic and conventional systems may be larger than 20 percent and Seufert *et al.* (2012) identify specific aspects (e.g. system and site characteristics) that affect the result of such comparisons. Nevertheless, a growing number of reports have progressively demonstrated that agroecology has to be considered as a serious challenger to conventional, or high-input agricultural systems. At the same time, few research projects have attempted to assess not only the agronomical impacts of agroecology, but also the impacts of the adoption of agroecological practices on socio-economic variables such as farm incomes, health and nutrition, labour demand and employment generation. As an example, a Scopus search on agroecology indicated that since 1995, the combinations of "agroecology + labour", "agroecology + employment", and "agroecology + income" provided only 8.2 percent of the overall search results for "agroecology".[1]

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[1] Based on a Scopus database analysis conducted on 21 May 2015. Cumulative results are from 1995-2015.

SCOPE AND BOUNDARIES

The aim of this chapter is to provide a first effort in approaching different ways of documenting the socio-economic effects of agroecology. This represents an initial attempt to understand the effects of agroecological practices at the farm level. Consequently, the results are not definitive.

A Scopus search was conducted in order to identify scientific work addressing the contribution of agroecological practices to a set of socio-economic indicators, which contribute to the sustainable livelihoods of farmers. A vote count analysis was then carried out on the identified research, which we present here including a discussion of the methodological challenges. The vote count analysis is supplemented by a series of complementary case studies.

We recognize a number of limitations of this initial analysis. First, we have chosen to adhere to the Sustainable Livelihoods (SL) Framework, as articulated by many initiatives and researchers. The SL Framework represents one of the most recognized tools to analyse poverty from a multi-dimensional perspective, which allows an improved understanding of social and economic relations at the farmer level. The SL Framework has been employed for many years in rural areas (Nelson *et al.*, 2010), including within FAO assessments (Baumann, 2002; Cleary *et al.*, 2003; Seshia and Scoones, 2003; Tayyib *et al.*, 2007; Garibaldi and Dondo, 2014). However, because of our need to focus on very specific aspects of sustainable livelihoods, our analysis is largely restricted to household-level capital endowments[2], explicitly not addressing other important endowments such as land tenure, environmental characteristics and governance systems, which can have significant impacts on household-level assets. We acknowledge this restriction of our analysis and focus, and suggest that these aspects need consideration in further research.

Second, our initial analysis is based strictly on a Scopus literature search, using a controlled vocabulary of search terms. This method was used as a means of utilizing strictly objective criteria for identifying evidence. At the same time, this approach may neglect other spheres of evidence. For example, a major restriction is that the grey literature originating from the community-level is not included. This is often an important source of information exchange, particularly in the field of agroecology.

SUSTAINABLE LIVELIHOODS FRAMEWORK AND INDICATORS

The SL Framework uses five kinds of assets (human, natural, financial, physical and social) to structure the analysis of the sustainability of livelihoods. The definition of each asset is provided in Table 1, along with the indicators used in the present study.

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[2] Relevant farm/community-level indicators have been identified in this study; although not all have been included in the initial quantitative analysis due to data limitations (see Table 1).

Table 1. **Description of livelihood assets and related socio-economic indicators at farmer level**

LIVELIHOOD ASSET:	POTENTIAL INDICATORS USED IN THIS STUDY:
Human capital: represents the skills, knowledge, ability to work and good health that together enable farmers to pursue different livelihood strategies and achieve their livelihood objectives	Labour productivity
	Labour demand
	Percentage of farmers (gender disaggregated) who participated in a training and subsequently decided to incorporate agroecology in their farm practices*
Natural capital: is the term used for the natural resource stocks from which resource flows and services useful for livelihoods (e.g. nutrient cycling, erosion protection) are derived	Not considered in this study, but widely studied in terms of the ecological performance of agroecological practices
Financial capital: denotes the financial resources that farmers use to achieve their livelihood objectives. There are two main sources of financial capital: » Available stocks » Regular inflows of money	Yield
	Farm profitability
	Income stability*
	Recognition/assessment of transition costs from conventional systems to agroecological systems*
Physical capital: comprises the basic infrastructure and producer goods needed to support livelihoods: » Infrastructure consists of changes to the physical environment that help farmers to meet their basic needs and to be more productive » Producer goods are the tools and equipment that farmers use to function more productively	Not considered in this study
Social capital: in the context of the SL Framework, refers to the social resources upon which farmers draw in pursuit of their livelihood objectives. These are developed through: » Networks and connectedness » Membership of formalized groups » Relationships of trust and reciprocity	Access to the market for the products of agroecology*
	Number and quality of registered groups (gender disaggregated) in a certain community*
	The presence of formal procedures/rules allowing stakeholders to influence decision-making processes*

* Quantitative data on these indicators have not been included in this initial stage of the analysis.

Source: DFID, 1999

Ten indicators have been selected in order to observe the general effects and trends of agroecological practices with respect to the SL Framework. Quantitative information has been gathered and analysed for the following indicators:

- **Yield:** refers to the measure of the amount of output produced by a farm;
- **Farm profitability:** is the difference between gross farm income and expenses;
- **Labour demand:** is the amount of demand for labour in the market;
- **Labour productivity:** is equal to the ratio between a volume measure of output (yield) and a measure of input use, which can be the total number of hours worked or total employment (head count).

In this initial analysis we considered just three of the five assets in the SL Framework (human, financial and social capital), and the indicators within these assets that pertain to household-level capital endowments. While we recognize that macro-level indicators are also of high importance for the livelihoods of farmers and pastoralists (e.g. Nkonya *et al.*, 2004), such an analysis goes beyond the scope of the current study. Certainly factors affecting farm incomes and livelihoods are far broader and interlinked. The full range of these factors merit consideration in future studies.

AGROECOLOGICAL PRACTICES

Identifying a set of agroecological practices to include in this review has substantial challenges. As emphasized in this volume, agroecology is not a package of technical practices, and management choices surrounding practices are always based on the location-specific context (Tittonell, 2015). Practices themselves are not distinct entities in an agroecological approach; agroecology is a set of principles that enables farmers to manage complex systems and find synergies among practices. Nonetheless, the transition process to agroecological systems begins with replacing conventional practices with more efficient and alternative practices (Gliessman, 2015). Thus, noting these caveats, we classified agroecological practices as those practices that: (i) reduce dependency on external inputs; and (ii) increase the productive capacity of biotic system components.

As a first step, an initial list of agroecological practices was identified, mainly based on the reports of Milder *et al.*, (2012) and Garbach *et al.*, (2014). Because of time constraints, only a subset of all the identified practices were considered at this stage of the analysis. A description of the practices that were actually considered is provided below:

- **Crop diversification:** refers to the addition of new crops or cropping systems to agricultural production on a particular farm taking into account the different returns from value-added crops with complementary marketing opportunities (Christiansen *et al.*, 2011).
- **Direct seeding:** Seeds are sown directly into the main field (Eskandari and Attar, 2015). Usually seeds are sown directly in permanent plant cover: residue from the previous crop that has been left on the ground, in addition to mulched dead or live cover (AFD/FFEM, 2007).
- **Minimal tillage:** aims to minimize soil disturbance, including reducing the number of tillage passes, tillage depth or stopping tillage completely. The definition of minimal tillage also includes reduced- and non-tillage practices (Rusinamhodzi *et al.*, 2011).
- **Perennial cultivation:** Perennial crops are crops that are alive year-round and are harvested multiple times before dying. In contrast, annuals die each year and must be replanted. Perennials may have periods of dieback but will regrow the following year. Technically, perennials can live for as few as two years, although those that live for three or more years are often considered as ‘true perennials’ (Batello *et al.*, 2014).
- **Water harvesting:** structures such as percolation ponds and check dams are made to help raise the water table and recharge bore wells in adjoining agricultural land (Kaushal *et al.*, 2005).

- **Water-use efficiency (practices):** This refers to efficiency gains made possible through suitable crop selection, proper irrigation scheduling, effective irrigation techniques, and using alternative sources of water for irrigation, such as recycled water. While not a practice *per se*, many different agroecological practices (permanent soil cover, biological nitrogen fixation, etc.) can positively affect water-use efficiency, and thus "water-use efficiency" was used as a search term to capture this category of practices.

METHODOLOGY

Vote count analysis

For the vote count analysis of the scientific literature, peer-reviewed articles and papers from conference proceedings were searched within the Scopus[3] database. The search terms used combined single practices (direct seeding, minimal tillage, perennial cultivation, crop diversification, water harvesting, and water-use efficiency) and key words (labour, profitability, revenue, cost, market access, and empowerment) which were selected according to the indicators described above. Both the practices and indicators were identified through a review of the existing literature and a subsequent process of consulting international experts in the field of agroecology. In this first phase of the analysis we mainly focused on practices related to crop production (e.g. minimal tillage and direct seeding). Despite this, we acknowledge that practices from forestry as well as integrated crop-livestock systems are of importance to agroecology and they will be included in a future extension of this work.

Not all of the combinations of 'agroecological practices' and 'keywords' generated a full list of possible options and because of the large amount of literature found for certain word combinations, only the top ten results, as assessed by Scopus at the time of the analysis, were taken into account. Thus, only a fraction of the complete set of relevant papers has been analysed so far and the results presented should be seen as a preliminary analysis. At the time of writing, 42 papers had been reviewed, with data extracted from 18 of these papers that met the following criteria: (i) the paper's abstract refers to at least one of the agroecological practices listed above; and (ii) the study provides meaningful information on the socio-economic indicators selected for this exercise. Yield data alone is insufficient to comply with this condition, as other indicators such as farm profitability or labour productivity are necessary for a more comprehensive assessment. Within these 18 studies, a larger number of actual comparisons were presented as a number of studies included more than one relevant comparison between agroecological and conventional practices.

An analytical framework has been developed to guide the systematic data extraction from the reviewed papers. As part of this framework a database was created and used to conduct the quantitative and qualitative analysis presented below. The database includes information on:

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[3] Available at: www.scopus.com

(i) author, source and publication date of the reviewed papers; (ii) agroecological practices or set of practices considered; (iii) socio-economic indicators (treated group and comparison baseline); and (iv) main findings and conclusions from the author(s) of the original papers.

A vote count technique, largely applied in ecology and evolutionary biology, was selected to analyse the available quantitative data. The vote count method was favoured over meta-regression as it responds better to the broad scope of the analysis conducted. Therefore, more studies could be included than in a meta-regression, which is limited to studies that contain appropriate documentation of methods (Prokopy *et al.*, 2008). The vote count method has been widely used to investigate farmers' adoption of conservation agriculture and best management practices (Knowler and Bradshaw, 2007; Prokopy *et al.*, 2008), and thus appears appropriate for our analysis.

The analysis comprised the following stages. First, the number of positive studies (showing benefits of agroecological practices compared with conventional practices) was compared with the number of negative studies (showing costs, or decreases in indicator values of agroecological practices compared with conventional practices). Absolute, relative and cumulative frequencies were then computed to compare and integrate the results of multiple studies and to identify general patterns (Milder *et al.*, 2012). Moreover, in order to see the general trends between adopting agroecological practices and socio-economic indicators, the percentage change between agroecological and conventional practice has been computed.

The percentage change is calculated using the following formula:

> $$\%\Delta x = 100 * (\Delta x / xc);$$
>
> Where $\Delta x = xa - xc$;
>
> xa = value obtained adopting agroecology practices;
>
> xc = value obtained adopting conventional practices.
>
> The vote count threshold is based on the percentage change as follows:
> Arrow ↑ (increased, positive studies): if the percentage change is > +5%;
> Arrow ↔ (neutral, neutral studies): if the percentage change is between -5%≥ and ≤+5%;
> Arrow ↓ (decreased, negative studies): if the percentage change is <-5%.

Case studies

In addition to the objective approach of the vote count method, a number of relevant case studies that provide evidence on agroecology's socio-economic impacts are introduced in the discussion of results below. These case studies are based on the presentation that Gaëtan Vanloqueren gave during the FAO International Symposium on Agroecology for Food Security and Nutrition. While each of the case studies is highly relevant, we are aware that they only touch on a subset of the topics discussed in this chapter.

ASSUMPTIONS AND LIMITATIONS

The assumptions and limitations of the vote count analysis carried out in this study are the following:

- Data from the same experiment that were reported in more than one publication have only been counted once.
- The organic price premium has not been taken into account in any of the reviewed studies that analyse farm profitability.
- For the costs that have been extracted from the reviewed studies, no differences have been taken into account between fixed and variable costs.
- The comparison between agroecological and conventional practices has been considered according to the *ceteris paribus* (other things equal) law; that is, all other conditions remaining constant.
- The comparison baseline for conventional agriculture was taken as that provided by the analysed paper. Consequently, it changes from one paper to another.
- Important aspects such as the ecological and environmental services provided through agroecological systems have not been directly considered in the analysis. This study focuses on a limited set of social and economic indicators, in line with the key points raised during the International Symposium on Agroecology for Food Security and Nutrition. We do recognize the need to consider these indicators in a holistic framework. However, very few of the identified studies would be eligible if we applied this criterion from the start of the analysis.
- The vote count provides an analysis of the adoption of certain practices rather than an analysis of the whole agroecological systems associated with the selected practices.
- The vote count analysis does not differentiate between the effects on socio-economic indicators at farm level in low-, medium- and high-income countries. Therefore, it provides a general overview of the socio-economic impacts of agroecological practices without providing a breakdown of these effects on different income groups.

GENERAL TRENDS BASED ON THE VOTE COUNT ANALYSIS AND CASE STUDIES

Agroecology and yield

The standard and most well-documented economic metric comparing alternative (often organic) production methods with conventional systems, focuses on yields. Compared with conventional agriculture, numerous studies have found that agroecological practices maintain or increase crop yields (Hobbs and Gupta, 2004; Pretty *et al*., 2006; Badgley *et al*., 2007; Kassam *et al*., 2009; Ponisio *et al*., 2015). In our vote count review, the positive relationship between agroecological practices and yields is supported: 60 percent of the comparisons (24 out of 40) included in the vote count analysis show an increase in crop yields when using agroecological instead of conventional practices (see Figure 1).

Agroecology and farm income/profitability

Arguably, of greater importance to individual farm enterprises is that both the results from the vote count analysis and existing specific case studies indicate a positive effect of agroecological practices on farm income or farm profitability. The vote count analysis indicates that 56 percent of relevant comparisons (22 out of 39) found an increase in farm profitability related to the use of agroecological practices (see Figure 1). Several studies on the impact of agroecology on income corroborate this evidence. For example, these include agroforestry in Zambia (Ajayi *et al.*, 2009), push-pull maize cropping in eastern Africa (Khan *et al.*, 2011), the System of Rice Intensification in various places (SRI-Rice, 2014) and animal integration into crop production in East Africa (Altieri and Nicholls, 2012). In Brazil, vegetative contours, reduced tillage, terracing and integrated nutrient management increased farm net income by over 100 percent, while conservation agriculture and agroforestry increased farm net income by over 160 percent (Branca *et al.*, 2011). In a study in the Philippines, organic farmers were found to have 1.5 times higher net incomes than conventional farmers (Altieri and Nicholls, 2012).

