BACKGROUND PAPER

THE CONTRIBUTION OF AGROECOLOGICAL APPROACHES TO REALIZING CLIMATE-RESILIENT AGRICULTURE

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Executive Summary

It is generally accepted that agriculture is a major driver of climate change as well as being acutely challenged to adapt to its effects. Agroecological approaches involve the application of integrated ecological, economic and social principles to the transition of smallholder farming systems, towards greater resilience. This involves adapting 13 generic agroecological principles to local circumstances. The principles include: diversification, recycling, and better connecting producers and consumers. Adaptation is done by scientists working closely with farmers and other stakeholders to co-create concrete, demand-led solutions to pressing problems as they are experienced locally rather than through imposing externally prefabricated solutions that may not be locally appropriate.

Agroecology comprises transdisciplinary science; sustainable agricultural practices; and, social movements that are precipitating widespread behaviour change. Agroecological principles map closely to principles of adaptation with the notable exception that while they often exhibit resilience benefits, these are incidental rather than representing an explicit response to climate signals. Current market failures (for example not costing pollution nor valuing the maintenance of soil organic carbon); and, perverse policy incentives (for example subsidizing use of artificial fertilizers and pesticides) combine to mitigate against decisions for farmers and other food system actors to adopt agroecological approaches despite their benefits for climate resilience.

Agroecology manifests at field, farm and landscape scales, for which different metrics of agricultural performance are relevant in order for agroecological practices to be fairly judged against alternatives. Operationalising new and holistic performance metrics for agriculture will require innovation in both public and private (value chain) sector governance.

There is extensive experience of agroecological practices contributing to addressing specific climate change effects, such as:

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contour hedgerows to reduce soil erosion caused by more intensive rainfall; shade trees to mitigate higher temperatures for crops as diverse as coffee, wheat and rice; and, encouraging optimum landscape level tree cover to realise nutritional benefits through increasing diversity of the diets of women and children and groundwater recharge. But, the largest contribution that agroecology makes to adaptation is often through better management of interactions at livelihood scales, conferring income and food security benefits. Robust evidence of the cost-effectiveness of agroecological practices *vis-à-vis* alternatives is lacking and collecting it is of urgent importance.

Despite an uneven playing field, there are examples of agroecology being adopted at scale. These include: farmer managed natural regeneration that is precipitating the regreening of parts of the Sahel in Africa, agroecological response to the newly arrived fall army worm epidemic in Africa, state level sponsorship of agroecology in Andhra Pradesh in India and policy change in Peru, France and Switzerland to support land restoration and biodiversity conservation.

Agroecological approaches have proven ability to simultaneously address specific climate hazards, enhance the resilience of farming systems to climate change and to improve the flow of a range of ecosystem services. They will only be widely adopted if actions are taken to level the playing field in respect of enabling policies, the collection of evidence and consumer choice. These actions need to be coupled with moving away from simplifying landscapes to embracing complexity, addressing option by context interactions and enabling integration both vertically (across scales) and horizontally (across sectors) to deliver a conducive environment within which agroecological approaches can co-exist alongside alternatives.

1. Introduction

This background paper focuses on the role that agroecological approaches can play in making food systems more agile in adapting to climate change as planetary boundaries are reached and exceeded, with a focus on the field and the farm scales, but recognizing key interactions with the landscape and food system scales. It highlights how agroecological practices on farms can enable adaptation, and what is required to scale these up to levels capable of reconciling the UN Sustainable Development Goal 2 (SDG 2), to end hunger, with SDG 15, to do so while enhancing rather than further depleting natural capital.

It is now widely recognized that a major transformation of food systems is needed to achieve food and nutrition security globally in the context of a changing climate, and that this will profoundly affect what people eat, as well as how it is produced, processed, transported, and sold. Bringing about such transitions to more sustainable and democratic agricultural systems that reconcile human and environmental health with social justice and, hence, are resilient, will not happen without major shifts in public policies and private sector contributions to the governance of value chains at international, national, and local levels, as well as the active encouragement of innovation across these scales.

Agroecology is increasingly seen as being able to contribute to transforming food systems by applying ecological principles to agriculture to ensure a regenerative use of natural resources and ecosystem services. Agroecology also embraces social and cultural aspects in developing equitable food systems within which all people can exercise choice over what they eat, and how and where it is produced. To this end, agroecology combines science, practice, and social movements that complement each other, although it is not inevitable that they remain in step with one another.

Environmental and societal drivers have led to an increasing moralization of debates around food. On the one hand, this creates an imperative for policy makers to act and, on the other hand, makes it more difficult for policy to be based on evidence, as opposed to evaluation of competing convictions. Agroecological principles that underpin food system transitions include both normative elements (e.g., they should be equitable) and causative elements (e.g., more diverse farming systems are more resilient). It is necessary to clarify, on the one hand, the normative assertions that should underpin the transition to more resilient farming and, on the other, the causative mechanisms that can bring it about.

This background paper explores these issues, highlighting scalable practices that enhance adaptive capacity of farms and the methods required for their successful scaling.

2. What is Agroecology?

Agroecology, at its most basic, is the application of ecological principles in agriculture. This is a complex concept, however, because both agriculture and ecology are dynamic fields, undergoing rapid change in response to mounting evidence that the global food system is unsustainable because agriculture, as currently practiced, is a major driver of climate change[1] and the breaching of other planetary boundaries.[2] Ecology refers both to a scientific discipline[3] and to political movements concerned with protection of the environment.[4] Agriculture is a subject focus rather than a scientific discipline, encompassing the set of practices through which people produce food to which various scientific disciplines are applied.[5] Agroecology encompasses all of this complexity.

Although ecological science began as a subdivision within biology, it has more recently emerged as an interdisciplinary field with many different branches, including political ecology,[6] many of which link biological, physical, and social sciences. Agriculture is also evolving, with an increasing realization that it is often not useful to separate production of food from other aspects of whole agri-food systems[7] that embrace the production and consumption of food and all that is involved between these two events along food chains.[8] This includes considering the multifunctionality of agriculture with respect to the full range of ecosystem services, such as water yield and quality, pollination, and biodiversity conservation, as well as food production, that are derived from agroecosystems.[9]

These trends in ecology and agriculture come together in an emerging transdisciplinary focus on understanding and managing coupled social-ecological systems.[10] A key reason agroecology is gaining traction in the discourse on adaptation is that it is perceived to bridge ecological and social dimensions associated with development of resilient food systems in the face of climate and other global change.[11] Today, agroecology embraces science, a set of practices, and a social movement,[12] as well as the integration of these three elements to design and implement more sustainable food systems. In practice, the three elements may not always be in step with one another, and tensions between science, on the one hand, and agroecological practice and social movements on the other, reveal a need for particular attention to be paid to the axiomatic agroecological principle of co-creation of knowledge (Box 2 and Figure 1).

2.1 Agroecological Science

The term "agroecology" first appeared early in the twentieth century to designate the application of ecological methods and principles in agricultural sciences.[13] In the 1950s and 1960s, Tischler published several articles on agroecological research, analyzing plants, animals, soils, climate, and their interactions, as well as the impact of human management on them.[14] The concept of "agroecosystem," considered as a domesticated, human-managed ecosystem, was introduced by Odum in 1969.[15] Agroecology began to move beyond the field and farm scales to embrace whole agroecosystems two decades later,[16] with important contributions emphasizing intercultural processes for constructing agroecological knowledge that included local knowledge.[17]

Building on these developments, Altieri defined agroecology as *"the application of ecological concepts and principles to the design and management of sustainable agroecosystems,"*[18] also reflected by the Food and Agriculture Organization (FAO) in stating that: *"Agroecological innovations apply ecological principles – such as recycling, resource use efficiency, reducing external inputs, diversification, integration, soil health and synergies, for the design of farming systems that strengthen the interactions between plants, animals, humans and the environment for food security and nutrition."*[19]

The focus of agroecology was further broadened to include a food systems focus a few years later,[20] encompassing alternative and local food networks, consumer-producer relationships, social agricultural networks, agri-food systems, food markets, and food procurement, leading to *"an integrated discipline that includes elements from agronomy, ecology, sociology and economics."*[21] Agroecology has since gone beyond an interdisciplinary approach[22] to embrace a transdisciplinary focus, seeking transformative solutions to real-world problems in the development of sustainable food systems, while striving towards inclusive engagement of all stakeholders in knowledge generation.[23]

BOX 1 Transdisciplinary Science

The High Level Panel of Experts on Food Security and Nutrition (HLPE)[24] describes transdisciplinary science (after Russel et al. 2008)[25] as having:

- A problem focus (research originates from and is contextualized in "real-world" problems);
- An evolving methodology (the research involves iterative, reflective processes that are responsive to the particular questions, settings, and research groupings involved); and
- Collaboration, including among transdisciplinary researchers, disciplinary researchers, and external actors with interests in the research.

2.2 Agroecological Practice

Partly in response to concerns about the effect agriculture was having on wildlife and the environment generated by Rachel Carson's book Silent Spring,[26] a set of agroecological practices emerged, aiming to move away from an "industrial agriculture model," dominated by large-scale specialized farms, relying heavily on fossil fuel and external artificial inputs, toward more environmentally friendly and sustainable agricultural systems, optimizing the use of biological processes and ecosystem functions.[27] The approach was summarized by Altieri, as designing complex and resilient agroecosystems that, by *"assembling crops, animals, trees, soils and other factors in spatially and temporally diversified schemes, favor natural processes and biological interactions that optimize synergies so that diversified farms are able to sponsor their own soil fertility, crop protection and productivity."*[28]

There is no definitive set of practices prescribed as agroecological.[29] It is easier to discuss practices as being more or less agroecological, depending on the extent to which they make use of ecological processes as opposed to external inputs; they are equitable, environmentally friendly, locally adapted and owned; and they are integrated within a systems approach, rather than focusing on single measures. Agroecological farming emphasizes diversification, mixed cultivation, intercropping, cultivar mixtures, habitat management techniques for crop-associated biodiversity, biological pest control, improvement of soil structure and health, biological nitrogen fixation, and the recycling of nutrients, energy, and "waste" as inputs to the production process.[30] Some of these practices have already been applied to varying extents in different parts of the world for decades, while others have been more recently developed with limited adoption to date.[31]

2.3 Social Movements

Agroecosystems, by definition, include the human communities that shape them, hence social and political dynamics are inevitably a central concern in agroecology.[32] Agroecological approaches have often arisen in response to agrarian crises, and in concert with broader efforts of social movements to initiate widespread change.[33] Agroecology has become the political framework under which many social movements and peasant organizations around the world defend their collective rights, and advocate for a diversity of agriculture and food systems practiced by small-scale food producers in different places.[34]

These social movements advocate for a strong connection to be made between agroecology, the right to food, food sovereignty, and environmental integrity. Food sovereignty is a broad concept focused on people's right to control who produces food and how, and what kind of food is produced. In February 2015, diverse social movements and organizations, representing small-scale food producers, gathered in Nyéléni, Mali, for an International Forum on Agroecology.[35] In their final declaration, they consider *"agroecology as a key element in the construction of food sovereignty."* For them, agroecology is not only *"a narrow set of technologies"* but, above all, a political struggle, requiring people to *"challenge and transform structures of power in society,"* addressing power imbalances and conflicts of interest, in order to *"generate local knowledge, promote social justice, nurture identity and culture, and strengthen the economic viability of rural areas."*

Social movements are equally important with respect to climate change, both regarding calling for action to address the current climate crisis, such as Extinction Rebellion,[36] and in protesting against the impacts of mitigation measures on people's immediate livelihoods, such as the Gilet Jaunes phenomenon.[37]

2.4 Principles of Agroecology

Many publications have articulated agroecological principles in different ways and these have been summarized by Nicholls et al. (2016) and more recently by the FAO and by the Coopération pour le Développment et la Solidarité (CIDSE).[38] These principles cover agricultural and ecological management of agri-food systems, as well as some wider ranging socio-economic, cultural and political principles that have emerged recently from the activity of social movements. HLPE, in consolidating these multiple sources, defined principles as *"statements that form a basis for a system of belief or reasoning that guide decisions and behavior,"* and distinguished normative principles that assert values (e.g., food systems should be equitable) from causative principles that explain relationships (e.g., more equitable food systems are likely to be more sustainable).[39] In either case, to be useful, they need to be fully explicit rather than retaining any ambiguity.

On this basis, a consolidated set of thirteen key agroecological principles were proposed (Box 2) that relate quite closely to the FAO's 10 elements of agroecology,[40] but are finer grained to conform with the requirement of being explicit.

Clearly there are linkages among these principles. For example, the greater functional biodiversity there is (Principle 5), the more scope there is for both enhancing positive ecological interactions through synergy (Principle 6) and promoting economic diversification (Principle 7), as shown in Figure 1 below, and explored in more detail in the next section on how agroecology generates adaptation benefits.