Agroecology and labour demand

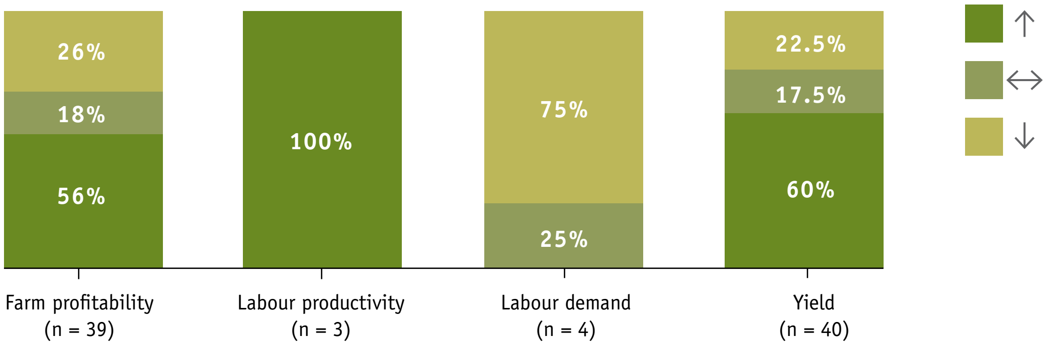
In terms of employment generation there are case studies pointing to the creation of employment through agroecological practices. Notable is the case of young men employed for land rehabilitation in Burkina Faso (Pretty *et al.*, 2011). Furthermore, by increasing the resilience of production systems, agroecological practices can also be associated with maintaining existing jobs better than conventional production systems (Holt-Giménez, 2002; IPCC, 2007). However, the vote count analysis shows a decrease in the labour demand when using agroecological practices in 75 percent of comparisons (3 out of 4, see Figure 1). This needs to be qualified, as three of the four comparisons that were included specifically looked at practices related to conservation agriculture (CA). CA is known to reduce workload and save energy in certain cases (Eskandari and Attar, 2015). The practice of direct seeding, combined with zero-tillage and mulching, makes CA considerably less labour intensive than conventional farming and also more cost effective. Dawe (2005) estimated that 5 person-days ha^{-1} were required for broadcasting compared with 25-50 person-days ha^{-1} required for transplanting. Newby *et al.* (2011) found a saving of about 30 person-days ha^{-1} using CA from a survey in Laos. The overall picture on the creation of jobs shows that on one hand a single agroecological practice can reduce labour demand at farm level, while on the other hand, overall agroecological management systems (e.g. agroforestry systems) can lead to the creation of economic opportunities, shifting the labour paradigm from labour saving to employment generation.

Agroecology and labour productivity

The review of three comparisons related to labour productivity showed increased productivity associated with agroecological practices in all three cases (3 out of 3, see Figure 1). All these comparisons however come from one study on CA; Lestrelin *et al.* (2011) provide detailed

results of a 4-year monitoring and evaluation study conducted in 21 villages in Laos on the agro-economic productivity of direct seeding mulch-based cropping systems compared with conventional tillage-based systems. On average, adopting agroecological practices increased labour productivity by about US$3.33 per day.

Figure 1. **Socio-economic indicators (relative frequencies)**



APPLYING A SOCIO-ECONOMIC LENS WHEN ASSESSING AGROECOLOGY

While an analysis of economic indicators can be useful when assessing agroecological practices, a wider socio-economic lens provides a more powerful framework for assessing the contribution of agroecology. A socio-economic perspective can help to address the full potential of agroecology, beyond food security to sustainable food systems that enhance human well-being. In this context, the Belgian Interdisciplinary Agroecology Research Group (GIRAF) identified the following five socio-economic principles underlying agroecology (Stassart *et al.*, 2012):

» Agroecology is about social organization generating collective knowledge and adaptability through networks involving producers (e.g. grassroots organization and community seed banks);

» Knowledge plays an essential role in agroecology recognizing the diversity of skills and knowledge (e.g. indigenous knowledge);

» Agroecology is about fostering autonomy allowing farmers to become less dependent from the fluctuation of the market (e.g. crop diversification);

» Agroecology seeks to improve social equity in food systems through mechanisms of solidarity (e.g. pricing systems along the food chain and farmer multinational cooperatives);

» Agroecology aims to improve/strengthen democracy at several levels: member's power within an organization is not based on their assets and decisions are taken through a democratic process.

Although a quantitative vote count analysis was not possible for some indicators (see above), the papers of Kaushal *et al.* (2005) and Lestrelin *et al.* (2011) provide valuable entry points to further examine the socio-economic principles of agroecology developed by Stassart *et al.* (2012). The potential socio-economic benefits stand alongside other positive externalities of agroecology, such as improved nutrition through more diverse production systems, and positive environmental externalities including improved soil and water quality (Garrity *et al.*, 2010). As is evident in the case study reports, the social organization aspect of agroecology is another important positive externality that builds social capital and empowers food producers and their communities (Kaushal *et al.*, 2005; Chikowo *et al.*, 2011).

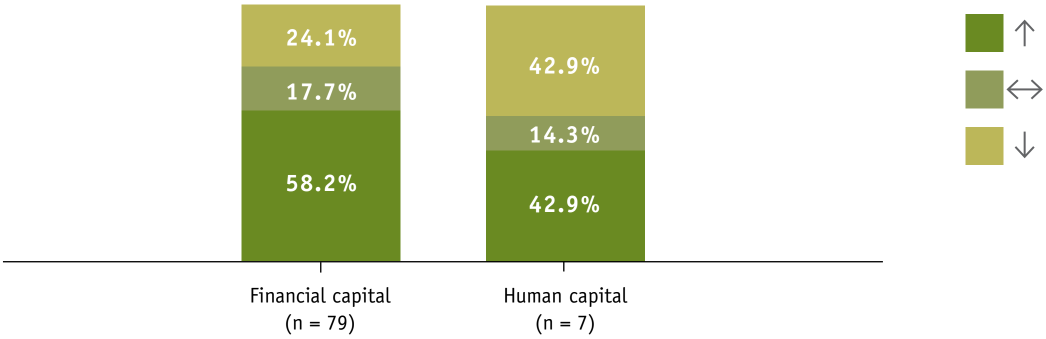
SUSTAINABLE LIVELIHOODS FRAMEWORK RESULTS

On the basis of 86 comparisons it has been possible to identify some general trends of adopting agroecological practices according to the SL Framework. The absolute frequencies of the indicators that fall under the same asset category (e.g. financial or human capital) have been summed under that asset and the relative frequencies have been computed for each asset category. So far only two out of three assets have yielded sufficient quantitative data: financial and human capital. While social capital has been included in the overall analysis it could not be included here because of a lack of quantitative data.

Figure 2 shows the relative frequencies of comparisons that referred to financial and human capital. On the one hand, financial capital increased using agroecological practices compared with conventional agriculture in 58.2 percent of comparisons (46 out of 79). On the other hand, human capital shows a balance between agroecological and conventional practices, with increases in 42.9 percent of comparisons (3 out of 7) that adopted agroecological practices.

Kaushal *et al.* (2005) provide qualitative evidence of a general positive impact of Community-Based Forest Management Systems in influencing decision-making processes. This evidence points to a positive effect of agroecological systems on social capital, but as a single study, it also points to the need for increased research on this relationship.

Figure 2. **Effects of adopting agroecological practices on the SL Framework (relative frequencies)**



CONCLUSION

This study has found preliminary evidence of agroecology's positive contribution to social and economic indicators. However, many possible dimensions of agroecology remain poorly documented. We advocate that efforts to document the socio-economic effects of agroecology – and not purely its economic effects – should be intensified. Such efforts should not only look at micro-level indicators such as income and profitability but also consider meso-level and macro-level issues such as overall employment or equity and governance. Even though only a limited number of papers have been reviewed so far, evidence suggests that agroecology enhances financial capital, human capital and social capital contributing to sustainable livelihoods at the farmer level. Through building this evidence base further, the mainstreaming of agroecology as a science, practice and movement can be supported and made more effective.

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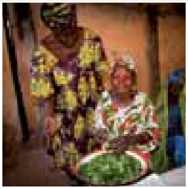

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LEARNING AND INNOVATING TOGETHER: A PARTNERSHIP BETWEEN FARMERS, SCIENTISTS, PUBLIC AND PRIVATE ORGANIZATIONS

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Abstract

Unlike the top-down approach of conventional research, participatory research methods offer a bottom-up approach, involving all major stakeholders from the beginning of a research project. Integration of the end users of research (i.e. farmers) enhances the acceptance and adoption of innovations, along with making the best use of the local knowledge that is available. The Research Institute of Organic Agriculture (FiBL), Switzerland – one of the world's leading institutions in the field of organic agricultural research – participates in numerous international projects, involving research, consultancy, training and development cooperation. With the objective of providing sound scientific information by comparative analysis of various agricultural management systems (e.g. conventional, organic, biodynamic), FiBL initiated a long-term research programme in 2007, called the Farming Systems Comparison in the Tropics (SysCom). Participatory On-farm Research (POR) is a strong component of the SysCom programme, along with Long Term Experiments (LTEs) running on four research sites across three tropical countries (Kenya, India and Bolivia).

POR involves the active participation of various stakeholders, including local farmers, extension workers, trade/industry partners and researchers, in problem identification, exploration of possible solutions and testing of the proposed innovations. Experiments are conducted on both research farms (mother trials) and farmers' fields (baby trials). Effective use of local knowledge and locally available resources is a priority in our POR work. Our participatory research activities on homemade organic pesticides and enhancing phosphorus availability have shown remarkable success. We have developed a methodology to produce compost enriched with acidulate rock phosphate (RP) using locally available materials and have standardized the methodologies for preparation of various botanical pesticides. To address the strong demand for organic cottonseed, we started participatory breeding activities that have developed into a large-scale breeding project (Green Cotton Project).

In addition to the local farmers, we work in participation with an industrial partner (bioRe India) in Madhya Pradesh state, India; bioRe ensures the supply of inputs and procurement/marketing of organic cotton produced by the local farmers. The SysCom programme is financially supported by a coordination committee of donors comprised of various public and private funding bodies. Backstopping by a well-qualified scientific advisory board ensures that the research conducted in SysCom meets international standards. This case study describes the success of this partnership between farmers, researchers, public and private institutions.

FIBL SWITZERLAND

FiBL is one of the world's leading institutions in the field of organic agriculture research and consultancy. FiBL's strengths include closely linked interdisciplinary research and the rapid transfer of knowledge from research, to extension, to agricultural practice. Committed to the international development of organic agriculture, FiBL works closely with the International Federation of Organic Agriculture Movements (IFOAM) and other international organizations. Along with its expertise in farming practices, organic soil management, plant production, holistic animal health, animal ethology, animal breeding, socio-economics, comprehensive analysis of the organic market, organic food processing and production, FiBL places a high priority on knowledge transfer into agricultural practice. This is achieved through FiBL's advisory work, training courses and expert reports, including dissemination through magazines, the monthly journal *bioaktuell*, technical leaflets, reference books, videos and internet material. As FiBL's competence in organic agriculture is sought after globally, it is involved in numerous international projects, including research, consultancy, training and development cooperation.

THE SYSCOM PROGRAMME

A net increase in global food availability was achieved during the last century by intensification of agricultural production using energy-intensive conventional agricultural practices (Trewavas, 2002; Tscharntke *et al.*, 2005). This development has been accompanied by deteriorating natural resources, caused by inefficient use of fertilizers, pesticides and fossil energy (Pimentel, 1996; Singh, 2000; Rigby and Càceres, 2001; Badgley *et al.*, 2007). Continuing with the same approach would be unsustainable. A more system-oriented approach like organic agriculture is preferable because it builds on the efficient use of available resources and the use of locally adapted technologies. The system-oriented approach is particularly promising in risk-prone tropical ecosystems with burgeoning populations. However, organic agriculture has been criticized as not being capable of 'feeding the world', as well as for its low labour productivity and high production risks (Kirchmann *et al.*, 2008; Seufert *et al.*, 2012). The advantages of organic farming systems in terms of resource efficiency, ecosystem functioning, soil fertility conservation and economic impact have been proven in a wide range of studies conducted under temperate environments mainly in industrialized countries (Offermann and Nieberg, 2000; Stolze *et al.*, 2000; Maeder *et al.*, 2002; Pimentel *et al.*, 2005). In recent years, organic agriculture has also gained ground in developing countries, although the experimental evidence on its comparative advantages under tropical conditions is rather limited. With the objective of establishing a scientific basis for discussions on the performance and potential of organic agriculture compared with conventional production systems in the tropics, FiBL is running the long-term SysCom programme to compare farming systems in Kenya, India and Bolivia. The programme is based on LTEs that capture and monitor the effects of contextual changes over time, together with the POR approach that aims to develop technological innovations and management practices adapted to local farmers' conditions.

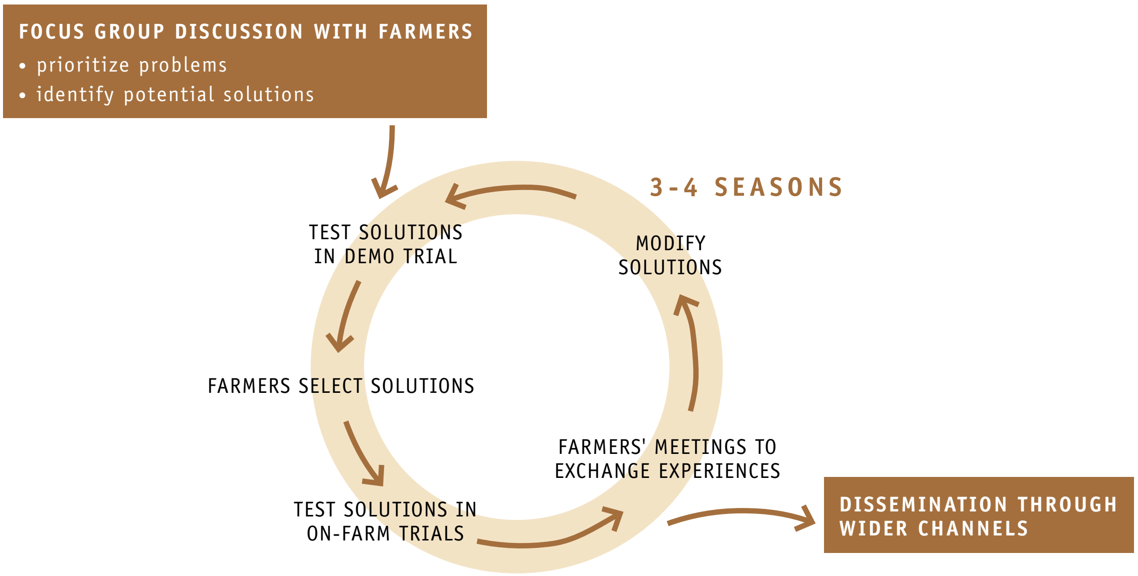
Started in 2007, the SysCom programme is coordinated by FiBL, with the project activities in the partner countries being implemented by local institutions. The International Centre of Insect Physiology and Ecology (ICIPE), bioRe Association and Ecotop are the main local partners in Kenya, India and Bolivia, respectively. In Kenya, the conventional and organic treatments are applied at two input levels in a three-year (six-season) crop rotation with maize, beans, vegetables and potatoes at two field sites. In Bolivia, conventional and organic cacao production systems are being studied in monoculture (full sun) and agroforestry (shaded) systems. In India, the trial compares organic, biodynamic, conventional and genetically modified Bt cotton farming systems in a two-year crop rotation with cotton, soybean and wheat as the main crops.

PARTICIPATORY ON-FARM RESEARCH

An important component of the SysCom programme is the use of the POR approach to develop locally adapted solutions for the most critical production challenges faced by the farmers. POR involves active participation of various stakeholders – particularly the farmers as end users of research – throughout the process of innovation development. We make use of an innovation cycle that includes the key steps of problem identification, exploration of possible solutions and testing of the proposed innovations (Figure 1). Focus group discussions, farmers' meetings and field visits help to prioritize problems and to identify potential solutions, thereby making effective use of local knowledge and locally available resources.

A 'mother-baby' trial concept is used to conduct field experiments on research farms (mother trials) as well as on farmers' fields (baby trials). 'Mother trials' are set up to test the potential solutions that have been identified within a scientific environment. 'Baby trials', on the other

Figure 1. **Innovation cycle used in Participatory On-farm Research**



hand, are conducted on the fields of local farmers to test these innovations under actual farm conditions, which present more realistic circumstances. While on-farm trials are conducted by the farmers themselves under the guidance of research staff, farmers also participate in each stage of experimentation from set-up to evaluation of the on-farm trials. The POR approach offers farmers an opportunity to gain experience in critical evaluation of new technologies and in overcoming the challenges of implementation by further adapting technologies to suit their particular requirements. If it becomes apparent that farmers need to know more in order to experiment by themselves, tailor-made trainings are offered.