Co-creation of knowledge is a central principle that underpins all the others, because it defines the legitimacy of agroecology developing in different ways in different localities as a result of local knowledge and experiential learning, in line with cultural and ecological specificities associated with different people and places. It is a notion that recent shifts in global scientific thinking are also trying to grapple with, through adopting an options by context paradigm in agricultural research that aims to achieve development outcomes.[42]

This explains the absence of a prescriptive set of agroecological practices, with agroecology instead being defined by a generic set of principles that may be applied variously in different locations by different people, resulting in a rich variety of locally adapted practices (as illustrated in Table 1). This flexibility of approach enhances the ability of agroecology to build climate resilience.[43]

Adapting generic principles to local context through co-learning, rather than promoting prescribed practices or technology, results in concrete practices suited to local circumstances and enables a demand-driven development agenda. The difference is analogous to that between manufacturing concrete items centrally and then distributing the same items to many people and places, as opposed to disseminating cement that is then mixed locally to manufacture concrete items that suit the people at each location.

The latter is more efficient where the suitability of items is heavily context-dependent, as for agricultural practices.[44] Where there are no practices that are suitable for particular contexts (people and places) a demand is created for innovation to address specific needs, generating a demand-driven development agenda. [45]

BOX 2 Principles of Agroecology

RECYCLING 1

Preferentially use local renewable resources and close, as far as possible, resource cycles of nutrients and biomass.

INPUT REDUCTION 2

Reduce or eliminate dependency on external inputs.

SOIL HEALTH 3

Secure and enhance soil health and functioning for improved plant growth, particularly by managing organic matter and by enhancing soil biological activity.

ANIMAL HEALTH 4

Ensure animal health and welfare.

BIODIVERSITY 5

Maintain and enhance diversity of species, functional diversity and genetic resources and maintain biodiversity in the agroecosystem over time and space at field, farm, and landscape scales.

SYNERGY 6

Enhance positive ecological interaction, synergy, integration, and complementarity among the elements of agroecosystems (plants, animals, trees, soil, water).

ECONOMIC DIVERSIFICATION 7

Diversify on-farm incomes by ensuring small-scale farmers have greater financial independence and value addition opportunities while enabling them to respond to demand from consumers.

CO-CREATION OF KNOWLEDGE 8

Enhance co-creation and horizontal sharing of knowledge, including local and scientific innovation, especially through farmer-to-farmer exchange.

SOCIAL VALUES AND DIETS 9

Build food systems based on the culture, identity, tradition, social and gender equity of local communities that provide healthy, diversified, seasonally, and culturally appropriate diets.

FAIRNESS 10

Support dignified and robust livelihoods for all actors engaged in food systems, especially small-scale food producers, based on fair trade, fair employment, and fair treatment of intellectual property rights.

CONNECTIVITY 11

Ensure proximity and confidence between producers and consumers through promotion of fair and short distribution networks and by re-embedding food systems into local economies.

LAND AND NATURAL RESOURCE GOVERNANCE 12

Recognize and support the needs and interests of family farmers, smallholders, and peasant food producers as sustainable managers and guardians of natural and genetic resources.

PARTICIPATION 13

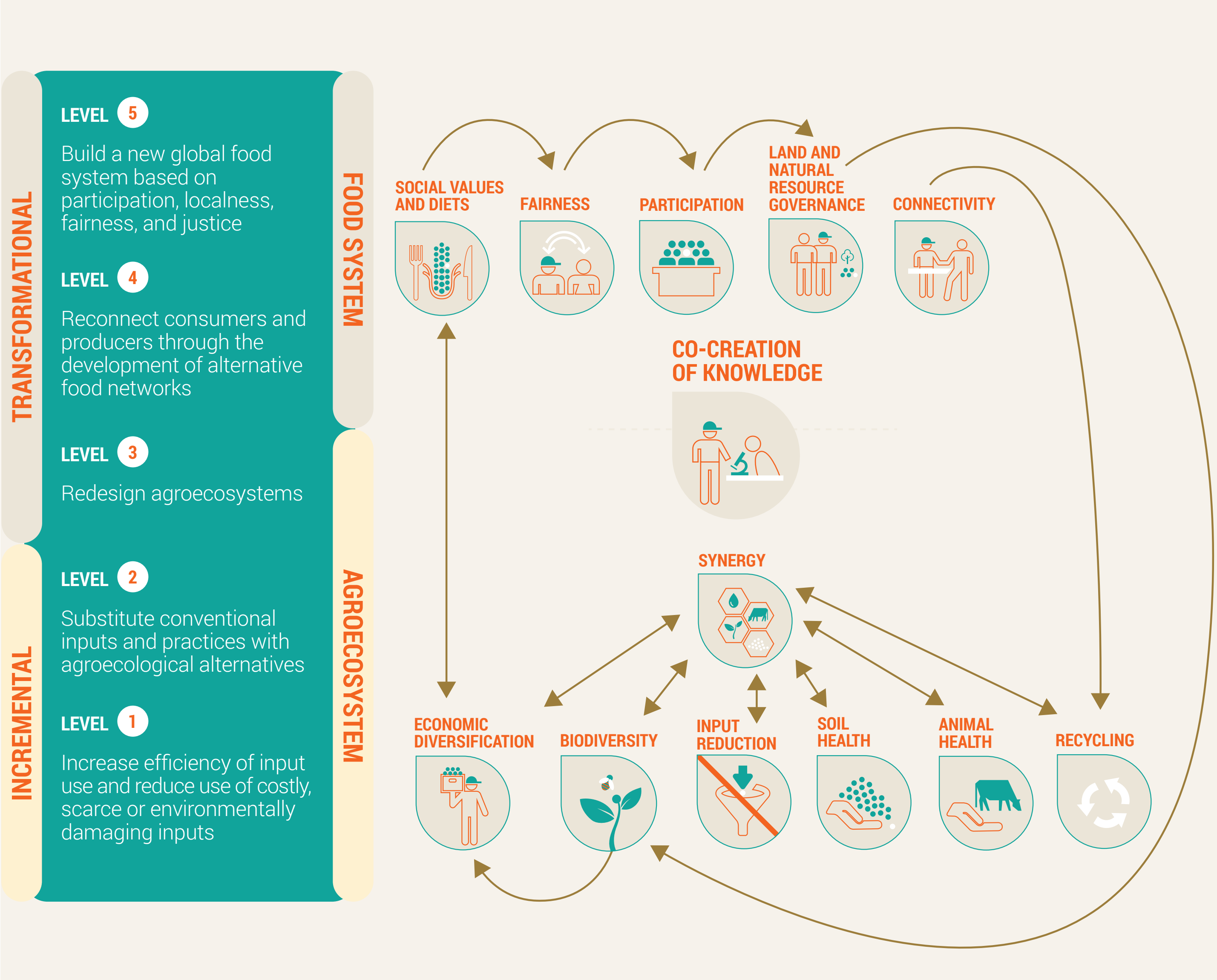
Encourage social organization and greater participation in decision-making by food producers and consumers to support decentralized governance and local adaptive management of agricultural and food systems.

Source: Based on the three principal contemporary sources in the HLPE 2019 and synthesized for the purposes of this report.[41]

2.5 Transitions to More Sustainable Food Systems

A key consequence of defining agroecology in terms of the application of principles, rather than as a set of practices, is that this implies that their application will result in changes to the agricultural and food systems to which they are applied. This is in line with the emerging consensus that there is an urgent imperative to transform current food systems (in terms of what people eat and how it is produced, stored, transported, processed, and sold) to bring food production in line with demand and the capacity of the planet to produce and absorb pollution and waste. This leads to a recognition that as different agroecological principles are applied, different levels of transition will occur,[46] involving either incremental or transformational change, depending on which principles are involved and at what scale they operate (Figure 1).

FIGURE 1 Five Levels of Transition to Agroecological Function at Agroecosystem and Food System Scales



Source: Adapted from Gliessman 2016 and HLPE 2019.[47]

Notes: Five levels of transition (1–2 incremental; 3–5 transformational) to agroecological function at agroecosystem (levels 1–3) and food system scales (levels 4–5), after Gliessman (2016) with the agroecological principles involved (see Box 2) adapted from HLPE (2019).[48] Arrows show major linkages among principles. Co-creation of knowledge underpins all other principles.

3. How Does Agroecology Contribute to Climate Change Adaptation?

Adopting Intergovernmental Panel on Climate Change (IPCC)[49] definitions of the related concepts of adaptation and resilience (Box 3), three key dimensions of adaptation can be drawn out. These are:

- Resilience, the ability to withstand climate impacts (shocks caused by extreme events) with more resilient agricultural systems clearly being better adapted;
- The process of adaptation (adjusting in response to a changing environment); and
- The state of "being adapted", the extent to which an agricultural system is well suited to current conditions, including the current uncertainty, which tends to increase as climate variability increases.

BOX 3 Definitions of Adaptation and Resilience

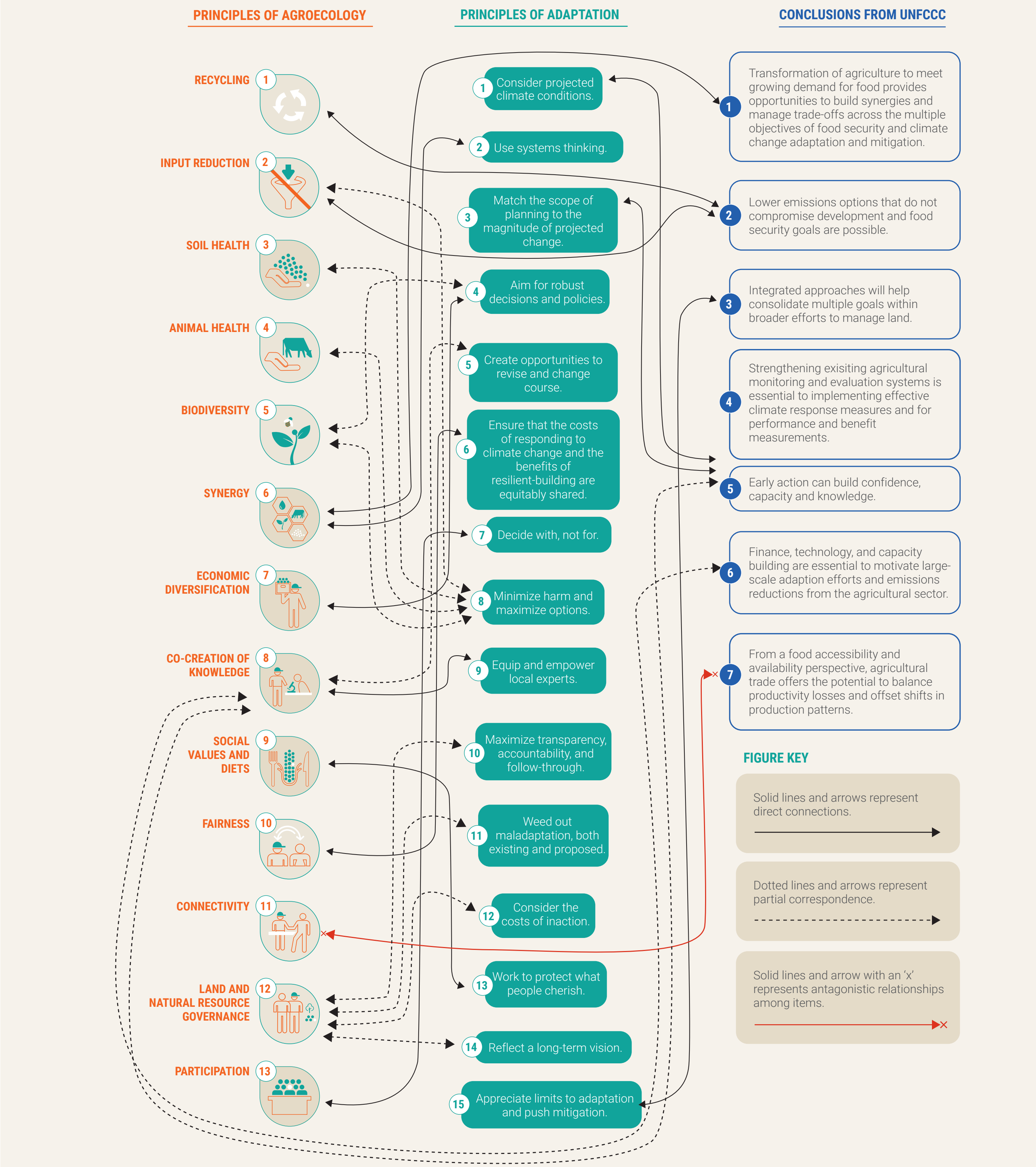
- **Adaptation** is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm, or exploit beneficial opportunities.
- **Resilience** is the capacity of social-ecological systems to cope with a hazardous event, trend, or disturbance, responding or reorganizing in ways that maintain the systems' essential function, identity, and structure while also maintaining the capacity for adaptation, learning, and transformation.