INVOLVEMENT OF STAKEHOLDERS

Besides local farmers, the active participation of various stakeholders, including researchers, extension workers, trade/industry partners and public institutions is a characteristic feature of the SysCom programme. The advantage of this structural arrangement is particularly evident in the case of India, where the project is set up in close collaboration with bioRe Association and bioRe India Ltd in Madhya Pradesh state (Figure 2). The bioRe Association is a farmers' body undertaking activities of social importance, such as the provision of health care and education in rural areas of Madhya Pradesh. The research division of bioRe Association aims to provide local solutions for sustainable agricultural production with a main focus on cotton, which is the most important cash crop in the region. The raw organic cotton is procured by bioRe India Ltd and processed for export to the international market. Besides maintaining a strict quality control, provisioning of seeds and inputs, and organizing the certification for organic farmers, bioRe's extension and training team also supports the farmers in obtaining optimal production of their organically cultivated cotton. Remei AG, one of the most important trade partners of bioRe, produces organic textiles for the Naturaline brand of Coop, which is a significant retailer in the Swiss market. With this arrangement, bioRe offers secure access to the global market for organic smallholder farmers. Furthermore, Coop is a significant donor to the research and development projects run by the bioRe Association. Along with continued support from the Swiss Agency for Development and Cooperation (SDC), Liechtenstein Development Service (LED) and Biovision Foundation, the Coop Sustainability Fund financed the SysCom programme until 2014. From 2015 onwards, the Coop Sustainability Fund is supporting research activities in India by means of a new project entitled long-term sustainability of organic cotton production in India, which is closely associated with SysCom. This is an exemplary model of the integration of research within agri-value chains, and will be published in the forthcoming FAO handbook on *Developing sustainable food value chains*.

In this research cooperation, the basic project management and research activities are conducted by the bioRe research staff under the supervision of FiBL researchers. In addition, core research activities are being carried out in collaboration with various universities and public research institutions. For example, Ph.D. and Master's thesis projects are being carried out in collaboration with Govt. Holkar Science College, Indore, the Swiss Federal Institute of Technology (ETH), Zurich, and the University of Hohenheim. Moreover, a number of Bachelor student projects have been undertaken in collaboration with the School of Agricultural, Forest and Food Sciences, Switzerland, the Zurich University of Applied Sciences and other academic institutions in Europe. A Scientific Advisory Board (SAB) comprised of internationally renowned agricultural scientists backstops the research work being conducted in the SysCom programme, ensuring that high standards are maintained.

ACHIEVEMENTS IN POR

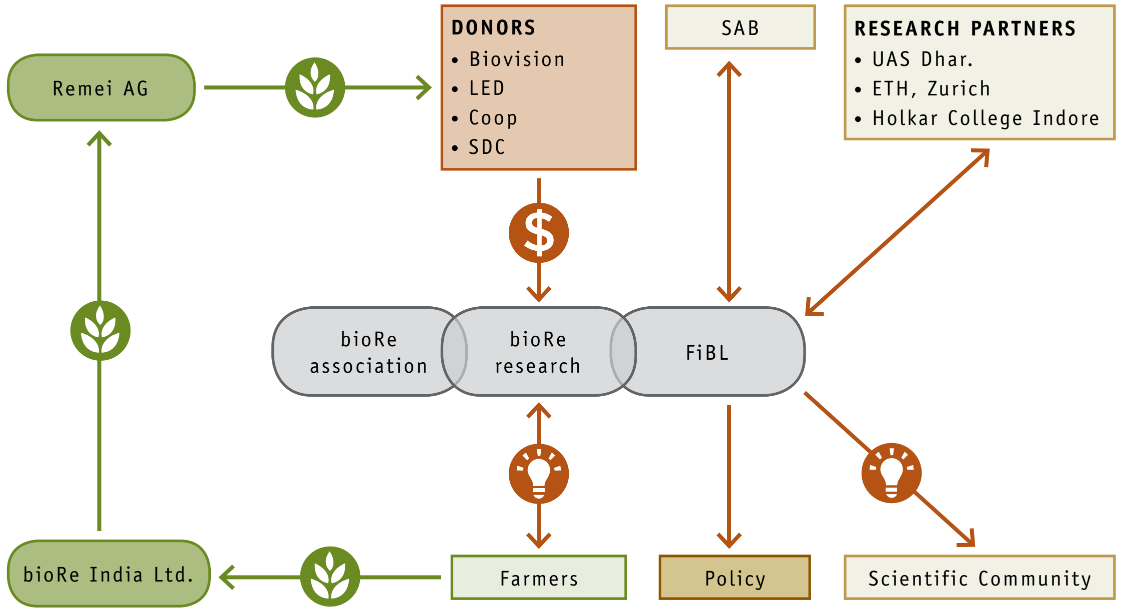
Using the participatory approach, two major challenges facing organic cotton farmers were identified: crop nutrition and pest control. In the brainstorming sessions we also explored various opportunities to overcome these challenges using local materials. To improve the nutrient supply for organic crop production, two lines of action were implemented in parallel: (i) improving farmyard manure management; and (ii) efficient use of RP on high pH soils. For the first line of action, a locally adapted compost making process was standardized in partnership with the farmers. For the second line of action, we tested a number of local products to acidulate RP to enhance the availability of phosphorus in organic agriculture. Experiments conducted on the bioRe research farm revealed that butter milk was the best locally available material for acidulation of RP. Subsequently, the two lines of action were combined together by incorporating the acidulated RP into well-prepared compost. Field trials were conducted on the research station as well as farmers' fields using the mother-baby trial concept, which led to the standardization of the methodology for RP enriched compost. To enhance the motivation and participation of local farmers in this project, a competition was run during 2013. Every farmer exhibited excellent commitment and participation; the farmer who produced the best manure using the standardized methodology was awarded a cow and a calf, while others also received consolation prizes. Further agronomic trials are being conducted on farmers' fields to quantify the effect of the methodology on the yield and quality of various crops.

In a similar manner, making the best use of available local knowledge, we have standardized the preparation methodologies of various botanical pesticides. These formulations and their dosages are being tested against specific pests (e.g. cotton bollworm, cutworms and sucking pests). Due to organic farmers' urgent need for high-quality cottonseed in India, POR trials with cotton cultivars started in 2010 and have since become a prominent national issue. This preliminary research resulted in the development of the Green Cotton Project, a large-scale associate project on participatory cotton cultivar evaluation and breeding, aiming for locally-adapted cultivars and seed sovereignty (Messmer *et al.*, 2013), in collaboration with NGOs, private and public institutions.

DISSEMINATION AND EXTENSION

The combination of the POR and LTE methods has proven successful in offering a suitable platform to provide practical solutions to the farming community. LTEs serve as important focal points for information and discussions on sustainable agricultural practices, attracting

Figure 2. **Involvement of various stakeholders in the research process**



hundreds of visitors every year, including farmers, extension workers and researchers. The direct involvement of farmers and other stakeholders in the POR approach helps in two ways. First, it ensures the success of the developed technology by already considering the interests of farmers from the beginning of the process. Second, through the participation of farmers, the newly developed technology is effectively disseminated by word of mouth.

In parallel, farmers and extension workers are being trained in pest-monitoring strategies. We have developed a number of leaflets and brochures to be used by farmers and extension workers, which are available to download for free on our website (www.systems-comparison.fibl.org/en/scp-publications/leaflets-brochures.html). In addition, the SysCom programme has made significant contributions towards capacity building by training project staff, 19 B.Sc. and M.Sc. students, six Ph.D. students and several interns in the three countries. For dissemination of the research results, three peer reviewed articles have been published in scientific journals, together with 45 conference contributions, and 30 international and national media releases and radio broadcasts.

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21

NILGIRI BIOSPHERE RESERVE: A CASE STUDY FROM INDIA

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ORGANIZATION AND DESCRIPTION OF THE AREA

The Keystone Foundation works on eco-development initiatives with indigenous communities in the Nilgiri Biosphere Reserve in the Western Ghats, spread mostly across Tamil Nadu and partly in Karnataka and Kerala. It has established strategies and practices that conserve biodiversity and address the livelihoods of forest dependent communities. Currently it has programmes with bees and forest biodiversity, traditional and organic agriculture, water and wetlands, environmental governance, organic market development and culture and local governance (see: www.keystone-foundation.org).

The Nilgiri Biosphere Reserve in the Western Ghats is home to the moist, dry, evergreen and montane (shola) tropical forests. The Western Ghats, and the Nilgiris in particular, harbour a wealth of flora and fauna; much of which is endemic to the region, e.g. the endangered Lion-tailed Macaque and the Nilgiri Tahr. However, the Nilgiri forest ecosystem is under pressure from the encroachment of tea and coffee plantations, commercial vegetable cultivation, illegal logging, and commercial tree plantations with exotic species initiated by the Forest Department.

The Nilgiri Biosphere Reserve is home to a large number of indigenous *Adivasi* communities, most of them forest dwellers and hunter-gatherers dependent on natural resources for their livelihoods. These distinct ethnic groups have small populations and live in geographical concentrations. Significant land-use changes have taken place in the Nilgiri forest over the past 200 years, with a steady shift towards the cultivation of commercial species and crops, both in the forest and in agricultural lands. The Kurumba and Irula communities cultivate minor millet, vegetable and fruit trees in their community land holdings. Variable rainfall and crop raiding by wild animals are two factors that threaten their food security. Many times, these threats have forced the community to discontinue farming practices, leading to large tracts of land becoming fallow and semi-wild. In addition, the collection of non-timber forest products (NTFPs) is an important traditional activity for the communities to meet their livelihood requirements. Previously, the entire family used to go into the forest to collect gooseberries, soapnuts, gallnuts, barks, roots and phoenix leaves (according to the season), which would then be sold to small traders. However, due to restrictions on the movements of the *Adivasi* and fluctuations in the yields of forest products, this activity is no longer as productive as it once was.

THE KURUMBAS’ TRADITIONAL COMMUNITY AND FARMING PRACTICES

The Kurumbas are classified as a hunter-gatherer community. Traditionally they lived off of forest resources and practising cultivation of an ‘old’ nature; some of which continues to the present day. In this system the land is cleared in the month of April and food crops like *ragi* (finger millet), pulses, greens and oil crops (sesame) are sown. This season is popularly known as *kar pattam*. The second cycle of sowing begins in the second week of July, which is a major cropping season for all the farmers. During this cycle, a variety of crops are cultivated. Crops are harvested in a continuous sequence from August until the end of December. This traditional system of farming is practised locally with numerous ceremonies, community participation, rituals, traditional governance, seed and pest management controls. Historically, this system has ensured the food and nutrition security of the Kurumbas.

When they lived in the forest, the community knowledge of the Kurumbas informed their practices, as reflected in the cultural aspects of their cuisine, birth, marriage and death, sacred groves, rituals and ceremonies. The community maintained certain beliefs and taboos for their fields and millet crops. However, displacement from the 1960s onwards because of various reasons has led to a gradual loss of these knowledge and traditions.

FEATURES OF THE KURUMBAS' TRADITIONAL PRACTICES AND KNOWLEDGE

The roles of women and men in agriculture

The practice of millet cultivation among the Kurumbas was the backbone of their culture and agriculture, as well as their relation to the land and forests. Millet crops were primarily dealt with by the women who, after playing an important role in the sowing, weeding and harvesting, were fully responsible for post-harvest, storage and use throughout the year. Men and women played an important role in this system, which also involved wider members of the family. Exchange of grains took place between relatives and many visits were made during the harvest time for eating delicacies in the fields like roasted maize, popped amaranthus with honey, etc.

Crop diversity

The community grew a diverse variety of main crops (tenai kadu), including both cereals and vegetables. Due to their proximity to forest areas, many wild varieties were also utilized in their millet fields (see Table 1 for a list of crops and wild foods including cereals, legumes, vegetables and fruits). Having such a high diversity of foods within a single field, combined with the knowledge of seed selection and storage, methods of storage, varied recipes of cooking and their nutritional factors was particularly valuable to the Kurumbas.

Table 1. **Diversity of crops and wild foods grown by the Kurumbas**

SERIAL No.	CEREALS	LEGUMES	VEGETABLES	FRUITS
1	*Amaranthus* spp.	*Avarai*	*Amaranthus* spp.	Banana
2	Finger millet (*ragi*)	*Dolichos lablab* (*mochai*)	Arrow root	Cape gooseberry
3	Foxtail millet (*thenai*)	Horse gram (*kollu*)	Beans	Guava
4	Little millet (*samai*)	*D. lablab* (*dora avarai*)	Brinjal (*kathirikai*)	Gooseberry
5	Maize (*makka cholam*)	*Ola avarai*	Small chilli (*jeeni malagai*)	Jackfruit
6		Pigeon pea	Wild chilli	
7			Coriander (*kothamalli*)	
8			Greens (*chukuti keerai*)	
9			Manathakkali	
10			Mustard (*kadugu*)	
11			*Nannari* (sarasaparilla)	
12			Tomatoes (*thakalli*)	
13			Small tomatoes	
14			Yam (*Dioscorea* spp.)	

Among the indigenous peoples of the Nilgiri Biosphere Reserve, intensive systems of agriculture were not common; rather, cropping systems featured high biodiversity and relied on traditional knowledge. Practices were closely woven into the communities' knowledge of medicine, child rearing and everyday foods. Their traditional farming practices emphasised the role of the *mannukaran* (farming expert), who held a great deal of knowledge about the soil, seasons and seeds. This meant that the community could cope with climatic variations and aberrations, which now threaten the cash crops in the area.

Ecological diversity

Millet fields had many wild species due to their proximity to the forest areas, and this had positive impacts on the health and nutrition of the Kurumba families who lived in harmony with nature (see the inset box below). The zero-level application of chemical inputs to farming systems that was traditionally practised by the Kurumbas played a critical role in maintaining the mountain ecosystems, water resources and a variety of life forms, including soil organisms, insects, reptiles, birds and mammals (although the birds were often considered a menace as they ate the crops off the panicles). The ecological diversity in these mixed farming systems was enabled by pollinators, seed dispersers, soil fertility and crop raiding.

Nostalgia

"In our old village we had common agricultural lands where our parents were doing millet cropping which was natural farming. Our main crops were finger millet, foxtail millet, little millet and pigeon pea (see Table 1). It was very simple and sustainable agriculture. We had a variety of foods, which provided us a lot of stamina. Our parents were well-built and very strong; as children we were also strong. We could walk long distances, do hard work (today's generation hardly works) and efficiency was our trademark. We had plenty of greens, fruit and other vegetables along with millets and pulses, which nourished our body, mind and soul. Our traditional food dishes were very delicious – the following are a few delicacies that we still remember:

- *Ragi rotti, kali, udur putti*
- *Samai: sapadu, upma, payasam*
- *Thenai: sapadu, kanji*

Makka cholam: kali, pori, sutti, pullungi vegavacchi chinna cholam: kali, kanji

Compared to our children, we were very healthy and good in stature, with lots of activities bubbling around our day-to-day life. We used to collect different fruits, tubers and greens from our fields and forest. Our families were very close. We were always with our parents and there was a lot of observation and communication which created deep connections with our culture."

(Janaki Amma, Village Pudukkadu, 24 July 2009)

Food sovereignty

The traditional biodiverse cropping system of the Kurumbas provided them with food and livelihood security. Millet was consumed for three to five months as this was the typical millet yield from a season. Millet was not sold in the open market in this region. Finger millet and foxtail millet preparations were the staple foods of the Kurumbas, providing about 17 meals per month (in general, tribal families have two meals a day, one each in the morning and evening). Uncultivated foods such as natural tubers, green leafy vegetables, wild fruit and mushrooms collected from the millet fields and forests also served as important food resources.