Source: Adapted from the IPCC 2014.[50]

In implementing policies and actions to achieve adaptation, these three dimensions become entangled with other societal values, such as a desire for equity, also evident in the principles of agroecology (Figure 2). In the same way that agroecological principles overlap to some extent, but also differ from those of alternative approaches to agricultural improvement, the 15 generic adaptation principles in Figure 2 represent one approach,[51] and should therefore be seen as illustrative rather than definitive. Both the agroecological and climate adaptation principles are also related to the seven conclusions of a policy brief on agriculture and climate change prepared to inform the United Nations Framework Convention on Climate Change (UNFCCC).[52]

The relationships evident in the diagram illustrate that most of the agroecological principles contribute to adaptation and that most adaptation principles are reflected in the agroecological principles. There are two key exceptions to this. Firstly, the agroecological principles do not explicitly encompass consideration of projected climate change. This is consistent with agroecological approaches often leading to unplanned climate adaptation benefits, while suggesting that incorporating more explicit consideration of climate change in the design of agroecological practices might enhance adaptation outcomes. Secondly, there is a potential antagonism between agroecological principle 11, related to better connecting producers and consumers and shortening supply chains, and conclusion 7 of the policy brief, which points to the use of trade to smooth out food distribution. There is need for careful consideration of the relative importance accorded to these alternative approaches and the contexts in which they are, and are not, relevant.

FIGURE 2 Correspondence between Principles of Agroecology and Climate Adaptation



Source: Developed by the authors.

Notes: Linkages among 13 principles of agroecology (from Box 1) on the left-hand side, 15 general principles of adaptation in the center,[53] and seven conclusions of a policy brief on agriculture and climate change prepared to inform UNFCCC on the right hand side.[54]

Typical climate change adaptation options in agriculture include:[55]

- Use of different varieties or species;
- New cropping practices, (e.g., different timing of planting);
- Greater use of water conservation and management technologies;
- Diversification of on-farm activities;
- Enhancement of agrobiodiversity;
- Adapted livestock and pasture management;
- Improved management of pests, diseases, and weeds; and
- Better use of short-term and seasonal climate forecasting to reduce production risks.

All but the last of these are encompassed by agroecological practices (see Table 1 below), and forecasting could equally well be applied to enhance agroecological or other types of farming.

With respect to the use of different crop species and varieties, there are differences in emphasis between agroecological approaches and the use of modern breeding and biotechnologies, such as genetic engineering. Concerns among proponents of agroecology about the use of modern biotechnologies center more on how the technologies are used and controlled than on the nature of the technologies themselves.[56] The present power asymmetry in the agricultural and food sectors among large corporations and smallholder farmers results in the application of biotechnologies often being incompatible with agroecological principles. Many modern varieties resulting from conventional breeding are adapted to monoculture.

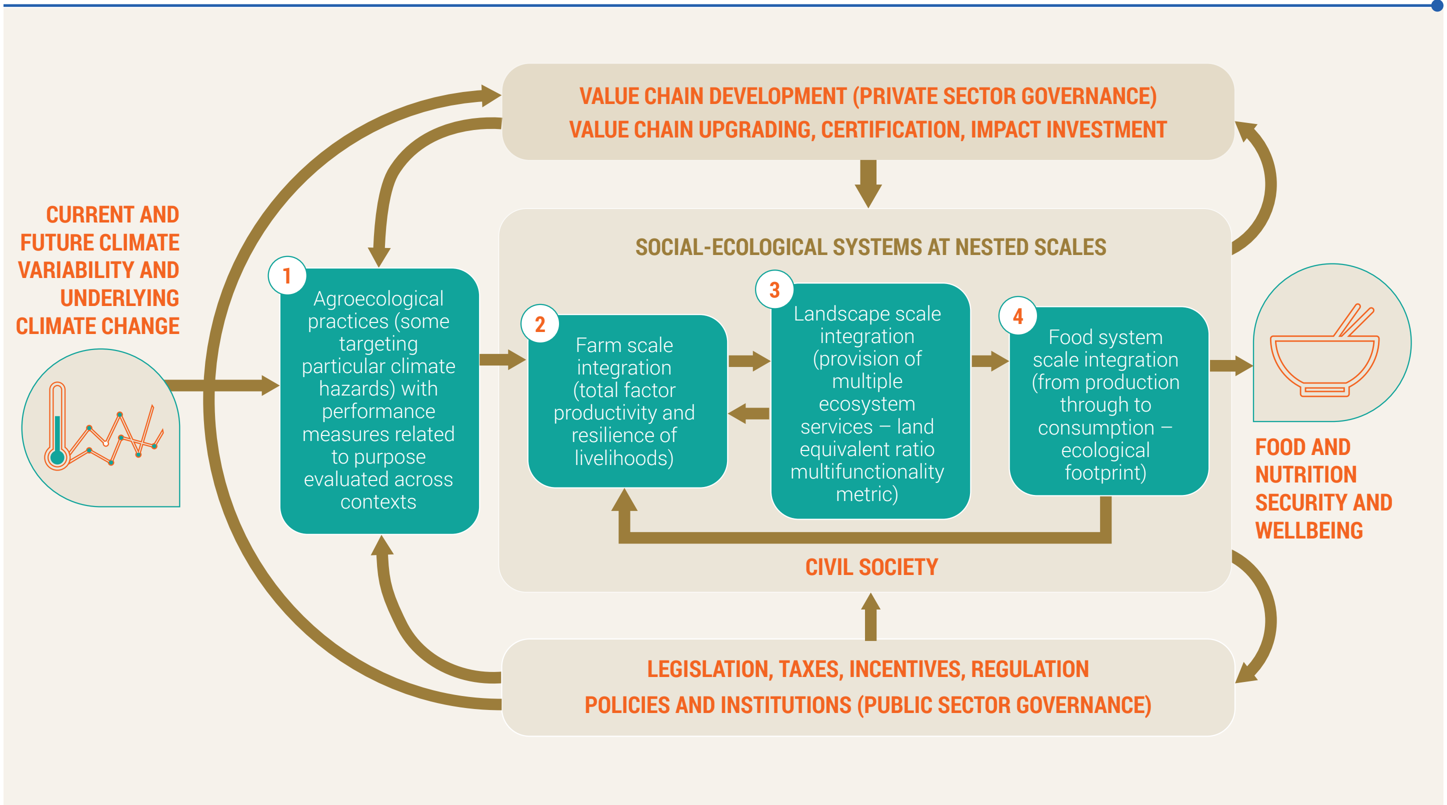
Participatory varietal selection, and breeding for performance in more diverse cropping contexts, may yield varieties better adapted for use in agroecological practices than those that do well in monoculture. For example, maize yield was increased by 30 percent in the mid-hills of Nepal through participatory varietal selection.[57] There, the maize was relay-cropped with millet on terraces with fodder trees on crop terrace risers. These fodder trees compete with the crop but are essential for feeding animals in the dry winter, hence ensuring provision of dung to fertilize crops. The better performing variety in this context had longer roots than the varieties it came to replace.[58]

Clearly, where crop breeding is directed at aims compatible with agroecology, including performance in diverse niches, and with respect to pest and disease resistance, as well as tolerance of drought and waterlogging, and where it is participatory, it can be an important aspect of agroecological improvement. In some cases, reverting to traditional varieties better adapted to climate variability[59] confers advantages or represents a more appropriate starting point for breeding and selection than do modern varieties.

There has often been recognition that adaptation benefits from agroecology may arise either directly from practices that improve the performance of agriculture in relation to particular hazards arising from climate change, or through less direct effects of system integration, resulting in more resilient landscapes and livelihoods.[60] This dichotomy, however, is problematic for two reasons. Firstly, by referring to direct and indirect benefits, there is a suggestion that the direct benefits may be more important, tangible, or of larger magnitude than indirect ones, although the converse is often the case: synergistic effects at system level are often more significant than those of individual practices. Secondly, it obscures the change in nature of adaptation benefits at different scales (field, farm, landscape, and food system), all of which involve integration at a specific scale.

To avoid such a dichotomy, adaptation benefits of agroecology are categorized in this background paper as those occurring at four scales. Each scale of integration can be associated with performance metrics and related to public and private sector governance mechanisms and behavior that can influence outcomes (Figure 3). Agroecological practices are currently undervalued because the externalities associated with alternatives (e.g., pollution, land degradation, and reduction in pollinators) are generally not taken into account by the performance measures used for agricultural systems. A key requirement for agroecological practices to be fairly evaluated against alternatives is the adoption of comprehensive performance metrics that take all of the impacts of agriculture into account (i.e., environmental, social, and economic).

FIGURE 3 Framework for Understanding Agroecological Adaptation to Climate Change across Scales and How It Is Influenced by Public and Private Sector Governance



Source: Developed by the authors.

The four scales of integration that interact with one another are as follows:

- At **field scale,** specific agroecological practices that may improve agricultural performance with respect to climate change include shade trees buffering rising temperatures to stabilize yield of crops like coffee,[61] and increasing the yield of food staples through lowering daytime temperatures and reducing heat stress;[62] diversity, increasing resilience of crops to climate-induced pest and disease pressures;[63] or increased soil carbon and mulch associated with increased water infiltration and holding capacity and reduced evaporation, improving resilience of crops to drought.[64]

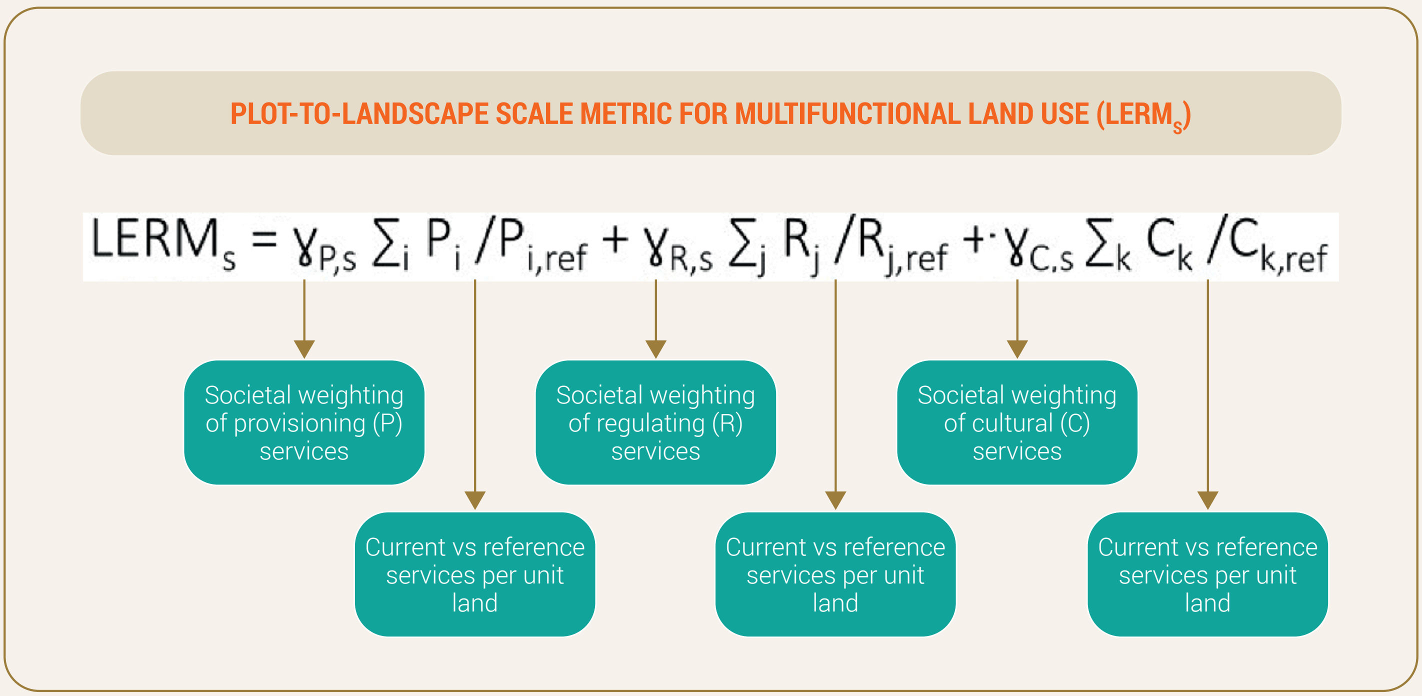
- At **farm (or livelihood) scale,** the integration of agroecological practices within farms may improve the Total Factor Productivity (TFP) and resilience of livelihoods. TFP has often been applied at national level as the ratio of aggregate output, for example, Gross Domestic Product (GDP) to aggregate inputs (of labor and capital), with the growth in output not explained by increased input, representing an increase in economic efficiency.[65] Applied to livelihoods, with appropriate measures of aggregate output and input, change in TFP measures whether livelihoods are improving or not across all dimensions.

  This often involves management of interactions among system components. For example, increased tree cover on farms in Ethiopia allows farmers to produce firewood on their farms to burn as fuel instead of dung, which can then be returned to fields to fertilize crops. The dung increases yield while, at the same time, the labor required to collect firewood is reduced, which can then be re-directed to other opportunities to improve livelihood resilience (Figure 4 and Table 2).

- At **landscape (or community) scale**, integration of agroecological practices across landscapes enables management of the provision of a range of Ecosystem Services (ES) that confer resilience, as measured by the plot to landscape scale metric for multifunctional land use, the Land Equivalent Ratio Metric (LERM).[66] A key bottleneck is that there are often neither policy instruments nor social capital present at the local landscape scales at which key ES, such as water yield and quality or habitat provision, first manifest and so can be managed.[67] Where landscape level management for a range of ES is implemented, there are clear implications for field and farm level agricultural practice and strong interactions across farm and landscape scales. These interactions are two-way, both in terms of how farmers view and influence landscape scale measures, such as the exclosure of land to foster restoration,[68] and conversely, how actions to manage ES, such as hedgerows or buffer strips to regulate water flow and provide flood protection,[69] may have differential value across landscapes, and hence for different farmers.[70]

- At **food system scale**, agroecological approaches connect production and consumption to deliver sustainable, climate-adapted whole food systems, as measured by their ecological footprint.[71]

BOX 4 Landscape Scale Metric for Multifunctional Land Use



Source: van Noordwijk et al. 2018.[72]

The first two of these scales (field and farm) are further elaborated below, while integration at landscape and food system scales are the subject of complementary background papers.

3.1 Field Level Practices

A compelling illustration of how adoption of individual agroecological practices can operate to improve farm-level adaptation to climate change is a recent inventory of agroecological practices for Africa and their contribution to climate adaptation.[73] Global warming is expected to proceed more rapidly on the African continent than elsewhere, with changes more pronounced for arid regions in the North and South than in humid central Africa.[74] The key combined effects of rising temperatures, increasingly variable and unpredictable rainfall, and higher frequency of extreme weather events, such as droughts and floods that farmers are already having to adapt to, include:

- Reduced access to water;
- Shorter growing seasons;
- Longer water deficit periods during crop growth (increased number of days without rain combined with higher potential evapotranspiration);
- Reduced availability and nutritional quality of animal fodder at key times; and
- Accelerating land degradation (because of higher temperatures) and changes in the distribution of insects and pathogens.[75]

Debray et al. (2019) focused on agropastoral land use in semiarid Africa and mixed-crop-livestock production in subhumid areas.[76] They used a combination of interviews with experts in African and French non-governmental agricultural organizations, and extensive literature review, to evaluate the contribution to climate adaptation of agroecological practices in use by farmers. These were mainly concerned with soil and water management, but also included diversification of production, pest and disease control, and livestock management (Table 1). They identified seven categories of agroecological practices contributing to adaptation that were related to:

- Preventing land degradation;
- Improving soil health;
- Better water management;
- Diversifying production;
- Adaptive crop management;
- Pest and disease control; and
- Managing livestock.

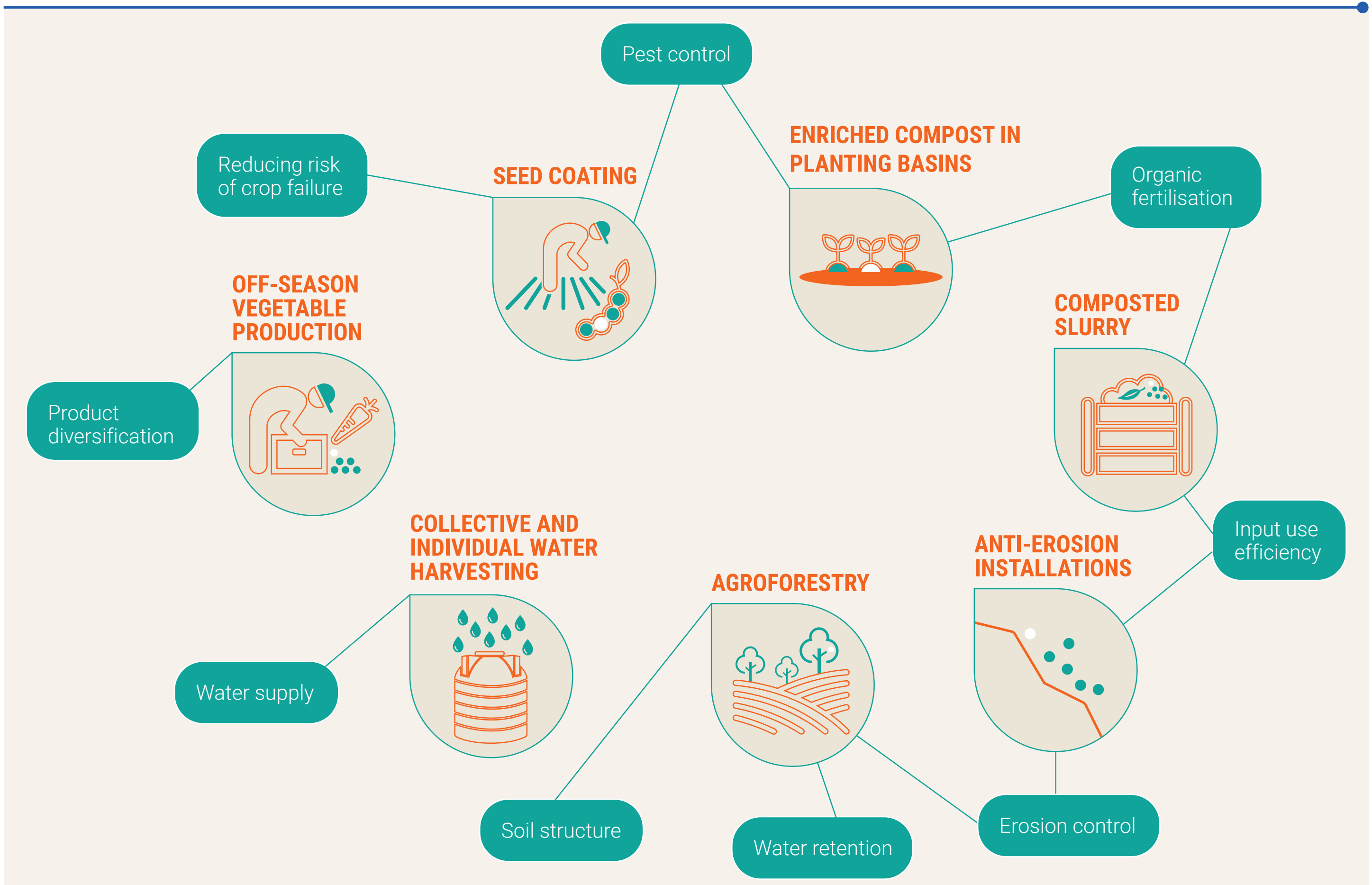
Key findings were that practices, even if not specifically implemented in response to climate change impacts, nevertheless contributed to adapting to either reduced or more variable rainfall, and to increased temperature.

The variety of agroecological practices evident in Table1, used in different combinations by different farmers according to their social, economic, and ecological context, illustrates how agroecological practices represent locally adapted innovation by farmers themselves, often based as much on their local knowledge as upon agricultural science.[77] Co-creation of knowledge is a fundamental principle applied when taking an agroecological approach (Figure 1), ensuring both the local relevance of the practices developed and the effectiveness of their spread horizontally from farmer to farmer, because farmers often put greater trust in the experience of other farmers than in the information from extension workers or researchers.[78]

Many of the agroecological practices inventoried by Debray et al. (2019), in addition to providing adaptation benefits, also enhance carbon sequestration.[79] In many cases, the adoption of multiple practices simultaneously was required to provide adaptation benefits, brought about by addressing several individual climate impacts at the same time, with many farmers using combinations of different practices. For example, in addressing soil fertility challenges, some farmers in Burkina Faso combine a number of individual practices that collect and use available water, improve soil fertility, and prevent land degradation (Figure 4). This involves them:

- Collecting water individually from roofs and catchment areas, and collectively from water reservoirs, mini dams, and wells, to improve their water supply;
- Using seed coating to reduce risks associated with dry sowing, droughts, consumption of seeds by ants, termites, and birds; and
- Introducing new, off-season vegetable production using water collected in wells and mini dams.

FIGURE 4 Typical Combinations of Soil and Water Management Practices that Ameliorate Impacts of Increasing Frequency and Severity of Drought in Burkina Faso



Source: Debray et al. 2019.[80]

TABLE 1 Key

Table 1 - Key

- Field
- Farm
- Interviews
- Publications
- Semiarid (SA)
- Subhumid (SH)
- n/a

TABLE 1 Contribution to Climate Change Adaptation of Agroecological Practices in Semiarid and Subhumid Zones of Africa

Agroecological Practice	Scale of Integration	Climate Adaptation Benefits	Constraints	Zone	Countries	*Evidence*[a]
Category i) Prevention of land degradation						
Rehabilitation and conservation of vegetation		• Soil fertility maintenance • Increased vegetation cover • Forage production • Improved water retention • Local biodiversity conservation • Crop protection against extreme climate events • Additional production	• Risk of animal browsing • Competition for water and nutrients • Potential pests' habitat • Cropped area reduction • Fire risk		Mali, Burkina Faso, Togo, Senegal, Malawi, Tanzania, Zambia	🔵 **3** ACF, AVSF, GRET. 🔴 **9** Aune 2011; Basquin et al. 2014; Bilgo et al. 2013; CILSS 2009; de Witte 2013; Dorlöchter and Nill 2012; Leroy 2015; Scholle 2015; Wezel and Rath 2002.[81]
Hedges	🌱 🏠			🟤🟢		
Agroforestry	🌱			🟤🟢		
Conservation of local tree species	🌱			🟤		
Direct sowing of local tree species	🌱			🟤		
Assisted natural regeneration	🌱			🟤🟢		
Erosion control		• Soil fertility improvement • Rehabilitation of degraded (crop) land • Increased vegetation cover • Improved water retention and infiltration • Decreased risk of crop loss during temporary drought in cropping season • Possible off-season production	• High labor demand • Training requirement • Flooding risk in very rainy years due to dam or weir damage • Collective organization		Burkina Faso, Togo, Niger, Chad, Mali, Kenya, Ethiopia, Tanzania, Uganda, Senegal, Cameroon, Cape Verde, Zambia	🔵 **1** AVSF. 🔴 **9** Berton et al. 2013; Bilgo et al. 2013; de Witte 2013; Diguingue 2010; Dorlöchter and Nill 2012; Leroy 2015; Mwanyoka 2015; Scholle 2015; Tumbo et al. 2010.[82]
Zai holes	🌱			🟤🟢		
Half moons	🌱			🟤		
Nardi trenches	🌱			🟤		
Stone bunds	🌱			🟤🟢		
Fanya Juu terraces	🌱			🟢		
Bench terracing	🌱			🟤🟢		
Contour bunding	🌱			🟤🟢		
Agricultural and silvopastoral benches	🌱			🟤		
Filtering embankments	🌱			🟤		
Grass strips between crop lines	🌱			🟤🟢		

TABLE 1 *Continued*

Agroecological Practice	Scale of Integration	Climate Adaptation Benefits	Constraints	Zone	Countries	*Evidence*[a]
Category ii) Improving soil health						
Use of organic fertilizers and material	•	• Soil fertility improvement • Improved water retention • Renewable energy production • GHG emissions reduction (only bio-digester) • Weed control • Erosion control	• Investment cost (bio-digester) • Competition for the use of crop residues • Seed availability • Workload	•	Mali, Democratic Republic of Congo, Tanzania, Cameroon	**2** AVSF, GRET. **3** Dorlöchter and Nill 2012; Roesch and Chapon 2014; Scholle 2015.[83]
Crop residues compost		•	•	●	•	•
Liquid compost		•	•	●	•	•
Biogas slurry		•	•	●	•	•
Cover crops		•	•	●	•	•
Green manure		•	•	●●	•	•
Mulching (e.g., with *Acacia tumida*)		•	•	●●	•	•
Introduction of soil-improving woody plants as windbreak and/or hedgerow	•	• Soil fertility improvement • Legumes for nitrogen fixation • Improved water retention • Wind and water erosion control • Increased permanent vegetation cover • Additional productions	• Cropped area reduction • Risk of animal browsing • Potential pests' habitat	●	Madagascar	**2** GRET, AVSF. **2** Aune 2011; Lheriteau and Rakontondramanana Ratrimo 2014.[84]
Category iii) Better water management						
Water collection devices	•	• Improved water retention • Water storage • Increased vegetation cover • Possible off-season production • Groundwater tables filling • Water supply improvement	• Technical knowledge requirement • Implementation costs • Risk of disease development • Finding consensus	•	Togo, Burkina Faso, Mauritania, Niger, Chad	**9** Bachar 2011; Bender 2009; BERCEF 2007; de Witte 2013; Dorlöchter and Nill 2012; Orlhac 2013; URD 2009; Stroesser 2015; Cornu 2011.[85]
Permeable stone dam		•	•	●	Mali, Tanzania	•
Sand dam		•	•	●	•	•
Mini dam		•	•	●	•	•
Weir		•	•	●	•	•
Pond		•	•	●	•	•
Water reservoir		•	•	●●	•	•
Collective water mgmt.		•	•	●●	•	•