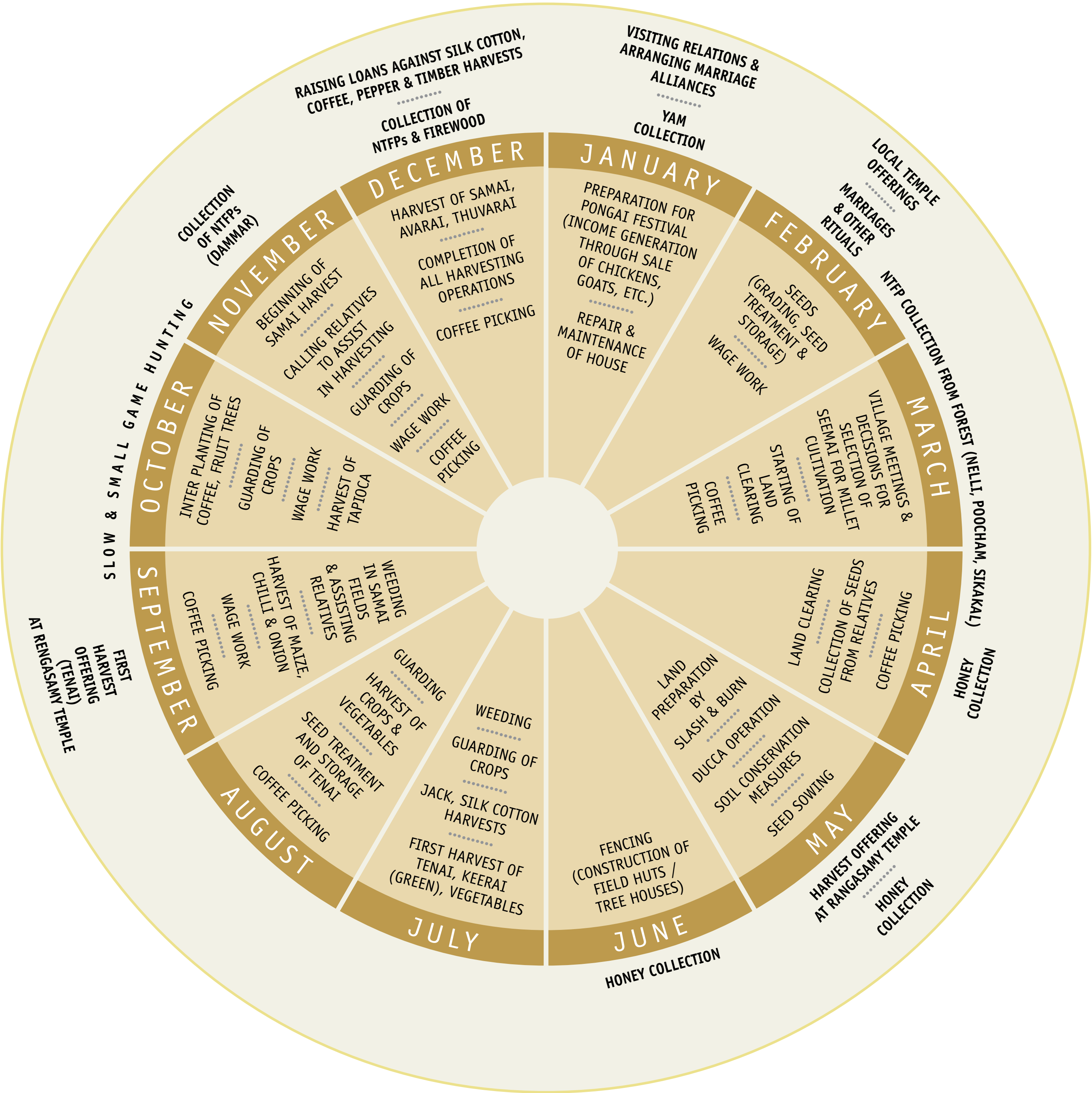
Livelihood security

Grain rather than money was given as wages to relatives and community members who contributed their labour to the agricultural operations such as weeding and harvesting. The traditional land was valued as an asset that was retrieved from the forest and protected from erosion, while the health of the soil was maintained. Millet cultivation was undertaken in vast tracts of rainfed land on hill slopes that required no irrigation. The cost of land preparation and cultivation was less expensive than for vegetable cultivation. The stalk and hay from the finger millet, little millet and foxtail millet was stored as fodder for livestock in the winter (see Figure 1: Calendar of livelihood activities).

Cultural aspects

Grain was communally offered to the deities during the annual rituals. The first harvest of all types of millets and cereals (a bunch of earheads/panicles) were selectively offered to the deity by placing them in the temple premises during the annual ritual or festivities. These grains were then shared among all the community members. Communal harvesting and threshing, *samai okkal*, was an event in which the men, women and children from the Kurumba community participated in the threshing and separation of the millet/grain. Threshing began in the late evening and went on throughout the night until all the harvested grain was threshed. This enabled the community to avoid the hot sun, and ensured communal participation because of the availability of labour in the evening. *Samai okkal* served as an opportunity for a cultural fest – songs, actions, traditional music and drumming, as well as the sharing of stories and interesting incidents from the time of guarding the field.

Figure 1. **Calendar of livelihood activities in Kurumba communities**



FACTORS THAT THREATEN THE TRADITIONAL KNOWLEDGE SYSTEM AND GENETIC RESOURCES OF THE KURUMBA COMMUNITY

Migration has led to great losses for the Kurumba community. At times, the food producers are now forced to become food purchasers. Their independence and dignity of life has been lost. Elephant attacks, which are directly attributable to the increase in urbanization at the foothills, have sometimes led to resettlement and rehabilitation without attention to the Kurumbas' needs and lifestyle. These processes are leading to a loss of their heritage. The changes of habitat and livelihoods have also impacted the transfer of knowledge from *mannukarans*, as these depend on cultivable land which is no longer available in many areas.

Discussions held with the Kurumba women were focused on nutrition, specifically related to their children who are now being raised on food available through the Public Distribution System (PDS). According to the women, the lack of traditional foods has negatively impacted on their health as they only eat rice and pulses grown with chemical inputs. They discussed the possibility of the PDS supplying millets, which would greatly enrich their diet. Millet cultivation is becoming rare in the Nilgiri, endangering seed stock, and resulting in the loss of several hill varieties of millet (especially little millet, beans and amaranthus varieties). The PDS system that provides rice rather than the Kurumbas' traditional diet of millets is slowly changing their food habits, leading to a nutritional and cultural loss.

THE KEYSTONE FOUNDATION'S COMMUNITY INTERVENTIONS

In areas where the Keystone Foundation is engaged with local communities, the possibilities for the future will require a substantial effort for the revival of community agricultural practices and community land rights. The Forest Rights Act (2006) enables claims to establish rights back to traditional lands. Coupled with appropriate technological interventions such as micro-irrigation and solar powered fencing, this can help to revive the traditional, diverse agricultural system of the Kurumbas and maintain the existing knowledge held by the older generation. Therefore, the Keystone Foundation is emphasising the importance of the nutritional qualities and environmental benefits of these foods and crops through food festivals and recipe competitions among the community, and by supporting community seed banks to help restore genetic diversity and agrobiodiversity. Through these efforts, the Keystone Foundation will help to enable the traditional knowledge and practices of the Kurumbas to be passed on to the younger generation.

Keystone has initiated the revival of traditional agriculture by documenting practices, creating seed banks and promoting millet and mixed cropping in the lands of the indigenous communities in the Nilgiri Biosphere Reserve. These interventions have had a wider impact on ownership, land-use patterns and livelihoods among the communities:

» Efforts to integrate agriculture and forest ecology have helped to conserve biodiversity. A study conducted in 2006 comparing different land-use practices in the Nilgiri Biosphere

Reserve revealed high insect and bird diversity in mixed plantations, i.e. coffee with traditional agriculture;

- Timber, medicinal, fibre, food and fuel species planted on *Adivasi* lands have increased the livelihood opportunities for families. High value crops like coffee, spices and fruits were promoted and grown organically for the market. Seed banks of traditional seeds ensure the free exchange and buildup of seed stocks;
- The cultural impact of efforts to revive traditional agriculture has changed the respect accorded to traditional leaders such as the *mannukaran*. Once again, the community works together to conserve seeds, guard the fields, celebrate sowing/harvest festivals, etc. Children and youth have been closely involved, drawing them back to their lands to sample a taste of their heritage;
- Community interventions have strengthened food sovereignty. From an overall well-being aspect, this has supported the health and wellness of *Adivasi* families. It has revived traditional cuisine and recipes and built nutritious diets. These efforts have also sparked interest among the *Adivasi* in other areas to follow the initiatives in their own way.

THE WAY AHEAD

While Keystone's initiatives have experienced some success, the Kurumbas still face many challenges. For example, soil fertility remains poor, rains are highly erratic, pest incidence is high under the forest canopy and there is hardly any return from coffee for the Kurumba families. Threats to food sovereignty, low incomes and poor nutrition are further concerns. In such a scenario, the revival of biodiversity on their lands is important to the community. They would like to enrich the coffee plantations with a variety of trees in order to provide food and income. However, the government schemes promoting tea and coffee cultivation, horticultural loans and subsidies are not designed for the Kurumbas' hilly lands, which have become neglected and fallow. Keystone's interventions with the community are seeking to regenerate these fallow lands by reviving the biodiversity of the traditional millet cropping system.

Looking forward, efforts to enhance agrobiodiversity and the livelihood security of the Kurumbas will require several interventions at the community and organizational levels:

- Document the biodiversity and sustain agriculture in the context of livelihood security;
- Research on-farm productivity and forest harvests, particularly yields and responses in the context of changing weather conditions;
- Increase the diversity of tree and crop species that are suited to the local climatic conditions in coffee plantations on forest land to provide natural yield insurance against pests, diseases and the vagaries of nature;
- Promote an exchange of learning between farmers, community-based organizations (CBOs) and network partners;
- Encourage biodiversity with sustainable farming practices on small landholdings;
- Enable farmers to conserve their own seeds/genetic resources;
- Document and identify local breeds for viable livestock rearing;
- Enable the rights of farmers and NTFP collectors in policy-making at the different levels of formulation and implementation.

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ACTIONAID'S EXPERIENCES IN AGROECOLOGY

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ActionAid is a global movement of people working together to further human rights for all and to defeat poverty. We have been working with over 15 million people in 45 countries for a world free from poverty and injustice. ActionAid works with local communities to understand their problems and help them break out of the cycle of poverty. ActionAid has been supporting local programmes in agroecology, in more than 30 countries in Asia, Africa and Latin America.

Climate Resilient Sustainable Agriculture (CRSA) is an initiative that ActionAid has been implementing, based on the concepts and practices of agroecology and on our Human Rights Based Approach. Our Human Rights Based Approach centres on supporting people living in poverty to become conscious of their rights, to organize themselves to claim their rights, and to hold duty bearers to account. We build on international human rights law, going beyond a legal or technical approach, by supporting people to analyse and confront power imbalances and taking the side of people living in poverty.

ActionAid proposes that agroecology can be a tool to increase the food sovereignty of women and men smallholder farmers and enhance their preparedness to face the impacts of climate change. This approach is based on the identification of the major problems and risks that local communities are facing, and/or are likely to face in the near future. Site-specific adaptation strategies are then designed and implemented to reduce vulnerabilities and increase the productivity, resistance and resilience of smallholder production systems.

The starting point of our approach is the knowledge and practices of the communities themselves. Although local knowledge cannot be seen as a panacea to all problems, it contains key insights that – when appropriately combined with scientific knowledge and modern technology – can help us to design and promote local food production systems that are better adapted to climate change and in tune with local contexts and needs.

Agroecology should not be seen as a model or a technological package that can be replicated anywhere at any time. There are very few practices that can be applied in a great number of situations. Rather, real alternatives are site-specific; they are highly dependent on the cultural, social, economic and environmental context in which they are generated. ActionAid's approach has more to do with introducing new ways of thinking, rather than distributing ready-made solutions.

THE TRANSITION PROCESS TO SUSTAINABLE AGRICULTURE

Every farmer can begin a process of transition to a more sustainable production system, from conventional farmers that are heavily dependent on external inputs to traditional smallholder farmers that rely mostly on internal inputs and on the natural fertility of soils.

This transition process will take some time; complex farming systems cannot be transformed suddenly. The redesign of production systems requires a series of small, well-planned and realistic steps. It requires that farmers take time to experiment, test and validate whether the small changes that they are adopting are bringing about positive results from social, cultural, economic and environmental perspectives.

ActionAid's Initiative on Agroecology is based on four main approaches and seven pillars. A visual summary of the main components of our initiative is shown in Figure 1:

Figure 1. **The approaches and pillars of ActionAid's Initiative on Agroecology**

FOUR MAIN APPROACHES:

1. Conducting participatory appraisals to identify local potentials and political and technical challenges.
2. Identifying, documenting, testing and diffusion of local knowledge/alternative practices and encouraging local innovation.
3. Promoting sustainability through appropriate agricultural research and extension services based on technologies that reduce dependence on external inputs and agrochemicals, help adapt to climate change, build on and reinforce local knowledge.
4. Empowering farming communities to promote sustainable agriculture through local, national and global campaining actions for policy and budgetary changes in favour of smallholders.

WITH A PARTICULAR FOCUS ON THE FOLLOWING SEVEN PILLARS:

ONE HOUSE, ONE COMPOST PIT: A CASE STUDY FROM NEPAL

Udayapur District is located in eastern Nepal. The region consists of both plains and hill areas, and many of the agricultural lands are prone to flooding. Women are the major food producers in this region. They are engaged in all stages of production, from planting to harvesting. Women's access to and ownership of land (whether jointly or individually) in Udayapur has increased over the years, enhancing economic opportunities for women in farming. However, changes in climatic conditions have been affecting agricultural production, forcing men to migrate to find work elsewhere. As a result, women's workload in agriculture has increased significantly.

A major problem facing farmers in this area is the increasing use of chemical fertilizers and pesticides in agriculture. These pesticides are damaging farmers' health and their

environment. Chemical fertilizers are also causing negative impacts on soil structure and soil organic matter. Alongside these impacts, pesticides and chemical fertilizers are a costly input for smallholder farmers, reducing the income that is available to spend on education and healthcare for their families.

The availability of good quality seeds is another challenge for farmers in this region. Farmers rely on markets for various seeds. Poor quality-control mechanisms and limited technical knowledge of imported seeds often results in low crop productivity. Smallholder farmers must also contend with climate change issues. Water sources have started drying up and unpredictable monsoons and floods have started to affect crop production. Because of these issues, and the limited income from farming, migration is high amongst men. This has resulted in a lack of agricultural labour in the area, increasing the burden on women farmers.

In response to these issues, ActionAid Nepal supported three women farmers' groups in their local rights programmes in Udayapur District. The objective of these groups is to promote sustainable agriculture in the region and to replace the use of chemicals in farming. The groups were registered with the District Agriculture Development Office (DADO) in 2013 and 2014. This enabled them to access services from DADO, which would have been difficult for individual farmers. DADO has provided the farmers' groups with seeds, as well as material support for irrigation.

Every member of each of the farmers' groups contributes money to a collective savings scheme. The Village Development Committee also provides budgetary support to the community for training sessions on organic farming techniques. Reflection-Action circles have been set up so that farmers can discuss and come up with solutions to their issues. ActionAid has provided training on the importance of soil organic matter, the impacts of pesticides on the environment and human health, and the need to reduce dependency on external inputs.

Following these trainings, the groups came up with an alternative strategy of promoting composting and the improved use of manure, which prevents the loss of nutrients from the soil. The farmers decided that every member of the group should have a compost pit at their home. Therefore, ActionAid Nepal facilitated a collective farming practice named 'One House, One Compost Pit' and the campaign was launched at local level in Udayapur.

ActionAid and the farmers worked together on the preparation and application of organic compost. Compost is prepared in pits by combining plant residues, bedding materials and manure, with effective micro-organisms that enhance the decomposition of the composting materials. The collectives also started using animal urine and other organic pesticides as an alternative to chemicals.

The beneficial effects of these compost pits have been noted in the community and other farmers have started to adopt this practice. Several farmers have also invested in the combination of crop production and animal rearing as a way to increase livelihood options and economic alternatives. They rear chickens and goats for meat and manure, cows for milk, oxen for manure and ploughing the fields, and buffaloes for milk and manure. These animals provide an additional source of income from meat and milk. Their manure saves money that would be spent on chemical fertilizers and is a major source of plant and soil nutrients. The farmers also practice mixed cropping; an alternative that may improve their resilience to climate change. In order to address the problems with irrigation, farmers in this region have started to use water harvest tanks, drip irrigation and drought-resistant crop varieties.

Over time, through the application of these sustainable farming techniques, smallholder farmers from Udayapur have been able to improve their productivity and the quality of their produce. The use of compost has improved soil structure and fertility, while simultaneously reducing the dependency of farmers on expensive chemical fertilizers. The new practices have significantly reduced farmers' production costs, meaning that the women are able to invest more in healthcare and education for their children. Moreover, the reduction in the use of chemical fertilizers and pesticides has improved the health of women farmers, providing them with a safer working environment. Consuming chemical-free food has also had a positive impact on the health of their families.

In addition, the farmers' groups have been able to use the cooperative savings scheme for loans to invest in extra income generating activities. In this way, the process of organizing farmers into cooperatives and local groups has improved the solidarity of the community. Moreover, ActionAid's capacity building on sustainable agricultural alternatives and raising awareness about the responsibilities of relevant government institutions has contributed to the empowerment of smallholder farmers (see the testimony of smallholder farmers from Udayapur below). The groups have managed to build a relationship with the local agricultural offices like DADO and the Agriculture Service Centres, allowing farmers to obtain seeds for their farming.

In order to expand the use of sustainable agriculture practices in this region, farmers still require additional technical support. Further lobbying and advocacy activities are needed to ensure that the Government provides assistance to smallholder farmers adopting sustainable agricultural practices. Looking to the future, the communities are well located close to the market place, offering the potential to increase their income by selling their products. There are further opportunities for the groups to work with different agricultural organizations in the area to share their learnings, and obtain technical and input support.

The women of Udayapur describe the success they have had using the new agroecological techniques:

> *"Soil has become easier to work with and I am convinced that crops are less infested by insects since I started using compost."*
>
> (Ganga Devi Chaudhary, chairperson of the Ramkrishna farmers' group)

> *"Use of compost has saved my expenditure on fertilizer purchase. Furthermore, I have also learnt to protect my crops from pests by using the locally available plants."*
>
> (Bindeswori Chaudhary, smallholder farmer from Udayapur)

> *"I had applied compost in Okra (lady's finger) crop. I did not have to buy chemical fertilizer and saved money. I have also observed improved soil quality after applying compost."*
>
> (Ramsunair Chaudhary, smallholder farmer from Udayapur)

This is an example of how the use of agroecology and collective farming can improve livelihoods. The adoption of the 'One House, One Compost Pit' campaign has reduced farmers' expenses, while at the same time improving soil structure and fertility. Through the adoption of this sustainable practice, families in Udayapur have become healthier through safer farming practices and the consumption of safer, better quality food. Although more needs to be done to ensure that the groups receive adequate government extension services in sustainable agriculture, women smallholder farmers are now more confident to ask for support from the Government.

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INTENSIVE SILVOPASTORAL SYSTEMS: SUSTAINABLE CATTLE RANCHING AND ENVIRONMENTAL MANAGEMENT

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Silvopastoral systems (SPS) are a type of agroforestry that allows the intensification of cattle production based on ecological processes such as photosynthesis, nitrogen fixation and the solubilization of soil phosphorus. SPS are recognized as an integrated approach to sustainable land use. Intensive silvopastoral systems (iSPS) are a type of SPS that combine high-density cultivation of fodder shrubs (4 000–40 000 plants ha^{-1}) with:

1. improved tropical grasses;
2. tree species or palms at densities of 100–600 trees ha^{-1}.

These systems are managed under rotational grazing with occupation periods of 12-24 hours and 40-50 day resting periods, including ad lib provision of water in each paddock (Calle *et al.*, 2012).

The iSPS is a successful example of integration and ecological intensification of production. Initially developed in Colombia, the production system has expanded to Mexico and Brazil, among other countries (Calle *et al.*, 2013).

Because of the structural and biological complexity of the system – with more than three strata of production including grass, shrubs and trees – cover and food resources for birds, mammals, reptiles and invertebrates are enhanced. The presence of nitrogen-fixing legumes and other tree species improves production and nutrient cycling and eliminates the need for chemical nitrogen fertilizers (Murgueitio *et al.*, 2011). Deep-rooted trees also contribute to the recovery of nutrients and water from deeper soil layers and increase carbon sequestration both below- and above-ground. Tree cover also provides better environmental conditions and welfare for cattle and delivers more biomass, nutrients and shade to the animals, reducing stress and improving production and body conditions (Broom *et al.*, 2013).

As a result of the positive interactions and nutrient cycling promoted in iSPS (particularly N_2-fixing trees and carbon sequestration), these systems produce more dry matter, digestible energy and crude protein per ha, and increase milk or meat production while reducing the need for chemical fertilizers and concentrate feeds (Murgueitio *et al.*, 2011). In a study conducted by Cuartas *et al.* (2015), animals grazing in iSPS had greater dry matter intake as a percentage of body weight (2.61 vs 2.04 percent) and greater intake of crude protein (954 vs 499 g day^{-1}), calcium (62.1 vs 36.2 g day^{-1}) and fat (94.2 vs 69.6 g day^{-1}) than those grazing in a monoculture pasture. When compared with degraded pastures, the amount of meat produced per ha increased from 74 to 1 060 kg ha^{-1} year^{-1} in Colombia. Similarly, compared with an improved pasture, an iSPS in Mexico increased meat production from 456 to 1 971 kg ha^{-1} year^{-1} (Solorio-Sánchez *et al.*, 2011). Importantly, this increase in dry matter intake and daily gain has not been accompanied by an increase in methane emissions per unit of weight gain (Molina *et al.*, 2014). Increases in meat and milk production and reductions in methane emissions are related to improved nutritional fodder quality in the iSPS compared with pastures in monoculture.

Trees in iSPS also promote higher carbon sequestration per ha. In iSPS, the above-ground carbon sequestration potential ranges from 1.5 Mg ha^{-1} yr^{-1} (Montagnini *et al.*, 2013) to 6.5 Mg ha^{-1} yr^{-1} (Kumar *et al.*, 1998).

Unlike conventional extensive cattle ranching, iSPS require rigorous management, administrative control and permanent adjustments based on careful monitoring. Management protocols focus on careful pasture rotations with strict control of grazing and pasture recovery, and a timely pruning of trees (Calle *et al.*, 2012). The proper functioning of iSPS requires a permanent supply of good quality water in mobile troughs and mineralized salt; live fences planted at the periphery and internal divisions of paddocks; electrical fencing or tape to concentrate grazing on narrow strips, and a non-violent handling of livestock. ISPS demand specialized knowledge about rotational grazing, cattle management practices and forestry. Producers need to be informed of the benefits of the system, and technicians need training on how to best advise farmers and workers in its implementation, management and maintenance (Calle *et al.*, 2013).

Perceived disadvantages of iSPS include reduced visibility within the farm and the need to embrace the aesthetics of exuberant vegetation, something that has proved challenging for most conventional cattle ranchers. It has been hypothesized that overexploitation of groundwater could be a negative aspect of iSPS, although Latin American experts have never raised this concern. ISPS meet the main requirements of an intelligent use of green water: they reduce water losses through runoff, increase infiltration of rainwater into the soil, increase water holding through soil organic matter, reduce evaporation and evapotranspiration, accumulate water in plant biomass and promote the harvest and storage of rainwater. Therefore, their overall effect on the water cycle and groundwater deposits is most likely a positive one.

The presence of trees leads to increased soil humidity through reduced evaporation under the canopy, which increases grass growth and resilience to drought. In terms of animal welfare, animals grazing in iSPS have a constant provision of good quality fodder, and their anxiety and fear are reduced as trees and shrubs provide the possibility of partial or complete concealment (Broom *et al.*, 2013). On hot days, shade provided by trees in iSPS can protect the animals from intense and direct solar radiation. The presence of trees reduces temperatures from 42 °C to 34 °C generating a microclimate that improves thermal comfort for grazing animals (Murgueitio *et al.*, 2013).

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NEW APPROACHES TO MEETING THE CHALLENGE OF AGROECOLOGY IN AN INTENSIVE FARMING CONTEXT

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INTRODUCTION

After working for nine years as a lecturer in sustainable agriculture and rural development, Quentin Delachapelle took over the family farm in one of France's main cereal-growing areas, with the aim of transforming it.

Over the years, the farm had evolved from a system that combined mixed crops with livestock to one that concentrated on industrial field crops. This shift and the intensive farming practices that resulted from it were typical of the changes undergone by French agriculture and the intensive agricultural model developed in France over the last 50-60 years. This model may have been justified in the post-war context, but today local environmental impacts, effects on farmers' health, increasingly high prices of chemical inputs (against a backdrop of high global demand and scarce energy resources) and a high level of dependency on Common Agricultural Policy (CAP) subsidies combine to raise serious doubts about the long-term viability of the model – all this at a time when the ability of the existing model to ensure food security for a growing world population is increasingly being questioned.

Quentin set out to improve the farm's economic and environmental efficiency – to make it more resilient and viable in the long term. Measures such as introducing green manures and legumes enabled him to cut pesticide use by half and reduce inorganic fertilizers. He soon reaped the benefits from improved soil quality and economic efficiency. Making the transition took a considerable commitment – the kind of commitment that comes from being part of a movement with a strong tradition of agroecology going back several decades. It would have been much harder for an isolated farmer producing crops for agro-industrial supply chains structured to meet short-term goals. Nevertheless, medium-term factors likely to affect the survival of both family farms and vibrant rural communities reinforce the arguments in favour of agroecology.

THE CIVAM NETWORK: A RURAL POPULAR EDUCATION MOVEMENT

The CIVAM[1] network was formed in the 1950s. It is rooted in the popular education movement and set out to empower farming families to make decisions for themselves and regain control over their lives. Today, it is made up of 120 local organizations spread throughout France, with a total of nearly 13 000 individual members. For the first 25 years of its existence, the CIVAM movement endorsed the drive to modernize French farming that went hand in hand with implementation of the CAP. CIVAM shifted direction when it became clear that the model that resulted from the CAP had exceeded its original goals. The damage to the environment caused by the CAP's focus on productivity and the increasing difficulty of maintaining farm viability prompted local groups of farmers to begin experimenting with new ways of improving the efficiency of their production systems.

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[1] Centres d'Initiatives pour Valoriser l'Agriculture et le Milieu rural: literally, "centres for initiatives to add value to farming and rural communities".

The CIVAM approach to agroecology means structuring all of the farm's operations around the farm ecosystem. Production systems are based on local soil type and climatic conditions; their components are selected to fit matter cycles (crops are grown to feed livestock, livestock provide fertiliser for crops, etc.); and farming practices are adapted to incorporate natural processes (legumes are introduced, rotations are lengthened, beneficial organisms are used, etc.). For all the components of the system to work together, farmers have to think holistically while continually monitoring individual components to see if they need adjusting. The aim is to build a more autonomous farm system that relies on natural processes and human labour, and to develop mutually beneficial relationships with other local stakeholder groups (farmers, consumers, local authorities, environmental agencies, NGOs, etc.). Environmental, economic and social aspects all have to be taken into account, as does the autonomy of the farm production system and the person implementing it – the farmer's ability to observe and understand how their production system works, to make decisions and to take appropriate action for themselves.

FROM A PREDOMINANTLY RURAL SOCIETY TO A LEADING CEREAL EXPORTER

Of the 55 million ha that make up the surface area of France, 28 million are farmed and 17 million are occupied by woodland (MAAF, 2015b). France has the highest level of agricultural production of any country in the European Union (EU), accounting for 18 percent of EU agricultural output (EU, 2015). Historically, two factors have played a crucial part in the changes that have taken place in French farm production systems: high labour costs and low land values. High labour costs have provided an incentive to shift towards supply chains and modes of production in which mechanization and chemical inputs make it possible to employ fewer people. These are further bolstered by the present system of CAP payments, which is based on the area of land farmed, regardless of the number of jobs per farm. As a result of the changes in production systems, since 1993 annual French cereal output has accounted for 20 percent of EU cereal output. Almost half of this is exported, primarily to EU countries (67 percent since 1993) and largely in the form of grain. Processed products represent only 16 percent of the total volume. Meanwhile, France suffers from a shortfall in livestock feed proteins (MAAF, 2015a).

Mixed farming systems combining livestock with a variety of crops were the norm among French family farms 50 years ago. These days, they are increasingly rare. Nearly a quarter of French farms now specialize in cereals and almost half of France's farmland is currently used to produce cereals. This specialization of farms and land area has created numerous environmental problems. Instead of minerals (e.g. N, P, K) being recycled on the farm, they are imported from external sources, wasting non-renewable resources. Water and air pollution from fertilizers (nitrate and phosphorus in the case of water and ammonia and nitrous oxide in the case of air) have been exacerbated along with water and soil pollution from pesticides. The replacement of pastures by annual crops, with the accompanying simplification of habitat mosaics and abundant use of pesticides, has resulted in a loss of biodiversity in farming areas, while high densities of irrigated maize crops aggravate tensions over water use. In addition, recent research suggests that specialization and particularly the shortening of rotations may play a part in the levelling-off of field crop yields that is now occurring (Butault *et al.*, 2010).

AGROECOLOGY AS A POTENTIAL JOBS CREATOR IN DEVELOPED COUNTRIES

Almost all of the incremental gains in overall productivity in agricultural production over the last decade can be put down to shrinkage of the agricultural workforce, which currently represents around 2 percent of the French workforce as a whole. Numerous indicators show that this trend is set to continue, albeit at a slower pace. Agriculture represents 12 percent of the workforce in rural areas (Berthod-Wurmser *et al.*, 2009).

What effect is this continuing loss of jobs in farming having on rural society? Some 20 percent of France's inhabitants live in rural areas (Berthod-Wurmser *et al.*, 2009). Local conditions vary considerably, but in general, the lack of social infrastructure and transport in rural areas greatly complicates the task of looking for work there. Even so, many households on low incomes are forced out of urban areas by the cost of housing.

The continuing loss of jobs in farming runs counter to the CAP's stated aims of rural development and maintaining rural communities. It is inappropriate in today's context of mass unemployment and social exclusion. It is time we re-examined the purpose of farming. Beyond its economic role as food producer, surely agriculture also has a non-commercial role to play in maintaining rural populations, protecting shared resources such as water, air and landscapes, and strengthening the fabric of communities?

A recent evaluation of various European dairy production systems has shown that the long grazing cycle systems developed by the CIVAM network, in which chemical inputs are kept to a minimum by adjusting outputs, generate two to four times higher net incomes and require eight to ten times less capital than northern European systems that rely heavily on inputs and capital. These systems also receive two to five times less public funding than their intensive counterparts and generate 50 percent more jobs per ha of farmland and more than two and a half times as many jobs in relation to milk output (FNCIVAM, 2009).

In macroeconomic terms, it is only by focusing on quality that products can compete (in domestic or export markets), and quality creates far more added value for rural communities than quantity. To recreate wealth in rural areas, it is vital to re-localize agriculture by identifying farm systems that can complement each other and by developing local distribution networks.