TABLE 1 *Continued*

Agroecological Practice	Scale of Integration	Climate Adaptation Benefits	Constraints	Zone	Countries	*Evidence*[a]
Category iv) Diversifying production						
Introduction of new crops		• Risk reduction for overall agricultural production • Local diets improvement • Additional income • Resistance to drought (castor oil)	• Lack of knowledge about new crops	● (brown)	Niger, Nigeria, Madagascar, Tanzania	● (blue) **2** AVSF, CARE. ● (red) **2** Aune 2011; Tumbo et al. 2010; Mbilinyi and Rwehumbiza 2010.[86]
Yam	[farm]			● (brown)		
Vegetables	[farm]			● (green)		
Cassava	[farm]			● (brown)		
Castor oil plant	[farm]			● (brown)		
Moringa	[plot] [farm]			● (green)		
Combination of crops		• Soil fertility improvement • Weed, pest and disease control • Increased crop diversity • Biodiversity enhancement • Risk reduction for overall agricultural production	• Input costs, availability and quality • Dry season production needs irrigation • Possible vegetation damage by goats		Democratic Republic of Congo, Mali, Senegal	● (blue) **4** ACF; Agrisud, AVSF, Terre et humanisme. ● (red) **1** Aune 2011.[87]
Wet and dry seasons crop rotation	[plot]			● (brown)		
Diversified crop rotation	[farm]			● (brown) ● (green)		
Mix of cultivars	[farm]			● (brown)		
Cereal/cowpea intercropping	[farm]			● (green)		
Introduction of animals		• Diversification with animals; • Risk and reduction for overall agricultural production			Senegal, Chad, Madagascar	● (blue) **3** AVSF, Salvaterra, URD
Small ruminants	[farm]			● (brown)		
Poultry	[farm]			● (brown)		
Beekeeping	[farm]			● (brown)		
Category v) Adapting crop management						
Sowing adaptation		• Early germination • Crop failure risk reduction • Seed protection against drought	• Uncertain crop germination and establishment • Equipment cost • Weed pressure		Tanzania, Senegal, Burkina Faso, Mali, Sudan, Ethiopia	● (blue) **1** AVSF. ● (red) **3** Aune 2011; AVSF 2011; Liwenga et al. 2012.[88]
Early preparation and sowing	[plot]			● (brown)		
Seed coating and dry sowing	[plot]			● (brown)		

TABLE 1 *Continued*

Agroecological Practice	Scale of Integration	Climate Adaptation Benefits	Constraints	Zone	Countries	*Evidence*[a]
Seed soaking	🌱			●		
Species and cultivar choice			• Crop failure risk reduction • Higher resistance to pests and diseases • Additional income for local seed producers • Agrobiodiversity conservation		Tanzania, Senegal, Niger, Cote d'Ivoire, Ethiopia, Burkina Faso, Mali, Madagascar	● **3** AVSF, CCFD, GRET. ● **5** Basquin et al. 2014; Bouziane et al. 2013; Comoé and Siegrist 2015; GRET 2011; Liwenga et al. 2012.[89]
Drought-tolerant crops	🌱			●●		
Shorter-term crop cultivars	🌱			●●		
Farmer local seed selection and dissemination	🏠			●●		
Soil working adaptation			• Soil fertility improvement • Improved water retention • Early crop maturity		Sub-Saharan Africa	● **1** Stroesser 2015.[90]
Minimum Tillage	🏠			●●		
Category vi) Pest and disease control						
		• Environmentally friendly pest and disease control • Pest attacks reduction • Cryptogamic diseases control			Mali, Burkina Faso, Madagascar	● **3** ACF, AVSF, RHK.
Compost enriched with Trichodermia	🏠			●		
Neem oil-based insecticide	🏠			●●		
Category vii) Managing livestock						
Feed improvement		• Feed ration and feed quality improvement • Residues valorization • Supplementary forage sources, especially during dry periods • Additional wood production	• Availability of supplementation • Technical knowledge requirement • Additional work		Sudan, Burkina Faso, Mali, Niger, Malawi, Tanzania, Zambia, Cameroon, Senegal, Chad	● **3** AVSF, GRET, Salvaterra. ● **5** Aune 2011; Franzel et al. 2014; Leroy 2015; Scholle 2015; Stroesser 2015.[91]
Crop residues as forage	🌱			●		
Fodder trees (e.g., *Faidherbia albida*)	🌱			●●		
Urea treatment of hay	🌱			●		
Mineral supplements for dairy animals	🏠			●		
Millet bran suppl.	🏠			●		

TABLE 1 *Continued*

Agroecological Practice	Scale of Integration	Climate Adaptation Benefits	Constraints	Zone	Countries	*Evidence*[a]
Hay production				●●		
Rotational grazing		• Overgrazing limitation • Soil fertility improvement • Increased vegetation cover • Biodiversity enhancement • Higher number of animals fed on the same surface	• Planning requirement • Equipment cost (fences/ surveillance)	●●	Burkina Faso, Mali, Niger, Cameroon, Senegal, Chad	● **1** Stroesser 2015.[92]
Regulation of animal movement		• Increased vegetation cover • Conservation of vegetation cover • Reduction of stocking rate • Rationalization of itineraries • Improved management of forage resources	• Collective organization requirement • Increasing land pressure of protected areas • Fences' absence		Tanzania, Zimbabwe, Burkina Faso	● **3** AVSF, CCFD, and Salvaterra. ● **1** Liwenga et al. 2012.[93]
Exclosures				●		
Reduced herd size				●		
Collective grazing on village territory				●		
Collective organization of transhumance				●		
Selection of drought-adapted cattle breeds		Animals' resistance to droughts	Lower productivity in favorable environment	●		● **1** AVSF.

Source: Adapted from Debray et al. 2019.[107]

Notes: SA: semiarid; SH: subhumid; DRC: Democratic Republic of the Congo; ACF: Action Contre la Fam; CARE: Cooperative for Relief and Assistance Everywhere; AVSF: Agronomes et Vétérinaires Sans Frontiers; GRET: Groupe de Recherches et d'Echanges Technologiques; URD: Urgence Réhabilitation Développement; CCFD: Comité Catholique Contre la Faim et pour le Développement; RHK: Réseau des Horticulteurs de Kayes; GHG: Greenhouse Gas.

[a] Based on literature review and structured interviews with 24 experts from 17 NGOs active in agricultural development in Africa.

While the inventory points to widespread use of agroecological practices in Africa that confer adaptation benefits, there are sparse quantitative data on the economic performance of the practices that would allow evaluation of trade-offs inherent in their adoption by farmers, or of adoption rates (although some adoption data are summarized for agroforestry in Table 2 below). Many agronomic innovations, even if impressive in terms of yield improvement, do not represent transformative options for smallholder farmers because their aggregate impact, with only a small land area, may not be sufficient to make a significant difference to the farm household or compensate for the extra investment and risk involved in adopting a new practice.[94]

Recent research on adoption of ecological intensification options in South Africa emphasized that the knowledge-intensive nature of the options made participatory interaction with farmers important for adoption, which was determined by farmers evaluating trade-offs among what they expected in terms of performance of innovations, the effort required to implement them, and social influences.[95]

Key constraints to adoption were lack of awareness, germplasm, and technical support. Despite this, a recent global assessment estimated that 163 million farmers (29 percent of those wordwide) were practicing forms of sustainable intensification on 453 M ha of agricultural land (9 percent of the wordwide total), but conflated agroecological practices and other forms of sustainable intensification.[96]

3.2 Farm or Livelihood Level Integration

Above and beyond the combination of practices at field level, many adaptation benefits of agroecological practices derive from system diversification at a livelihood scale, with greater functional diversity of components (particularly integration of trees and livestock with cropping), resulting in gains from managing interactions among components. Thereby both productivity and resilience gains are realized.

Agroforestry practices provide a good illustration of this, where much of the contribution that trees make to agricultural production systems is through system intensification, involving interactions with other livelihood components (Figure 5 and Table 2). Farmers are concerned about the total factor productivity of their whole livelihood, not only the contributions from crop and livestock productivity, and this is influenced by how their labor is used. This needs to be taken into consideration for agricultural innovations to be adopted and viable within the livelihood context that they are intended for.[97] For example, on-farm tree fodder production can increase livestock productivity while reducing labor required to collect fodder, hence freeing labor and time for other additional paths to intensification.[98] In some contexts, food security is constrained by lack or shortages of fuel to cook, or dung is used as fuel. On-farm firewood production alleviates the fuel constraint, and dung can therefore be used as fertilizer, which thereby increases soil fertility and crop yield, and frees up labor.[99]

Trees can also play a key role in restoring and maintaining soil health, because they are associated with higher abundance and activity of beneficial soil organisms, as well as contributing to soil fertility through tightening nutrient and water cycling, consequently improving nutrient and water use efficiency, and thereby closing yield gaps of staple food crops.[100]

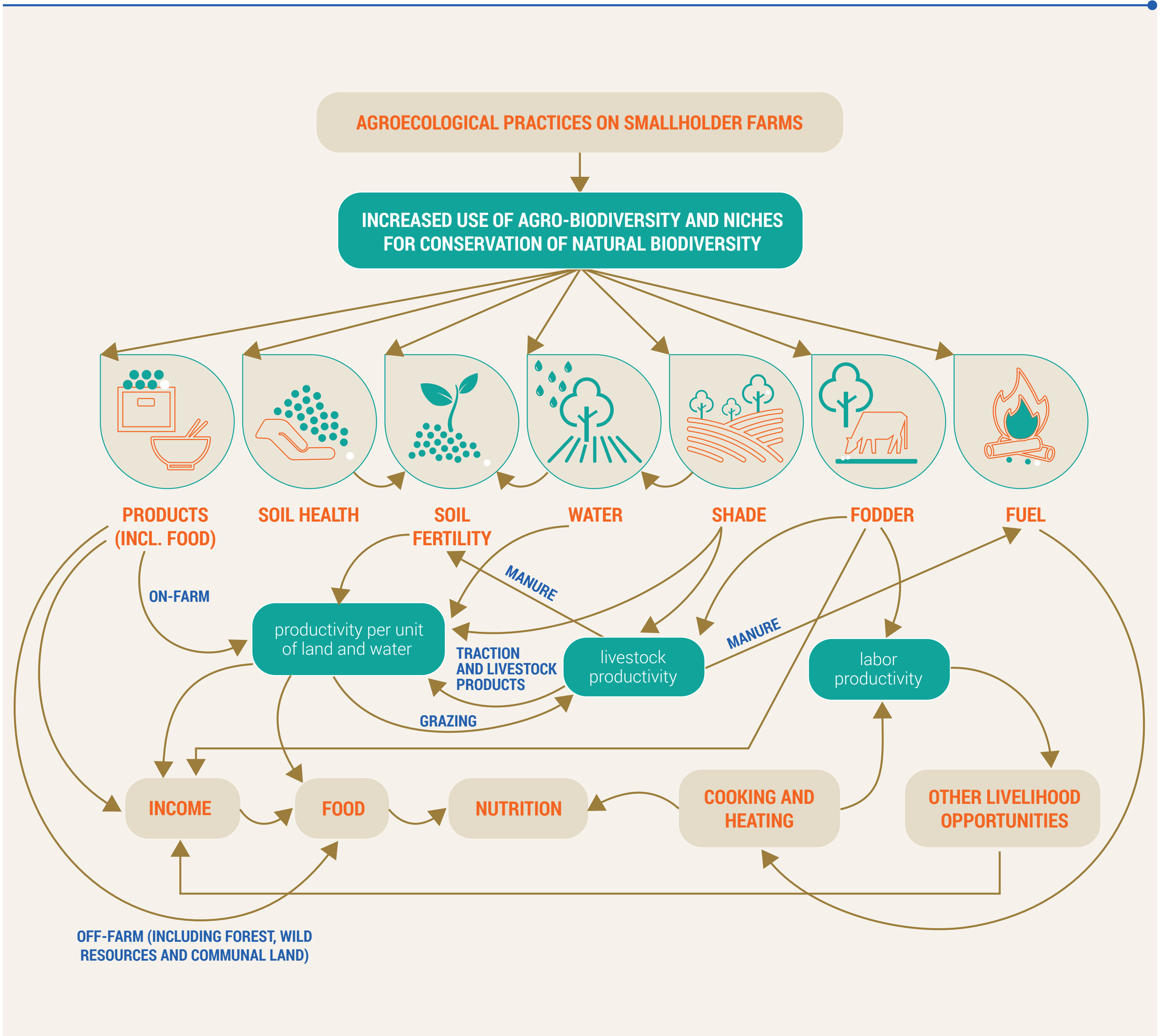
3.3 Mitigation Co-Benefits

The adoption of agroecological practices generally leads to higher carbon storage in both soil,[101] and, especially where perennial plants are part of the species mix, in vegetation.[102] There has been a lively debate on the relative importance of increasing soil organic carbon for adaptation and mitigation, with greater consensus about its role in improving the resilience of soils to future climate change than in mitigating emissions.[103] In contrast, the carbon storage potential of trees on farms is globally significant, with an estimated carbon stock of more than 34 Gt and net global sequestration of 0.75 Gt yr^{-1} due to the global increase of tree cover on agricultural land, which is not taken into account in greenhouse gas accounting of the Intergovernmental Panel on Climate Change (IPCC).[104] The global total masks differences regionally, with Brazil, Indonesia, China, and India having the largest increases, while Argentina, Myanmar, and Sierra Leone had large decreases.