REDUCING CHEMICAL INPUTS: A CRUCIAL ISSUE FOR THE VIABILITY OF FRENCH FARMING

In the process of modernizing its agriculture, France developed supply chains and modes of production that relied heavily on mechanization and chemical inputs. France is now the world's third biggest consumer of pesticides and uses more pesticides than any other EU country. It faces growing pressure over the direct and indirect impacts of pesticides on users' health and increased tolerance by pests. In 2012, pesticides were detected in French rivers at 89 percent of measuring points and are routinely found in air samples (SOeS, 2015).

France uses more soluble nitrate fertilizer than any other country except the United States of America, accounting for 12 percent of global consumption. Inorganic fertilizers make up a sizeable proportion of French farmers' costs. For the agricultural sector as a whole, they represent an average of 15 percent of procurement costs and 5 percent of total expenditure. For field crops, they represent over 30 percent of procurement costs and 12 percent of total expenditure (GCL Développement Durable, 2010). Inorganic fertilizers play an important part in the major environmental problems of nitrate pollution of groundwater, eutrophication of aquatic habitats and greenhouse gas emissions, and are therefore subject to increasingly strict regulations. In addition, France imports almost all the raw materials used in their manufacture, making it highly vulnerable to fluctuations in world prices.

Following the period when the intensive farming model was introduced (1960-1980), the effectiveness of farm consumables such as fertilizers and pesticides improved between 1980 and 1995. From 1996 onwards, this trend was reversed. Trials conducted by members of the CIVAM network have demonstrated that economic and agri-environmental performance can simultaneously be improved by adopting alternative techniques that increase overall productivity and the productivity of farm consumables while reducing inputs. For example, transitional measures introduced on cereal-growing farms, either because farmers have found themselves in a technical *cul-de-sac* (e.g. the development of herbicide resistance in weeds) or for health reasons (e.g. occupational diseases caused by pesticides), have made it possible to reduce pesticide use by 50 percent with no loss of income in the medium term. From a food security perspective, lowering inputs may result in a slight drop in output (amounting to less than 10 percent), but this should be kept in perspective, given the impact of other factors such as the expected rise in output in developing countries, especially where there are strong agroecological movements, and losses due to waste by supply chains in developed countries (Butault *et al*., 2010).

OVERCOMING THE PROBLEM OF SOCIAL AND TECHNICAL "LOCK-IN"

The French farming and food processing sectors were set up in tandem. This led to a high degree of geographical specialization in farming systems, with livestock and crop production developing in different areas, and processing industries being concentrated in a few locations to facilitate quality control and make it easier to regulate volumes and structure supply chains. Appropriateness of scale is vital when implementing agroecological measures. Restoration of biodiversity or protection of water resources cannot be achieved at farm scale; to be successful, restoration efforts have to involve a number of stakeholders. Therefore, the social aspects of agroecology have to be taken into account if the technical and economic challenges are to be met.

Economic theorists have developed the concept of “lock-in” to describe one of the obstacles that hampers the transition to greater sustainability (Vanloqueren and Baret, 2009). Practitioners of agroecology are typically confronted with the prevailing view in agro-industrial supply chains that production must be tailored to purchasers’ requirements and not the reverse. However, it is hard to believe that farmers who adopt agroecological practices will have difficulty finding outlets for their products, given that farms are increasingly being asked to provide goods outside the traditional range of products. The barrier to development of a wider range of crops in France is not demand but competition with existing supply chains. To surmount barriers of this kind, the CIVAM network brings groups of local stakeholders together to develop supply chains for the new products that result from new kinds of farm production systems. For instance, a number of hemp-growers pooled their resources to buy equipment and worked with local building tradespeople to promote use of their products in local eco-home construction.

The numerous technical and economic advisers available to French farmers invariably think in terms of the short-term goals of existing supply chains. Embarking on a transition towards agroecology means taking a medium-term view that is not (or only very marginally) alluded to in public policies and traditional economic indicators. Consequently, groups of farmers like CIVAM are increasingly joining forces with civil society groups (consumer organizations, environmental agencies, NGOs, etc.) to free themselves from the constraints of existing supply chains, move towards more sustainable farming practices, and establish processing and distribution systems that are suited to local needs. It should be noted that outside of specific funding for certified organic farming, public funding criteria pay very little heed to environmental impact, and even less to on-farm employment levels. Over 80 percent of CAP funding distributed in France is devoted to supporting supply chains’ short-term competitiveness, and only part of the remainder is allocated to rural development and agri-environmental schemes.

The form of agroecology practised by the CIVAM network places farmers in a better position to cope with unexpected events, enabling them to regain the initiative and adapt their operations to local contexts. Many are meeting new needs and working together to improve their farm production systems at the same time as working with local authorities to find local outlets for their products. As might be expected in a popular education movement, group discussion of farming practices is central. For a group to function successfully, it has to include farmers who act as researchers, conducting trials and sharing, discussing and passing on their experiences. Although praise is often heaped on initiatives of this kind by those in authority, the policies they advocate still do not offer sufficient incentives for such practices to become widespread.

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AGROECOLOGY IN SEMI-ARID REGIONS: PRACTICES AND LESSONS FOR FOOD AND NUTRITION SECURITY

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INTRODUCTION

This case study offers some reflections on the actions of the Brazilian Semi-arid Articulation (*Articulação Semiárido Brasileiro* – ASA), through the P1MC and P1+2 programmes, which seek to interact with agroecological practices targeting food and nutrition security for thousands of families in the Brazilian semi-arid region. The case study aims to demonstrate how this experience has affected the lives of families, both in terms of food and nutrition security, and through access to short marketing circuits that guarantee and increase the income of these families. It shows how the P1+2 programme, in conjunction with other public programmes and policies to strengthen family farming, has been helping to improve families' quality of life, by extending hydraulic infrastructure to store rainwater, and by implementing productive backyards (*quintais produtivos*) and other technologies. The final part of the case study explains the main lessons learned from the implementation of the P1+2 programme, highlighting the social participation and contribution of the families involved in the programme, as well as the main difficulties encountered in the process. It also notes the challenges and constraints that have been identified through this experience.

The ASA is a network of over 1 300 civil society organizations that manage and develop policies for coexistence with the semi-arid region. Its mission is to strengthen the role of civil society in constructing participatory processes for sustainable development and coexistence with the semi-arid region, based on cultural values and social justice. The entities forming the ASA are organized in forums and networks in the nine states that comprise the Brazilian semi-arid region: Bahia, Ceará, Paraíba, Pernambuco, Alagoas, Piauí, Sergipe, Minas Gerais and Rio Grande do Norte.

The semi-arid region has a climate characterized by major droughts and long dry periods with an irregular distribution of rainfall. Accordingly, one of the main lessons learned through the programmes concerns the storage methods adopted by farming families. These methods involve storing rainwater for multiple uses, through social technologies together with a process of knowledge construction through courses and exchanges, and stockpiling animal feed through an agroecological management of the environment.

AGROECOLOGY AND COEXISTENCE WITH THE SEMI-ARID REGION

Agroecology seeks to understand the role of the multiple elements that participate in processes developed by societies to modify nature for the purpose of obtaining food and other resources needed for social reproduction. For this to occur, a systemic approach is fundamental for constructing an agroecological strategy, including a study of ecological processes such as recycling, energy flows, food/predation chains, competition relations, ecological succession, etc. It is further necessary to draw on information from the past, including the processes that form agro-ecosystems, and update them to the current context; we refer to this as the concept of coevolution. In addition, attempts must be made to understand and interpret the relationships between humans/social groups and nature, including the important contributions of local knowledge, science, research centres and development groups – this is known as the ethnoecology concept. These processes give rise to a variety of practices and experiences in agroecological management and production, which are being developed in different parts of Brazil.

From the perspective of the collective construction and valuation of traditional and local knowledge, ASA has been developing and organizing processes of coexistence with the Brazilian semi-arid region over the last 15 years. The P1MC programme, now consolidated as a public policy, has become a benchmark in terms of social technology for storing rainwater for human consumption.

In the belief that water is not a consumer good, but a basic human right, while at the same time being a necessary food for life and an input for the production of other foods, the ASA developed the Programme of Training and Social Mobilization for Coexistence with the Semi-arid Region (*Programa de Formação e Mobilização Social para a Convivência com o Semiárido)* through two programmes – P1MC and P1+2.

The objective of P1MC is to mobilize and include people throughout the semi-arid region to secure access to potable water for drinking and cooking, using plate cisterns. Altogether these form a decentralized storage infrastructure with a capacity of 16 trillion litres of water. The P1+2 programme aims to construct participatory rural development processes in the Brazilian semi-arid region, while promoting sovereignty, food and nutrition security, and job and income creation for farming families, by facilitating access to, and sustainable management of, land and water for food production.

The programmes in question apply simple collective technologies for capturing and storing water for human consumption and food production. They also strengthen other initiatives for coexistence with the semi-arid region, such as the development of agroecological knowledge; credit cooperatives targeting family and peasant farming; seed banks or houses for native or creole seeds; solidarity-based revolving funds; livestock breeding; contextualized education; combating desertification; etc. These are universally used and easy-to-understand technologies, which can be applied in other semi-arid regions and areas of seasonal planting. They have been experimented with in countries such as Honduras, Argentina, Haiti and others.

IMPLEMENTATIONS INVOLVED IN P1+2

Currently, the entities comprising the ASA are implementing a number of rainwater-capture and exploitation technologies in the nine states of the Brazilian semi-arid region.

The productive aspects of the technologies that have been adopted by the families are supported by their implementation strategies. Strategies such as strengthening seed houses/banks and implementing agroforestry, complement the implementation of P1+2 technologies, recovering and strengthening traditional cropping and poultry breeding practices. These technologies and implementation strategies are described below.

Sidewalk cistern *(cisterna calçadão)*:

This is a technology for capturing and storing rainwater which has helped to improve the quality of life of many farming families in the Brazilian semi-arid region, based on producing in backyards and quenching animal thirst. It is a cistern with the capacity to store 52 000 litres of water. The water flows from the sidewalk to the cistern through a pipe linking one to the other.

Water storage trench *(barreiro-trincheira)*:

This should be built deep on flat land, preferably without stones, and lined by plastic sheeting. Any stones or roots in the land should be removed to avoid perforating the sheet. The trench must be covered with cement tiles to avoid water loss through evaporation. The trenches usually have capacity for roughly 132 million litres of water. Their cost is low, considering the amount of water accumulated over several years.

Underground reservoir *(barragem subterrânea)*:

This technology takes advantage of run-off water and small creeks in the region, by storing water in the ground. The soil humidity acquired in the rainy period lasts for longer in the soil, where fruit trees and vegetables can be planted. This technology is transforming the landscape and properties of many families in the semi-arid region.

Stone tank *(tanque de pedra)*:

This is a common technology in mountainous areas containing flagstones, which serve as areas for capturing rainwater. It makes use of long cracks or natural holes in granite to store rainwater. While the volume varies greatly, capacity is increased by building brick walls in the lowest part, which serve as a dam to accumulate the water; the higher the walls, the greater the storage capacity.

Rainwater catchment lagoon (barraginha):

The '*barraginha*' is a small lagoon built on land worn away by water erosion. It is dug as a semi-circular basin of roughly 16 m diameter, generally using excavating machinery. The excavated earth is piled around the edge, forming a half-ring dam to hold the water. These catchment lagoons produce better results when several are built in the same area, one after another, so that after a rain storm, any overflow can supply the next lagoon, and so on successively.

Public water pump (*bomba d'água popular* – BAP):

The objective of the BAP is to take advantage of disused wells to extract underground water through manual equipment using a hand-wheel. When turned, the wheel draws large volumes of water with little physical effort. The water is used for drinking. The pump can be set up in wells of up to 80 m deep. In 40 m wells, it can draw up to 1 000 litres of water per hour. It is a low-cost, community-use technology and is easy to operate.

Seed houses or banks:

These are spaces for storing native seeds that guarantee planting each year for farming families or communities. To implement the community seed house or bank, it is necessary to set aside a place for storing the seeds.

Agroforestry:

This is a production system that seeks to imitate nature. In agroforestry there are many types of plants, all cultivated in the same area, producing a wide variety of products: fruit, grains, flowers, roots, tubers, firewood, timber and seeds.

Productive backyard:

This is an example of diversified production on the property. The technology consists of traditional crop growing and poultry breeding practices around the house.

RESULTS ACHIEVED, CONSTRAINTS AND DIFFICULTIES TO BE OVERCOME

One of the aspects that is valued and disseminated in the P1+2 programme is the protagonist role played by the families. According to this political-methodological approach, farmers cease to be seen as passive beneficiaries of public programmes, but rather as subjects of rights who are capable of developing their own life projects. That change of approach distinguishes the P1+2 from other conventional rural development programmes or those targeting productive inclusion for the poorest families, by creating social environments that foster a strengthening of the associative fabric and promote relations of reciprocity and solidarity.

Some of the results obtained from these management approaches show a significant improvement in food and nutrition security, including through the production of vegetables consumed by the families. The water stored supports herds of small livestock such as chickens and pigs, thereby maintaining the families' stock of small animals and thus strengthening the supply of animal protein in their diets. After serving the family food table, the surplus produced is destined for free agroecological fairs and institutional markets, thereby implementing short marketing circuits such as the Food Procurement Programme and the National School Food Programme.

After five years of successive droughts in the region, some families who were included in the P1+2 said that coping with this period was "suffered" with less difficulty than in previous periods when they had no way to store rainwater for production and small animals. It appears that there were no significant outbreaks of hunger or intense migratory processes, phenomena that usually occur in the region during these periods.

Although there have been positive results, there are also some constraints that still need to be overcome. The small scale of many properties in the semi-arid region prevents the families from storing the larger volumes of water needed for production and for stockpiling food for family consumption and animal feed. In this regard, for the productive inclusion proposal to develop further in the rural area, the agendas of access to land and defence of territories in traditional communities need to be prioritized once more. Apart from that, policies on technical assistance and rural extension, and rural credit, need to be retargeted to strengthen the strategies for coexistence with the semi-arid region that are being improved on a decentralized basis by family farmers and their communities.

The capacity that the families included in the P1MC and P1+2 programmes are demonstrating for improving their strategies of production and resource storage indicates a promising way to make the Brazilian semi-arid region increasingly more productive and sustainable. That is why ASA Brasil supports a rural development model guided by the agroecological approach, which does not use agrochemicals and which values and supports native seeds. The goal is to produce diversified and healthy food, improve working conditions and, in particular, promote a decent life for farming families. Like the P1MC, the P1+2 programme should be consolidated as a public policy based on its results that have demonstrated the power to change the course of regional development – enabling the families to migrate from the position they occupied 'below' the poverty line, to attain the threshold of dignity and citizenship in this country.

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NATURALEZA VIVA

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INTRODUCTION

Naturaleza Viva[1] is an agroecological farm situated in Guadalupe Norte, in the province of Santa Fe, Argentina. We are located 815 km to the north of the city of Buenos Aires.

On 200 ha of third-category soils, we produce milk, cheeses, yoghurt, ricotta, butter, cream, jams, honey, juices, conserves, sausages, oils and wholemeal flours. Our foods are free from pollutants such as agrochemicals, genetically modified organisms, hormones and antibiotics.

We see our farm as a living organism comprising elements and creatures that live together and interact: soil, water, air, sun, plants, animals and human beings. In this living organism, the human being is a manager of productive processes based on the rhythms of nature, such as the climate, the seasons and cosmic forces.

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[1] Further information about Naturaleza Viva is available at: www.naturalezavivaargentina.jimdo.com. An interview with the founders of the farm, Remo and Irmina, can be found on the FAO YouTube channel: www.youtube.com/watch?v=kquQQfOPGgI&index=4&list=PLzp5NgJ2-dK6MxE6JDy4-FlLbuLUfQfHe.

Our daily objective is to produce healthy and life-giving food, and to achieve ecological, economic and social sustainability.

OUR PRODUCTIVE APPROACH: INTEGRATION

In 1987, we started an agroecological process, where step-by-step and through trial and error, we gradually built Naturaleza Viva, virtually copying the biological processes of Mother Nature herself. In that year, we stopped using inputs that negatively affect life and we adopted methodologies that multiply the soil's natural processes.

That decision meant swimming against the tide. In our area, monocropping was spreading, along with rural exodus, the use of agrochemicals and the poisoning of peasant farmers. We learned to transition from a practice of productive diversity to a practice of integration. We are proud of the production cycles that can be seen in our farm. Much of the waste material is reused as inputs in the following phase of the cycle. For example, the cows feed on our pastures; they give us milk with which we make cheeses. The whey produced as waste in the preparation of the cheeses is then used to feed pigs and cows, from which we produce sausages. Then, with the production of our sunflower fields we make oil and the expeller is used to feed cows, pigs and poultry. The dung produced by pigs and cows is used as an input for our biodigester. The gas produced is used in the processes of preparing food and in the houses on our farm. The biodigester also produces fertilizers for the field, our vegetable gardens and fruit orchards. Our goal is to further improve integration to increase the energy and productive efficiency of the farm.

Over the years we realized that it was essential to bring value-added products to the market. We stopped selling our primary produce and started to sell processed food products. This enabled us to significantly increase the farm's income and to be less exposed to the vagaries of the market.

OUR HISTORY

Naturaleza Viva was launched in 1987, but its roots stretch further back to the Catholic Rural Movement in which we participated from 1968 to 1972. The agrarian leagues and movements that arose in Argentina in the late-1960s and early-1970s encouraged the organization of small-scale producers and rural farm labourers. We struggled to put an end to the monopolies, ensuring a fair level of prices and land ownership. Our participation in this social change movement resulted in political persecution. In 1975 we took refuge in the forest to escape the military task forces which a year later would seize power and impose state terrorism until 1983. This military dictatorship in Argentina left 30 000 social militants disappeared. We were among those who were able to escape. We spent four years in the Chaco forest, where two of our children were born.

A paradox of our story is that when we succeeded in getting out of the country in 1979, we were accepted as refugees by the Office of the United Nations High Commissioner for Refugees (UNHCR). In 2014, at the FAO International Symposium on Agroecology for Food Security and Nutrition we were invited to present our experience in agriculture.

When we were able to return to the country in 1983, we brought with us two opposing experiences. The experience of life in the forest, which taught us more about links with nature; and the experience of living in large European cities with high levels of pollution, consumerism and waste.

Back in our own land, we have proposed to build a production system and a rural development model that was different from what had previously been imposed. We see ourselves as keeping the dreams of disappeared and assassinated comrades alive. Our commitment is to a way of doing and creating that solves the problems of hunger and protects the planet.

WHAT WE LEARNED AND ACHIEVED

Since 1987, we have learned to grow away from an agriculture based on external inputs, rising costs for farmers, and techniques for controlling diseases, insects and weeds by extermination – what we call “technologies of death”.

Instead, we developed our own technologies, based on daily ingenuity and practice, aimed at strengthening life and fertility. To that end, we concentrate on making sure that the nutrients are retained in our land. We learned to sell nutritional energy and not minerals. In 27 years, Naturaleza Viva has grown and accomplished many achievements:

- When we started out we had 30 trees, today we have 15 000.
- The phosphorus in the soil increased from 5 to 25 ppm, and we have doubled the amount of organic material in the land.
- We were a family and now there are 15 of us living off the income of the farm.
- We now have homes built of natural construction material, using materials that are found on our farm such as adobe, cane and clay. They are homes of greater thermal comfort and reduced energy costs.
- We have changed from selling primary produce to commercializing processed products. Our products reach a wide network of consumers across the country looking for natural food that is pollution-free. We estimate that over 10 000 families are currently obtaining this benefit; and the current trend of growth is exponential.

We have developed links with networks of ecologically aware consumers in the different regions of the country. This allows us to communicate to our buyers the notion that consumption is also tied to seasonal cycles; that permanent year-round stocks are impossible; and that non-industrial production practices are not all the same. We work with them to construct alternative rules of exchange that are not merely tied to supply and demand. We are committed to ensuring that our products reach consumers’ tables at prices that are consistent with production costs. There are over 600 direct buyers in our proprietary marketing network.

The farm’s operations are open to the community, and it receives visits from schools, delegations and families interested in finding out about our experience. Every year, we receive 1 800 visitors and some 60 interns and volunteers.

Figure 1. **Annual production of Naturaleza Viva**

OUR ANNUAL WORK PRODUCES:	
70 tonnes of sunflower	= 25 000 litres of oil
65 tonnes of wheat	= 65 tonnes of flour
5 tonnes of linseed (20-70 litres of oil pressed per hour)	= 1 750 litres of oil
130 cows and 120 calves	= 20 000 kg of meat
70 pigs	= 7 000 kg of meat
70-90 cows producing milk	5 000 kg of milk caramel (*dulce de leche*)
	30 000 kg of gouda cheese
	Yogurt, butter, ricotta
Fruit trees	Jams, juices, fruits in syrup
Other wholemeal flours: maize, amaranth, soya, sesame, linseed and rice; wholemeal bread	
Reserves of pasturage for the winter	
Apiculture	
Poultry breeding	
Medicinal plants (rue, chamomile, nettle, rosemary, lavender, aloe vera, marigold)	

THE NEW RURALITY

In 2014, just 7 percent of the Argentinian population lived in the countryside. One can drive for hours across an immense deserted pampa wetland before reaching urban cordons that suffer from overcrowding and precarious conditions. This causes an unbalanced distribution of the population, with non-inclusive social development. Territorial development and productive systems need to change. The solution to the problem of hunger, production and the problems of urbanization is to propose a new rurality.

If we were to replicate the experience of Naturaleza Viva throughout Argentina, we could raise the number of peasant producers and workers who could live decently in the rural area, producing diverse and high quality foods, from 400 000 to 4 million. Argentina has over 40 million ha of agricultural land, with mostly highly fertile soil.

This new rurality would make it possible to reverse the desolation of our countryside, creating genuine jobs. If, instead of paying corporations for agrochemicals, we invested in creating formal jobs through agroecology, the local development of currently forgotten communities would be possible. This new reality would also mean changing the role of agricultural professionals and opening up spaces for other disciplines to participate in the construction of the new model.

Each new agroecological producer who can set up and grow will be contributing to the health of all the Argentinian people. We are convinced that under this development model, we would be able to multiply the country's income and achieve a good quality of life for people in both the countryside and the city.

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URBAN AND PERI-URBAN AGROECOLOGICAL PRODUCTION SYSTEMS

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Note: This chapter builds upon the presentation made by Rilma Roman, ANAP (Asociación Nacional de Agricultores Pequeños de Cuba) at the International Symposium

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BACKGROUND: PARADIGM SHIFT AFTER THE REVOLUTION

Agriculture in Cuba rapidly modernized after the 1959 Revolution. Production started to rely increasingly on the Green Revolution package of technologies – including hybrid seeds, large chemical inputs and the use of machinery. A large proportion of these inputs were imported, while Cuba also served as a supplier of agricultural commodities, mostly export crops that were produced in monocultures (Rosset, 2005).

The collapse of the Soviet Union and the United States of America's embargo put an end to the era of easy and cheap access to chemical inputs that had made possible the rapid expansion of the Green Revolution in Cuba. In the early 1990s, as the government announced the start of the Special Period in Peacetime austerity programme, imports of oil were reduced by more than half and access to irrigation and the importation of foodstuffs also experienced sharp cuts (Rosset, 2005). After decades of reliance on chemicals for agricultural production, these changes imposed serious consequences on the Cuban people, including food insecurity, low levels of agricultural productivity and environmental degradation. In particular, soils had been affected by increasing levels of degradation, including salinity, low moisture retention and low organic matter content, which contributed to the constraints on productivity.

Throughout the country, there was an urgent need to increase production in order to provide for the food needs of the population. This need was met with an effort to shift production towards a low-input, organic-based model. Within this paradigm, the government encouraged the use of ecologically sound practices such as biofertilizers, earthworms, compost, livestock-cropping systems and intercropping. Biological methods rather than pesticides and herbicides were applied in order to suppress weeds and control diseases, and organic inputs replaced those agrochemicals that were no longer available (Kissing *et al.*, 2009).

LAND REDISTRIBUTION AND THE URBAN AND PERI-URBAN FARMERS' MOVEMENT

Governmental support has been a crucial factor in strengthening and rapidly scaling up the efforts of the smallholder agroecological movement. In the early years after the Revolution, as part of the efforts towards the reconversion of the country's agricultural sector, private farming was encouraged by a land reform process that turned large-scale, state-owned farms, which represented about 80 percent of the agricultural land in the country, into worker-owned cooperatives (Rosset, 2005). Additionally, the government started supporting the creation of small urban and peri-urban micro farms on state-owned land that had been abandoned (Altieri and Funes-Monzote, 2012). A growing number of people started seeking vacant small spaces in urban areas and made efforts to recover them and turn them back to productive agricultural uses. This was often done through *organopónicos*, or high-yielding urban and peri-urban gardens, which were set up by constructing protective barriers around furrows in the ground, enabling local urban dwellers to make use of poor soils and restore them by gradually incorporating organic matter in the ground and using low-input agroecological technologies such as integrated pest management (IPM), crop rotation and drip irrigation (FAO, 2014). These organic gardens helped ensure sufficient food for family consumption and moved horticultural crops – that had until then travelled long distances, hence losing quality and requiring large amounts of petrol for transportation – closer to the city. Far from being a form of subsistence farming, such gardens can produce a wide range of vegetables all year-round with yields as high as 20 kg m^{-2} (FAO, 2014).

Agroecological urban and peri-urban agriculture in Cuba is still strongly supported by the government and implemented under two national schemes. Among other policy initiatives, the Cuban Association for Organic Agriculture (ACAO) was developed from the Higher Institute for Agricultural Science of Havana to help better align Cuban agriculture with agroecological principles. ACAO worked to improve awareness of agroecological principles, increase research and teaching, coordinate farming activities and provide advice to producers, governments and NGOs.

The agroecological movement has been advancing hand in hand with the *campesino-a-campesino* method – the farmer-to-farmer extension approach based on the principle that farmers will be more interested in following the suggestions of other successful farmers rather than extension agents (Rosset *et al.*, 2011). Over the past two decades, more than 100 000 families – that is one-third of all farmers in Cuba – have been involved in the movement, working in yards, small farms and plots not exceeding 2-3 ha (Machín Sosa *et al.*, 2013). These systems favour the interaction of crop and livestock production, optimize and make the most out of available land and spaces and stimulate local production. The result is a system that is both sustainable and autonomous, which is capable of recycling large amounts of nutrients and able to harness the potential of local resources.

As a result, Cuba has managed to increase the number of people involved in agriculture, by including people that had never worked in the sector before. This is in contrast to the global scenario of declining numbers of farmers. Urban and peri-urban agriculture in Havana alone accounts for about 35 000 ha of land, which includes not only *organopónicos,* but also over 300 intensive gardens and hundreds of crop and livestock farms (FAO, 2014). It supplies approximately 50 percent of the fresh vegetables and fruits that are produced in the country, and has generated more than 300 000 jobs, of which 23 percent of those employed are women and 26 percent are youth under 35 years of age (AUSC, 2015).

Alongside promoting employment and increasing agricultural production, the movement plays a role in preserving and enhancing natural resources including soils, and in promoting the participation of not only farmers but women, children and entire families. Agricultural technicians in approximately 3 000 circles of interest across the country involve local youth by sharing knowledge on urban food production and agroecological farming, helping them to rediscover not only the productive aspect of farming but also cultural and ecological values and respect for nature (FAO, 2014).

Figure 1. **Urban and peri-urban agriculture in Havana, Cuba**

NUMBER OF RESIDENTS ENGAGED IN SOME FORM OF AGRICULTURE	AREA UNDER AGRICULTURAL PRODUCTION (HA)	VEGETABLES (TONNES)	FRUITS (TONNES)	ROOTS AND TUBERS (TONNES)	COW, BUFFALO AND GOAT MILK (MILLION LITRES)	MEAT (TONNES)
90 000	35 900	63 000	20 000	10 000	10.5	1 700

Note: Production data are from the year 2012

Source: FAO, 2014

CONCLUSIONS

Cuba represents a good example of how agroecological smallholder farming can be a viable alternative for producing food crops sustainably at a country-level scale. Through a multifaceted strategy based on the large-scale application of low-cost agroecological techniques, education and knowledge sharing programmes, and strong governmental support, Cuba has managed to respond to the food needs of its population by dramatically improving food production in just over two decades. While the solutions implemented in Cuba may partly be the result of local institutional and environmental enabling conditions, tailoring agroecological practices (e.g. low-cost irrigation techniques, soil rehabilitation through the use of organic fertilizers, IPM strategies for pest control) to different contexts will play a key role in scaling up production in an ecological manner, and drastically reducing the effects of conventionally managed agricultural production on human and environmental systems. Applying agroecological practices in urban and peri-urban agricultural systems will also help tackle some of the issues that will specifically burden urban and peri-urban areas in the coming decades as a consequence of the forecast growth in numbers of urban residents. Among the critical issues that agroecological urban farming can help address are pressures on urban infrastructure (as it reduces the needs for water and provides higher retention capacity of rainwater compared with built areas), pollution of water and air resources (thanks to a reduced use of chemicals) and urban food security – by shortening the food chain and providing food that is not only higher in quantity but that also has higher nutritional value at a lower cost to city dwellers.

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SONGHAI INTENSIVE AND REGENERATIVE AGRICULTURE: AN AGROECOLOGICAL SYSTEM DEPLOYING AFRICA'S ENVIRONMENTAL CAPITAL

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THE SONGHAI AGRICULTURAL MODEL

The first step in solving the challenges we are facing today is to realize that they are totally different from what we have seen before. It is not just one or two problems scattered here and there. This crisis is global and multifaceted. The problems of food security, social conflict and environmental degradation seem to be interconnected – suggesting that we are facing a systemic problem that requires a holistic and broad-based approach.

Unfortunately, most of the solutions we have seen so far seem to be piecemeal and symptomatic therapies that hardly work. We are operating from a mechanistic paradigm developed centuries ago. In the best cases, these solutions are simply band aid endeavours. In many cases however, they end up creating more problems. Today, more and more people are realizing that we have reached a point in history that calls for deep changes.

It is becoming clear that the solutions to our problems can no longer be found in the present day logic. We need a radical shift in our vision of the world and way of thinking, encompassing the way we see ourselves and relate to each other; our relationship with the environment; our scientific and technical orientations; our production systems; and the ways we exchange and consume our products and services.

Modern sciences are providing us with fundamentally different and refreshing frameworks to explain our human dynamics and that of our planet. From these sources, a systemic paradigm called bio-mimicry has emerged with completely new and different technological orientations. This paradigm engages and challenges us to learn from the basic principles of the workings of our planet that have existed for more than three billion years.

Songhai believes that by seeing our planet from this world view, we will be in a better position to design and re-engineer our way out of these interrelated crises. This new paradigm has to be appropriated and deployed if we are really committed to designing and creating organizations, industries and economic activities that are capable of solving our present day problems. Some of the principles of this new paradigm are:

- synergy;
- symbiosis;
- complementarity;
- collaboration;
- supplementarity.

The Songhai initiative can be seen as the harnessing of these principles to develop new and appropriate technological and developmental trajectories. It is an integrated development system that organically creates dynamic linkages and synergies between the environment, agriculture, industry and services – and also within each of these sub-systems. According to this perspective, the basis of sustainability is producing more with less.

Songhai develops and promotes a process that strives to harness the regenerative forces in nature to develop an agriculture that is not only multifunctional but enhances benevolent cycles and pathways, in order to:

- produce food in sufficient quantities to promote healthy living and disease prevention;
- improve the environment (soil health, food web, soil structure, etc.);
- build sustainability and biodiversity.

The merits of a development strategy based on this type of agriculture are many. It is not only safe, affordable, high yielding, high quality and sustainable, but it is also effective in solving environmental problems in both rural and urban areas and building a strong base for an inclusive and diversified economy.