Agroecological practices vary in their carbon sequestration and storage potential, with measured complex multistrata agroforests having a mean C stock of 77.9 Mg C ha^{-1} (range 12–228) and mean sequestration of 3.12 Mg C ha^{-1} yr^{-1} (1.0–6.7); compared to Sahelian parklands 33.4 Mg C ha^{-1} (5.7–70.8) and 0.5 Mg C ha^{-1} yr^{-1} (0.2–0.8); and rotational woodlots 18.5 Mg C ha^{-1} (11.6–25.5) and 3.9 Mg C ha^{-1} yr^{-1} (2.2–5.8).[105] Local farming practices affect tree cover on farms and the attendant carbon storage. Agroecological practices also use fewer fossil fuel derived inputs than alternatives, and strive to recycle biomass and nutrients. This often results in agricultural production with a lower carbon footprint, although the role of ruminant livestock in some agroecological practices complicates this.

It is important to draw a distinction here between climate-smart agriculture and agroecology. While many agroecological practices are classified as climate-smart because they contribute to adaptation and mitigation, not all climate-smart practices follow agroecological principles. For example, no or minimum tillage practices, combined with the use of herbicides rather than mechanical options to destroy weeds, may be considered climate-smart but not agroecological.[106]

FIGURE 5 Agroecological Practices Have Adaptation Benefits for Smallholder Livelihoods through System Integration



Source: Developed by the authors.

Notes: See quantification of interactive effects for agroforestry practices in Table 2.

TABLE 2 Evidence of How Trees as Components of Agroecological Practices Increase Functional Biodiversity and Economic Diversification, Contributing to Productivity and Resilience of Smallholder Livelihoods

	Resilience Benefits Related to Elements in Figure 5	Nature and Magnitude of Effect	Sources
1.	**Soil fertility/ Erosion control**	It is well established that trees in crop fields can: • Fix nitrogen (typically 50 to 320 kg ha^{-1} yr^{-1} but around 150 kg ha^{-1} yr^{-1} for the fertilizer tree systems widely adopted by smallholder farmers (see 8 below); • Capture nutrients leached below the crop rooting zone and return them to surface soil via litter and root turnover (e.g., 42 kg N ha^{-1} recycled by deep-rooting trees intercropped with fertilized maize, and about half this for shallower rooting species such as *Gliricidia sepium*, favored by farmers because of their easy establishment, fast growth and nitrogen fixation), increasing nutrient use efficiency (e.g., N use efficiency of fertilizer tree systems with maize ranging from 49–59% compared to 10–22% for use of only inorganic fertilizer on maize monoculture); and • Control soil erosion, especially using contour hedgerows on sloping land with high rainfall intensity (e.g., reducing soil loss by 80% on gradients of up to 25^{o} representing retention of between 1.8 to 12.7 t ha^{-1} of soil and the nutrients contained therein).	Glover et al. 2012; Schroth and Sinclair 2003; van Noordwijk et al. 2004; Sileshi et al. 2014; Ng 2008.[108]
2.	**Soil health**	Soil health refers to maintaining long-term soil fertility indicated by Soil Organic Carbon (SOC) and the ecosystem structure of soil biota. It has been established across a range of site conditions that beneficial soil organisms are (1.1–5.6 times) more abundant and generally more active in crop fields with trees than those without and closer to, rather than further away from, trees in crop fields. SOC varies across contexts but can be maintained at up to 300 Mg C ha^{-1} even in cultivated fields through agroforestry practices. Research now focuses on which mixtures of tree species will deliver improvement and maintenance of soil health in different contexts.	Barrios et al. 2012; Orgiazzi et al. 2016.[109]
3.	**Water**	Trees impact water balances in several ways, but the most important trade-off in agricultural terms is that of increased infiltration and lower bare soil evaporation versus the amount of water transpired by trees (which can be controlled by manipulating the amount and phenology of leaf area through tree species choice, spacing, and pruning). This results in groundwater recharge in the seasonally dry tropics being maximized with an intermediate level of tree cover across agricultural landscapes. Evaporation is typically 30–60% of rainfall in semiarid environments, and trees in crop fields reduce it, such as by 35% when intercropped with food crops in Kenya (21% of rainfall) and by 41% with shade trees in coffee. Much higher infiltration (up to 60 times higher in intensively grazed silvopasture than pasture without trees) reduces flood risk as well as controlling erosion and contributing to groundwater recharge.	Ilstedt et al. 2016; Bayala and Wallace 2015; Carrol et al. 2004.[110]
4.	**Shade**	Shade in silvopastoral systems reduces heat stress in animals (particularly cattle) estimated to cost US$1.2 billion yr^{-1} in lost production in the U.S. dairy industry alone, to be higher in the tropics, and likely to increase as a result of climate change. Shade is increasingly important as a means of ameliorating climate change effects in crops, with tree shade buffering high temperatures to prolong grain filling in cereals and bean yield (and quality) in coffee. For example, wheat yields in Ethiopia were 26– 86% higher (0.5 to 0.7 t ha^{-1} yr^{-1}) under *Faidherbia albida* trees than in monoculture, with proportionally larger effects in low yielding (drier) years. The area suitable for growing coffee globally is predicted to reduce by 19% overall, with differential regional effects depending on altitude and latitude. Shade trees can reduce temperatures of coffee by up to 2^{o}C, corresponding to the rise in mean global temperature expected by 2050, but require concomitant management to control competition.	Bayala et al. 2015; Ovalle-Rivera et al. 2015; Key et al. 2014; Sida et al 2018.[111]
5.	**Fodder/Livestock productivity**	The value of increased milk production through using tree fodder in Kenya was measured at between US$62 and 122 per annum for a household with one cow, contributing from 17–33% of what is required for a household to exit poverty. This does not include benefits from firewood, soil fertility improvement, soil erosion control, fencing, stakes, and sale of seedlings also derived from the same trees. More than 305,000 farmers have adopted fodder trees directly through the East African Dairy Development Project (EADD) in Kenya, Rwanda, Tanzania, and Uganda, with a vibrant market for fodder tree seedlings emerging in Kenya, indicating considerable spontaneous (but as yet unquantified) diffusion beyond direct project beneficiaries. New markets for green fodder are developing (e.g., in India demand exceeded supply by an estimated deficit of 696 M t yr^{-1} in 2015, creating opportunities that are particularly promising for women to exploit).	Franzel et al. 2014; Mishra and Pathak 2015; Place et al. 2009.[112]

TABLE 2 *Continued*

	Resilience Benefits Related to Elements in Figure 5	Nature and Magnitude of Effect	Sources
6.	**Fuel/Cooking/Heating**	Woodfuel meets around a tenth of the world's energy demand, most significantly in Africa, where around 760 million people rely on firewood and charcoal as their primary source of energy for cooking. The annual value of local trade in charcoal in Africa is over US$8 billion, employing 7 million people. A systems analysis of firewood and fodder usage in the highlands of Ethiopia revealed a mean household firewood deficit (of articulated demand over actual supply) of 5.95 t yr^{-1} and mean use of 3.2 t yr^{-1} with burning of 0.47 to 0.97 t dung hh^{-1} yr^{-1} depending on access to state forest resources. The nutrients in the burned dung represent potential cereal yield of 143 kg or 94% of per capita annual cereal demand (18% of mean aggregate household demand). National statistics indicate 34% of rural households taking more than one hour and 36% requiring more than two hours per day to collect firewood.	Dawson et al. 2013; Duguma et al. 2013; Mosa et al. 2016.[113]
7.	**Income**	Trees produce a number of globally and locally traded high value products important for smallholder income. Fodder and charcoal are covered already in rows 5 and 6 above. Fruit trees can produce high annual income per unit land for smallholders, while providing other ecosystem services. For example, the Forests, Trees and Agroforestry (FTA) AFLi project reported a mean of US$2,240 ha^{-1} yr^{-1} for son tra (*Docynia indica*) and US$3,563 ha^{-1} yr^{-1} for longan (*Dimocarpus longan*) when intercropped with maize on sloping land in Northern Vietnam.[114] Additional value over a maize monoculture with a 15-year time frame and 10% discount rate was US$8,250 to 14,530, with breakeven after 5–8 years. Planting fodder grasses to bridge the lag between investment and return was doubly effective, providing immediate income and, in enabling stall feeding of animals, reducing risk of livestock damage to establishing trees. While the Net Present Value (NPV) of silvicultural improvements for timber production alone from the FTA Kanoppi project in Indonesia were not attractive for farmers or investors at US$1,241 ha-[1] on a 20-year cycle and 8% discount rate, combining with Non-Timber Forest Products (NTFPs) increased the NPV to US$4,951 ha^{-1}, intercropping to US$6,678 ha^{-1} and sustainable intensification with all three combined to US$11,627 ha^{-1}.[115] Much less intensive management required for Farmer-Managed Natural Regeneration (FMNR) of trees in the Sahel (Mali, Burkina Faso, Niger, and Senegal) resulted in extra income from tree products of US$73 to 200 per household, despite selling only 15–25% of harvested product. In contrast, coffee and cocoa are predominantly internationally traded (with an annual export value of US$10 and 11 billion respectively), although mainly produced by smallholders (over 80% of production involving 15 and 6.5 million smallholders, respectively) with yields well below potential (550 kg ha^{-1} and 370 to 670 kg ha^{-1} respectively) and declining as plantations age, pests and diseases build up, and soil fertility declines. Sustainable intensification through agroforestry tackles these multiple challenges, including a degree of climate change adaptation and livelihood diversification.	Binam et al. 2015; Vaast and Somarriba 2014; Angelsen et al. 2014; Dawson et al. 2013.[116]
8.	**Food (security)/Land productivity**	Meta-analysis across sub-Saharan Africa showed that fertilizer trees produced a mean maize yield increase of 1.3 and 1.6 t ha^{-1} for non-coppiced and coppiced fertilizer tree systems, respectively, over unfertilized sole maize (farmer default practice). Over half a million farmers have adopted fertilizer tree systems in Southern Africa (Zambia and Malawi), in the absence of supportive policy frameworks. (On the contrary, incentives, such as fertilizer subsidy, often favor use of inorganic fertilizer.) This has resulted in between 57 and 114 extra person days of maize consumption per household per year, affecting the food security of over 2.5 million people. Subsequent analysis of maize yield in four different agroforestry practices nationally across Malawi revealed large variation in performance among farms (5–8 fold, with the top 20% of farmers achieving yield increases of over 2 t ha^{-1} yr^{-1}), indicating the scope for increasing both food yield and adoption through improved matching of practices to context and developing a supportive enabling environment.	Sileshi et al. 2008; Ajayi et al. 2011; Garrity et al. 2010; Coe et al. 2019; Bai et al. 2008; Lal et al. 2012; Stavi and Lal 2015.[117]

TABLE 2 *Continued*

	Resilience Benefits Related to Elements in Figure 5	Nature and Magnitude of Effect	Sources
9.	**Nutrition**	There is a significant positive relationship between some indicators of dietary quality of children under five and landscape-scale tree cover in Africa, with a statistically significant positive relationship between tree cover and dietary diversity, while fruit and vegetable consumption increases with tree cover up to a peak of 45% tree cover after which it declines. Wild fruits, fungi, and vegetables from forests are a crucial source of micronutrients in many rural and smallholder communities, and often provide a major contribution to cash income at the household level. Bushmeat and fuelwood for subsistence and income generation contribute both directly and indirectly to food security and nutrition in sub-Saharan Africa, South-East Asia and Latin America. Dietary diversity was found to be 12–14% higher in households practicing FMNR than those who had access to fewer trees across four countries in the Sahel. Recent research has shown that it is possible to exploit differences in phenology of fruit tree species to provide critical nutritional supplements (particularly of Vitamins A, C and B6) and maintain dietary diversity throughout the year. This is the case even in dry environments, where extensive tree root systems and water storage in succulent roots allow trees to be productive at those times in the year when herbaceous vegetation cannot supply this nutritional diversity without irrigation. In Machakos in Kenya, an average household can achieve year round dietary diversity with 20 trees of 10 species, either dispersed throughout their farm (on borders, around the home, and in fields) or in an 8 m x 18 m (0.015 ha) fruit orchard.	Binam et al. 2015; Dawson et al. 2013; Kehlenbeck and McMullin 2015; Ickowitz et al. 2014; Sunderland et al. 2013.[118]

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4. Examples of Agroecological Approaches Enhancing the Resilience of Farming Systems

This section looks at several instances where agroecological practices are being applied at scale, both to demonstrate that this is possible, and to draw lessons about what leads to success. It includes a scheme in India to promote agroecological farming methods across the entire state of Andhra Pradesh, innovative agroecological approaches to control the recent Fall Army Worm (FAW) epidemic across Africa, regreening of the Sahel, and national policies in Peru and Europe.