A major value proposition of the Songhai endeavour is the commitment to break the vicious cycles of poverty that underpin socio-economic conflicts in developing countries. This is

achieved by creating a natural and integrated farming system that is based on low-cost inputs and the recycling of by-products and waste. It is an agricultural system that is site-specific because it strives to harness the services provided by the ecosystem in which it is practised, in turn creating products with specific qualities that reflect the influence of the '*terroir*'.

At Songhai, we are committed to develop regenerative farming technologies that bring into play the forces of synergy in nature that have been ignored by conventional methods. It is clear to us that the future of agriculture will no longer be primarily a chemical process, but largely a biological process. We have to relearn the way we practise agriculture – from the way we view the soil and its fertility, to the way we maintain, nourish and protect our plants and animals, to the way we condition and market them.

In other words, we must learn how to harness our environmental capital. This will be necessary in order to transform the rural sector to become productive, efficient and remunerative, while tackling the employment problem and slowing down the massive population exodus from rural areas. It is imperative to make our rural sector sustainable and competitive. This is a necessary pathway towards a viable, broad-based and inclusive economy.

Songhai advocates unlocking the potential of the environmental capital of Africa, particularly through the development of healthy living soils. We believe that maintaining healthy living soils, which we refer to as 'super soils', creates an enabling environment that maximizes synergies, such as the symbiotic associations performed by mycorrhizal fungi. Healthy soils positively impact the soil food web and build soil structure. In contrast, the use of synthetic fertilizers can disrupt these interactions. Developing healthy living soils increases the availability of plant nutrients and supports enabling environmental conditions. Ultimately, this promotes plant health and productivity and contributes to our vision of sustainable socio-economic development.

Conclusion and Recommendations

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RECOMMENDATIONS AND NEXT STEPS IN BRINGING AGROECOLOGY TO SCALE

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INTRODUCTION

As demonstrated by a robust and growing evidence base, agroecology is capable of providing multiple benefits for people and for the environment. Agroecology strengthens food security and nutrition, while maintaining healthy ecosystems that are the basis of agricultural production. By restoring degraded landscapes, agroecology helps to produce food where it is most needed. Through its focus on maximizing the ecosystem services and biodiversity that are provided free of charge by nature, agroecology fits the reality of smallholder producers. In addition, the strong emphasis on social interactions empowers farmers and communities, creating opportunities for viable rural livelihoods. As the impacts of climate change are already a reality, agroecology can play a key role in adaptation, enhancing the resilience of the poorest and most vulnerable people living in rural areas of developing countries.

Based on these synergies, agroecology has great potential to contribute to the achievement of the post-2015 Sustainable Development agenda. The new Sustainable Development Goals are highly integrated and cross-cutting, recognizing the importance of bridging the gap between agriculture and the environment, while providing rural employment and sustaining livelihoods. In this context, agroecology provides a comprehensive paradigm for food security and development, encompassing the need for regenerative and productive farming systems that are adaptable to climate change and are socially equitable.

During the International Symposium on Agroecology for Food Security and Nutrition, FAO provided a neutral forum to discuss the role of agroecology in strengthening food security and nutrition in a sustainable manner. The Symposium opened a global dialogue, where key stakeholders representing governments, civil society, science and academia, the private sector and the UN system gathered to share their experiences in agroecology. From the lessons learned, the following recommendations and next steps have been identified to scale up the positive impacts of agroecology.

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Peasant trainers from the National Coordination of Peasants' Organizations of Mali teaching about agroecology

RECOMMENDATIONS AND NEXT STEPS

Continuing the conversation at regional and national levels

Following on from the success of the International Symposium, FAO will continue to support a framework for international dialogue on agroecology, starting with three regional meetings in 2015. The first Regional Meeting on Agroecology for Food Security and Nutrition in Latin America and the Caribbean was successfully held in Brasília, Brazil, on 24-26 June, 2015. Two more regional meetings will be held in Africa and Asia, during November, 2015. Further expressions of interest have been registered to hold regional meetings in China, Europe and North America in the future.

Through the regional meetings – including the participation of civil society and other stakeholders – countries will continue the discussions initiated in Rome as they move towards the implementation of initiatives and strategies to advance agroecology. Regional level initiatives such as the Ecological Organic Agriculture Initiative of the African Union or the work of the Community of Latin American and Caribbean States (CELAC) on family farming have already taken steps to promote practices and policies that support agroecological principles. Such initiatives offer an opportunity for South-South cooperation in developing concrete actions to support agroecology.

Based on the regional meetings and stakeholders' interests and needs, the next steps for FAO's work on agroecology will be defined.

Continue to strengthen the evidence base in support of agroecology

Agroecological systems are knowledge intensive and science based. The International Symposium helped to strengthen and consolidate the evidence base in support of agroecology, with key contributions contained in these Proceedings. However, there is still a wide disparity in research attention given to agroecological systems compared with conventional agriculture. The International Assessment of Agricultural Knowledge, Science and Technology for Development concluded in 2008: "An increase and strengthening of AKST [Agricultural Knowledge, Science and Technology] towards agroecological sciences will contribute to addressing environmental issues while maintaining and increasing productivity." This implies a new interdisciplinary approach to agricultural research that embraces complexity. Agroecological approaches focus strongly on locally available resources, blending scientific and traditional knowledge, with producers at the centre of the learning and innovation process, and knowledge as a 'co-production' between producers and formal scientists.

The Symposium also highlighted a number of key questions and areas that require further investigation:

» A fundamental question is how widely is agroecology practised? How many producers practise agroecological methods worldwide, and at what scale?

- Chapter 16 of these Proceedings outlines factors in social organization that have helped to scale up agroecology, yet also points to the need to prioritize social science and self-study by rural social movements, to help draw systematic lessons from successful experiences;
- What are the links between agroecological systems and dietary factors that influence health and disease? Chapter 18 makes an urgent call for transdisciplinary research in agriculture, ecology and public health in order to explore these connections;
- What impact do agroecological systems have on socio-economic variables? Chapter 19 provides a preliminary analysis and identifies future research priorities in this area;
- What should investments into agroecology look like and how can they catalyse transformational change?
- How can the private sector best contribute to make food systems more sustainable?
- How can markets for agroecological products be built and strengthened where they already exist?

FAO sees its role in this area as a facilitator between different actors, including national research and development programmes, academia, social movements, farmers' associations and the private sector, to contribute to the strengthening of the evidence base for agroecology.

Build and strengthen networks in support of agroecology

Agroecology is already taking place on-the-ground, spread through social movements and methodologies such as the *campesino-a-campesino* ('farmer-to-farmer') methodology. These approaches have been highly successful in promoting farmer innovation and horizontal sharing between peers. Such movements involve large numbers of peasant and family farmers in self-organized processes. Because agroecology is grounded in local socio-ecological conditions, social process methods have significant advantages over traditional top-down methods of extension that prescribe ready-to-use technical packages.

Countries, NGOs, intergovernmental organizations such as FAO, and other international institutions can help catalyse the spread of agroecology by supporting these existing social movements and networks. They can learn from the experiences of organizations such as La Via Campesina to support agroecological networks in countries and regions where agroecology is a more recent and developing concept.

One concrete measure is to establish new farmer–researcher networks to support and empower smallholder producers, unleash their local and traditional knowledge, and improve the research–innovation cycle to enhance rural livelihoods and sustainable food systems. FAO's vision is to connect these farmer–researcher networks through an online Agroecology Knowledge Hub. FAO will further integrate agroecology into its existing work at the national level, including the development of agroecology curricula for Farmer Field Schools (FFS). The participatory FFS approach, which prioritizes experiential learning, is well suited to support capacity building on agroecological approaches.

Policy support to provide an enabling environment for agroecology, smallholder family farming and agrobiodiversity

Agroecology has entered the vocabulary of governments and international bodies, with policies established in numerous countries in Latin America and Europe. Both Brazil and France have adopted national agroecology plans. Agroecological approaches have been recognized, among others, within the Committee on World Food Security, in the Secretary-General's 2013 report on Agricultural Technology for Development and by the 17th UN Commission on Sustainable Development. This proves that policy processes can help scale up agroecology at national and international levels.

Policy support helps provide an enabling environment for agroecology to flourish. During the International Symposium, a number of specific priorities were identified:

» Protect the rights of smallholders and family farmers to access agrobiodiversity at no costs, which is a critical input for agroecological systems and is increasingly being restricted;
» Conserve agrobiodiversity as an essential resource for future adaptation, through *in situ* and *ex situ* measures;
» Internalize the environmental externalities in production costs to place agroecological systems on a level playing field with conventional industrial agriculture;
» Provide farmers and land managers with incentives to promote the protection and enhancement of ecosystem services through good agricultural practices;
» Strengthen the link between agricultural and nutrition policies;
» Encourage short commercialization circuits and local food systems (e.g. through procurement policies).

FAO stands ready to assist interested member countries to develop new opportunities in agroecology, including offering support to identify and implement policies, strategies and innovations that contribute to sustainable food systems.

Invest in agroecology

Most of the investment in agricultural research during the last five decades has been directed towards monocultures. As a result there is an urgent need, but also attendant opportunities, to redirect investment towards applications of agroecology to address the current and future challenges facing global food systems.

A distinguished group of over 300 scientists and experts from across the United States of America recently delivered a *Statement of Support for Public Investment in Agroecological Research*[1], calling for greater public investment in agroecological research. They note that agroecology has a proven record of meeting farming challenges in a cost-effective manner. Moreover, while other approaches also offer promising solutions, they are more likely to already benefit from private sector support. Agroecology is less likely to be supported by the private

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[1] http://www.ucsusa.org/our-work/food-agriculture/solutions/advance-sustainable-agriculture/scientists-call-public-investment-agroecology#.Vhu8nrSqpBd

sector because one of its goals is to reduce farmers' dependence on purchased external inputs. This leaves the public sector with the primary responsibility to fund agroecological research in the interests of farmers and society.

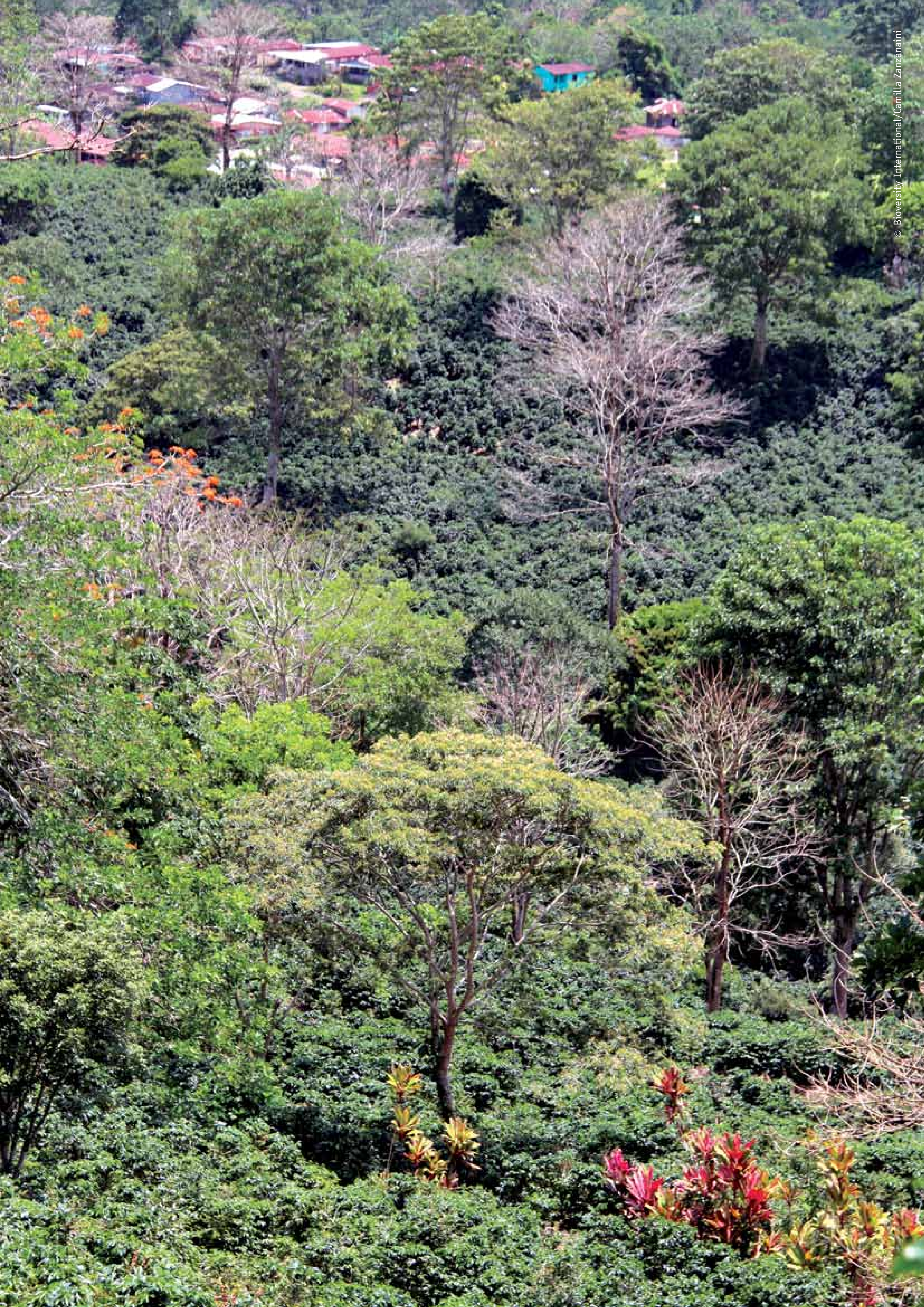
It should not be forgotten that farmers themselves are the largest investors in agriculture and adequate investment in agroecology will ultimately also depend on providing farmers with further means as well as giving them access to agroecological inputs and products. Therefore, financial infrastructure such as credit markets and farmers' insurances that support diversification and a transition to agroecology should be made available to smallholders and family farmers. Additionally, participatory guarantee systems should be strengthened and supported as should products and inputs needed for agroecological farms.

FAO sees agroecology as a 'good investment' for farmers, the environment and wider society.

CONCLUSION

In summary, we urgently need new alternatives to address the current and future challenges facing our food systems. Agroecology represents a promising option, capable of providing win-win solutions by enhancing food security and nutrition, restoring and maintaining healthy ecosystems, delivering sustainable livelihoods to smallholders and building resilience to adapt to climate change. To scale up the positive impacts of agroecology FAO will continue to support a framework for international dialogue on agroecology at the regional and national levels. It will be important to continue to strengthen the evidence base in support of agroecology, especially to address some of the key questions identified at the International Symposium. Countries, intergovernmental organizations and other stakeholders should support existing networks and promote new initiatives such as farmer–researcher networks to build and strengthen networks for agroecology. Through policy support, countries have a key role to play in establishing an enabling environment for agroecology, smallholder family farming and agrobiodiversity. Finally, there are opportunities for public and private actors to invest in agroecology to realize its full potential.

During the final wrap-up session of the International Symposium, Steve Gliessman and Pablo Tittonell reported the key findings and themes to the plenary. They asserted that agroecology provides an action-oriented approach to develop alternative food systems: "The Symposium emphatically demonstrated that the stakeholders represented have everything necessary to make this transformation happen. It only requires action, vision, responsibility towards future generations and above all courage."



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AGROECOLOGY is the science of applying ecological concepts and principles to the design and management of sustainable food systems.* It focuses on the interactions between plants, animals, humans and the environment. Agroecological practices work in harmony with these interactions, applying innovative solutions that harness and conserve biodiversity. Agroecology is practised in all corners of the world, with the traditional and local knowledge of family farmers at its core. Through an integrative approach, agroecology is a realm where science, practice and social movements converge to seek a transition to sustainable food systems, built upon the foundations of equity, participation and justice.




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