4.1 Scaling up Climate Resilient Zero Budget Natural Farming in Andhra Pradesh

Climate Resilient Zero Budget Natural Farming (CRZBNF) aims to build resilience to increasingly frequent drought, floods and cyclones experienced in Andhra Pradesh as a result of climate change, while accumulating carbon in soil and perennial vegetation as well as making more efficient use of water to reverse an alarming lowering of the water table. The practice of Zero Budget Natural Farming (ZBNF) began in the southern Indian state of Karnataka, where is it estimated that 100,000 farm families use the methods, while, at the national level, it is estimated that millions of farmers use ZBNF, most prominently in the southern Indian states of Andhra Pradesh, Kerala, and Tamil Nadu.[119] In 2015, the government of Andhra Pradesh announced a policy aimed at reaching 500,000 farmers with ZBNF by 2020 (about 8 percent of farmers in the state), and now targets transitioning the whole state to this approach, embracing six million farming households. The prominence of the approach at state and national level has led to a polarized debate about the evidence base underpinning investment in ZBNF,[120] and the relationship between the particular set of practices promoted under ZBNF and other agroecological, organic farming, and sustainable intensification approaches.[121]

Interest in ZBNF methods arose, in part, from the high rates of farmer debt, originating from the cost of fertilizer, seed, mechanized agriculture, and irrigation, which has been linked to high suicide rates. More than a quarter of a million farmers have committed suicide in India in the last two decades. "Zero Budget," which means not relying on credit, and not buying inputs, promises to put an end to heavy debt by drastically reducing production costs. "Natural farming" means farming with nature and without purchased chemical inputs. ZBNF methods include mulching, intercropping, controlled irrigation, contour bunds, local earthworm species, and the use of fermented microbial culture and seed treatment, which combines cow dung, sugar, pulse flour, urine, and soil. At the local level, ZBNF operates mainly through volunteers, who come from farmer organizations and community leaders, motivated by the founder of the movement, Subhash Palekar, an agricultural scientist who has written many publications on the methods. At the state level, intensive five-day training camps are held, with support from volunteers and allied organizations. A survey of 97 ZBNF farmers reported increased yield, seed diversity, produce quality, household food autonomy, income, and health, alongside reduced farm expenses and credit needs.[122] The successful implementation of agroecological approaches by farmers in India has relied on several key strategies (Table 3).

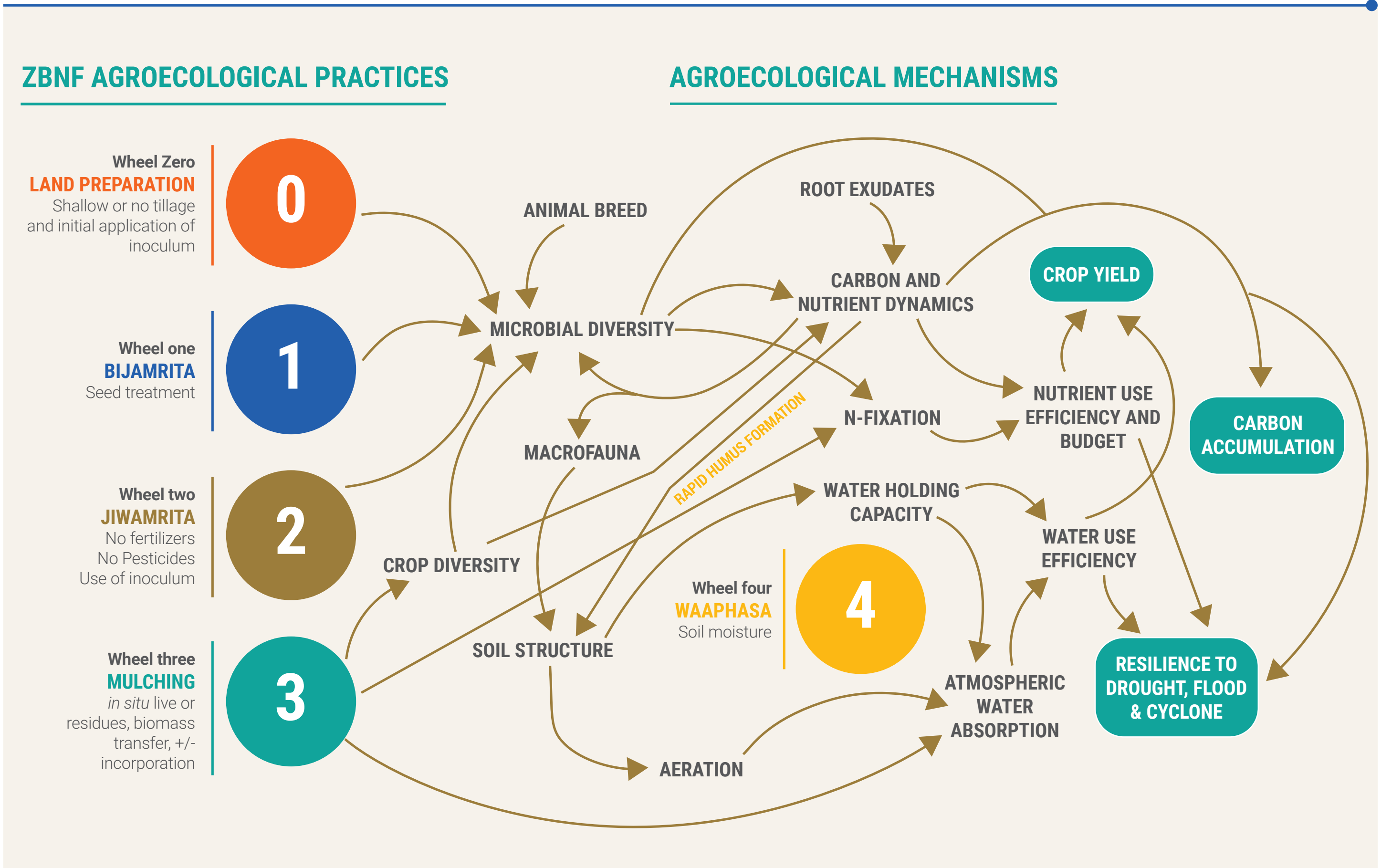
There is some disagreement about the scientific basis and sustainability of some of the agroecological practices promoted by the social movement, which has led to a constructive dialogue among ZBNF practitioners, promoters of the approach, and scientists interested in understanding how and why the practices are spreading rapidly among farmers. This has resulted in clarifying the mechanisms that different stakeholders think are at play in translating practices, such as seed treatment, regular application of inoculum, and maintaining ground cover (with live or dead mulch), into higher and more resilient yields (Figure 6). These are now the subject of systematic experimentation, involving the social movement working together with scientists to measure the magnitude of the different proposed relationships. Ownership of the research process by the social movement, rather than by scientists working separately from proponents of the approach, is thought to be essential for widespread acceptance of results.

TABLE 3 Elements of Successful Strategies for Implementing Zero Budget Natural Farming in India

Strategic Element	Zero Budget Natural Farming Application
Charismatic leadership	A highly charismatic teacher, Subhash Palekar, has played a key role in motivating and promoting Zero Budget Natural Farming (ZBNF) methods through books, training, and other public venues.
Horizontal pedagogical practices	While Palekar teaches in a more vertical manner, most of the teaching is done through farmer-to-farmer exchanges and mentoring.
Favorable public policy	Training is provided at the state level in several Indian states. The state of Andhra Pradesh pledges to support 500,000 farmers to be trained in ZBNF by 2020.
Local and favorable markets	At least eight shops exclusively retail ZBNF produce in cities such as Bangalore and Mysore but marketing remains a challenge.
Social organization	State organized training camps and informal networks support training and ongoing support for ZBNF with links to allied organizations.
Effective farming practices	Farmers report improved yields, food quality, income, and reduced farm expenses and credit.
Cultural legitimacy	ZBNF is framed in socially and culturally significant ways, addressing the credit and debt concerns of farmers, and linking practices to spiritual and socially relevant concepts.

Sources: Kumar 2018; La Via Campesina n.d.; Khadse et al. 2018.[123]

FIGURE 6 Proposed Mechanisms by Which Zero Budget Natural Farming Agroecological Practices (the wheels on the left) Impact Soil Health and Hence Crop Yield, Resilience to Climate Extremes, and Carbon Accumulation



Source: Brainstorming workshop on the science underpinning ZBNF soil effects, Vijayawada, 30–31 August, 2018.
Notes: Each arrow represents a mechanism; ZBNF: Zero Budget Natural Farming.

The causal diagram depicted in Figure 6 was the result of structured stakeholder engagement,[124] and embraces all mechanisms that any of the stakeholders considered important. Discussion among stakeholders established that the initial four wheels of ZBNF did not all correspond to practices; the fourth wheel was, in fact, a consequence of the other practices (and so its location was adjusted), and land preparation practices had initially been omitted and so were added as wheel zero. The importance of the diagram is that it demonstrates that knowledge from both scientists and ZBNF proponents in the social movement are comparable, and can be represented and discussed using a common framework.

4.2 Agroecological Responses to Control FAW

A key issue in climate change adaptation is coping with changes in pest and disease incidence and spread. Agroecological approaches to pest and disease control avoid farmers and states becoming dependent on chemical control that undermines natural enemies; they adopt practices that, on the contrary, actively encourage natural enemies, healthier crops, and soils better able to withstand attack and incorporate barriers to transmission. A contemporary example of the agroecological control of the recent FAW outbreak in Africa illustrates this.[125] FAW, a voracious agricultural pest native from North and South America, was first detected on the African continent in 2016.[126] Since then it has spread across sub-Saharan Africa, affecting thousands of hectares of cropland, causing up to US$13 billion per annum in crop losses,[127] and threatening the livelihoods of millions of farmers. In their haste to respond to FAW, governments have sometimes promoted imprudent use of chemical pesticides, which, aside from human health and environmental risks, are likely to undermine pest management strategies that depend on natural enemies.[128] Agroecological approaches offer context-specific, culturally appropriate, low-cost, biologicial pest control options that can be integrated into existing efforts to improve farm incomes and resilience (see Table 3).

Options for which there is sufficient scientific evidence to warrant immediate promotion include:

- Sustainable soil and land management, which improves crop health and resilience to pest attack;[129]
- Intercropping, which can reduce egg laying by pests through volatile chemical deterrence,[130] increase pest mortality when they must disperse among plants,[131] and provide habitat for natural enemies within the field;[132] and
- Diversifying the farm environment through crop rotation, agroforestry, and management of (semi-) natural habitats at multiple spatial scales, which provides habitat for a variety of natural enemies.[133]

Application of push-pull pest control, where "push" plants are used to repel pests, and "trap" plants to attract them away from crops (already established as effective for maize stem borer) was also found effective for FAW, leading to a 2.8 fold increase in yield with low net costs of implementation, since the intercrops used were a useful fodder for cattle.[134] These agroecological approaches are now being advocated as a core component of integrated pest management programs for FAW in sub-Saharan Africa, in combination with crop breeding, classical biological control, and selective use of chemical pesticides.[135] There are a variety of specific practices, so that farmers can choose those that suit their circumstances, and field trials embedded within scaling up programs for FAW control are being used to tailor recommendations to local circumstances.[136]

4.3 Regreening the Sahel

Vegetation cover in the Sahel is affected both by changes in climate and how people use the landscape, resulting in complex shifts, driven over the last few decades by increases in both rainfall and population over large areas, resulting in higher vegetation cover but declining tree species diversity.[137] Traditional land use involves the maintenance of parklands, where crops are grown under scattered trees, which may also provide important products for subsistence and sale.[138] Extensive and detailed local knowledge underpinning management of trees in parklands has been documented.[139] The recent regreening observed in the Sahel, following a period of prolonged drought and degradation, has created a lot of interest in Farmer-Managed Natural Regeneration (FMNR) of trees, where farmers actively protect and manage tree seedlings in their fields. This occurs across the Sahel and is associated with increased tree cover on over 5 million hectares in Niger alone.[140]

Recent research involving 300 parkland fields in four countries (Burkina Faso, Mali, Niger, and Senegal) found that soil fertility, as indicated by soil total carbon and exchangeable bases, was enhanced by trees.[141] Trees increased the total carbon content of the top 10 cm of soil by a factor of between 1.04 –1.47 in soils with >70 percent sand content. This pattern was observed both in fields with a high density of young trees (resulting from changes in the way farmers are managing natural regeneration), as well as in fields with a few old trees. Soil carbon increases were more pronounced in sandier soils. Meta-analysis of effects of agroecological practices on cereal crop yield across the Sahel, involving 63 studies, revealed that while parkland trees, green manure, mulching, crop rotation, and intercropping all increased cereal yields (maize, millet, and sorghum), when appropriate tree species were used (on average by between 0.24 to 0.76 t ha^{-1} across sites, where mean control yields varied from 0.51 to 2.00 t ha^{-1}), notwithstanding huge variation in performance of practices across contexts.[142] Hence, matching options with the contexts in which they perform well is of paramount importance for promoting their more widespread adoption.[143]

Since not all farmers are actively managing regeneration, economic research across the same range of sites as the soils research in parkland fields across four countries, comparing farmers who were actively managing natural regeneration with those who were not, revealed significant livelihood benefits to the practice.[144] These included increased crop production (15–30 percent depending on the crop, tree species, and parkland density), as well as a 34–38 percent increase in the products harvested from trees, leading to a mean increase in annual household income of US$200, even though only 10–25 percent of harvested tree products were sold. Tree products were more important for women than men, although women often had little say about regreening decisions, leading to research now focused on determining whether regreening outcomes can be influenced by gender transformative action.[145]

There is some debate around the extent to which the recent resurgence in active farmer management of tree regeneration has been spontaneously driven by farmers,[146] stimulated by the action of non-governmental organizations[147] or enabled by policy change.[148] In practice, it appears that all three interact strongly. In Niger, for example, in response to a perceived lack of enforcement of restrictive forestry regulations (Code forestier) that had limited farmers' ability to benefit from timber and fuelwood sales from trees in their fields, farmers began more active management. This led the government of Niger to revise forest legislation in 2004 to formalize this, while development projects have actively encouraged farmers and supported them in managing regeneration since the mid-1980s.[149]

FMNR across the Sahel is already a widespread agroecological practice that is helping farmers adapt to climate change through improving their livelihood resilience. There is clearly potential for increasing its areal extent and intensity. However, for livelihood gains to be sustainable, considerations likely to be important, and hence requiring attention, are to build on, rather than supplant, local knowledge; maintain tree species diversity, which may require enrichment planting; combine FMNR with other agroecological practices that improve soil and water conservation; and to develop markets for tree products. Given that many tree products are most important for women, but current gender norms and relations often restrict their role in management decisions, addressing gender equity could be expected to have a profound impact on the tree species that are regenerated and how the benefits from them are used to improve livelihood resilience.

4.4 Policies that Promote Agroecology at Scale

In many parts of the world, land and tree tenure are contentious and can be a constraint to adoption of climate smart agricultural practices that represent a long-term investment in the land.[150] In order to encourage more climate resilient land use at the agricultural frontier in the Peruvian Amazon, the government constituted an innovative legal provision in 2011, referred to as agroforestry concessions.[151] This grants formal land title (in the form of a 40-year renewable lease) to farmers who had encroached on forest land before the law was passed, provided that they commit to conserve forest remnants; maintain, or establish agroforestry on 20 percent or more of the land; and to implement soil and water conservation measures. The provision has significance with respect to the Peruvian national commitment to restore a land area of 3.5 M ha under the 20 x 20 initiative.[152] The form of implementation of the national policy is ultimately determined by guidelines whose implementation is the responsibility of devolved regional governments.

In supporting the development of these guidelines, Robiglio and Reyes (2016) identified a mix of possible interventions that are consistent both with existing farmer livelihoods, and with land and tree conservation strategies, including restoration of forest cover through planting, promotion of succession in fallows, agroforestry, and enrichment of fallows in areas maintained for crop production.[153] Their analysis suggested that the provision had potential to offer tens of thousands of farmers a route to acquiring land rights, dependent on implementation of restorative practices. However, this was only likely to be realized if the implementation of guidelines accommodated livelihood aspirations of farmers by:

- Incorporating the concept of temporal interactions in the definition of agroforestry so that fallows are allowed to revert to agricultural use;

- Applying the provision to whole farms (that may consist of multiple land parcels), rather than individual fields, allowing farmers flexibility to manage a shifting mosaic of land use practices across their farm; and
- Taking account of the heterogeneity of farmers' social, economic, and ecological contexts that make different restorative options relevant for different farmers.

Climate change is exacerbating biodiversity losses have accelerated in Europe (as evidenced by rapid declines in pollinators, habitat, insects, and birds) linked also to industrial methods of agriculture.[154] Maintaining and increasing biodiversity is a key strategy for climate adaptation. Two key policy initiatives at national level provide examples of how to address biodiversity as a public good through agroecological approaches as detailed by HLPE (2019).[155]

In Switzerland, the government undertook a participatory consultation of its agricultural subsidy program, which involved farmers' unions, non-profit organizations, and environmental and business groups. They also carried out an impact assessment, which took into account economic, environmental, and social dimensions of the subsidy program. As a result, a new Agricultural Policy (2014–17) was implemented, which increased budgetary payments for the agricultural sector, and provided direct payments to producers who included biodiversity-friendly practices in their farming system. Economic projections suggest that both incomes and productivity will be higher as a result of these reforms.[156]

In France, a new law to transition to agroecology nationally was initiated by the former French agriculture minister, proposing a transformation of agriculture to meet economic, environmental, and social performance goals.[157] This initiative included many stakeholders (public service, academia, NGOs, farmers, and educational institutions), and included efforts to reduce use of pesticides, antibiotics, and energy, and to increase organic agriculture. By 2018, €10 million had been invested, about 7,500 farms or 9,000 farmers were engaged in agroecological initiatives, and organic production had increased through collaborations called the economic and environmental interest groupings. These are collectives of farmers (with other stakeholder partners) recognized by the government, who engage in a multi-year project of modification or consolidation of their agroecological practice. While there has not been a significant impact to date on biodiversity, there has been an increased mobilization and awareness about agroecology as a viable approach to change agricultural production modes and transform the agrifood system in the French context.[158]

These two examples point to the potential for agroecology to be used as a policy approach for both large and small farms in Europe to halt biodiversity losses, with critical support needed from civil society, governments, business groups, social movements, and researchers to address remaining barriers to widespread adoption of agroecological practices.[159]

5. Challenges and Opportunities in Scaling up Adoption of Agroecological Practices

In the previous section, several examples of how agroecological practices are being adopted at scale to build climate resilience were explored. Drawing lessons from these examples and the preceding analysis of agroecological principles and how they are applied, this section focuses on the barriers to adoption of agroecological approaches at scale. It focuses on how they can be overcome through actions of public and private sector governance following the framework set out in Figure 2, and by focusing on the field and farm scales of integration. The key constraints are grouped into three broad categories relating to:

1. Creating a **level playing field** upon which agroecological approaches can be judged and decisions made to invest in them;
2. Embracing the **complexity** required for generic agroecological principles to be locally adapted to suit highly variable contexts; and
3. Enabling **integration** across sectors and scales necessary to foster holistic, rather than fragmented, implementation of policy.

5.1 Creating a Level Playing Field

At the present time agroecological approaches are at a serious disadvantage relative to alternatives because of **market failures** that undervalue them, **perverse policies** that are antagonistic to them, and **low investment** in research about them and for their implementation.

Addressing market failures

Decisions about investing in agroecology by farmers and other public and private sector actors are distorted because many impacts of agricultural systems do not have market prices, and so are not factored into decisions; these are referred to as externalities. This has been increasingly recognized over the last quarter of a century through attempts to value ecosystem services and develop payment, or other reward mechanisms, for farmers who adopt practices that either reduce negative, or enhance positive externalities.[160] The following three key ways to address this deserve continued attention:

- ***Consumer choices***

  A key principle of agroecological approaches is to more closely connect producers and consumers (Box 2, Figure 1). There is an increasing interest by food consumers in where and how the food that they eat is produced, processed, stored, transported, and sold, driven by concerns about human and planetary health.[161] In addition to driving private and public sector market interventions (often via civil society), consumers can directly influence the profitability of adopting agroecological practices at farm level through their purchasing decisions. These, in turn, affect the market access and price of agroecological products relative to alternatives.

  This is only possible where it is known where and how food is produced, it is labeled accordingly, and the labeling is trusted by consumers, requiring development of both tracking mechanisms and bridging social capital among producers and consumers. Both the public and private sectors invest in trying to influence consumer choice through shaping choice architecture; that is, the ways in which choices are presented to consumers and the use of personalized nudges towards particular purchasing decisions.[162]

  Advances in Information and Communication Technology (ICT) and the emergence of big data, on the one hand, hold a promise of increasing the agency of consumers to participate in more democratically controlled food systems; by better connecting consumers with producers in ways that would be likely to favor agroecologically produced food.[163] On the other hand, they present a danger of an increasingly concentrated corporate food retail sector nudging consumer choices toward what is profitable for the industry in the short term, rather than what is healthy for people and the planet in the long term.[164] Who controls ICT and big data and how it is used are likely to be critical for the future development of agroecological practices.

- ***Public and private sector market interventions***

  Public sector investment affects markets directly (through the purchasing decisions of public sector institutions) and indirectly (through regulation and provision of incentives to use particular inputs by subsidizing their use or the price paid for products). Civil society, in some contexts, is exerting pressure for public procurement of food for institutions, such as schools and hospitals, to deliberately favor agroecologically produced food.[165]

  Current incentives in many contexts, such as fertilizer subsidies, distort markets against adoption of agroecological practices. However, true cost accounting,[166] coupled with ecological compensation,[167] are policy levers that are gaining increasing attention as a means to factor externalities into the cost of production. This creates a level playing field for investments in agroecological practices *vis à vis* alternatives. These positive incentives for socially and ecologically sustainable production are coupled with regulations that penalize negative externalities.

  Private sector actors are also increasingly active in the governance of value chains through value chain upgrading that enables consumer choices, and through impact investment and sustainable finance mechanisms (often nurtured by public policy) that may support adoption of agroecological practice. However, reliable sustainability indicators (discussed under performance metrics below) need to be operationalized. Moves within the private sector to upgrade agricultural value chains,[168] and participate in certification schemes that guarantee sustainability and social justice along food chains, can contribute to enabling consumer choices (discussed above) that favor agroecological practice.[169]

  Small-scale producers, however, often have difficulties in accessing centralized certification schemes,[170] which has led to the development of Participatory Guarantee Systems (PGS). This is an innovation in standards in which the oversight system for certification is created through a democratic process involving producers, experts, and consumers who ensure that standards are acceptable to all.[171] Key bottlenecks in harnessing private finance to support adoption of agroecological practices are the need to aggregate the activity of small-scale producers for them to be able to access finance, and the predominance of slow variables (such as the accumulation of organic carbon in soils) in determining the sustainability of agroecological practices. This often results in a lag between investment and visible returns, requiring patient capital. Essentially, adopting agroecological practices, particularly with perennial plant components, represents an investment in ecological infrastructure that enhances ecosystem performance, conferring climate resilience in the long term.

- ***Performance metrics***

  A key to unlocking both public and private investment in agroecological practices is the development and adoption of comprehensive performance metrics for agricultural systems that take into account all social, economic, and ecological impacts, so effective comparisons can be made among alternative investments and, where finance is conditional on sustainability, this can be reliably assessed. Until recently, performance has been assessed largely in terms of yield per unit area and economic returns, which (as explained above) do not incorporate many key social and environmental impacts. Appropriate metrics vary with the scale of integration (Figure 3). For field level performance they vary with the purpose of the practice, and generally involve several complementary metrics, such as crop yield, income, water use efficiency, and carbon sequestration for FMNR, but would include impacts on natural enemy populations for control practices for FAW and, in many cases, pollinator populations, as for coffee agroforestry practices. At farm (or livelihood) level, the key metric for adaptation in smallholder systems relates to the resilience of livelihoods, which is indicated by TFP and how it is constituted. A key to understanding farmer decisions to adopt field level practices is their impact on TFP at livelihood level, with more broadly based livelihoods (related to the biodiversity and economic diversification principles of agroecology, Box 2 and Figure 1) conferring greater resilience.

  It is important to note strong feedbacks from landscape scale (such as plot to landscape scale multifunctionality) and food system scale (such as ecological footprint) metrics to decisions made at farm level to adopt agroecological practices. The landscape metric is calibrated to societal value based on where the landscape is located, and the food system metric depends on the cultural specificity of diet and consumption patterns, as well as production methods, processing, and transport. This highlights the context-specific nature of appropriate metrics. While compressing multifunctionality into single indices has value, it also involves, often implicit, trade-offs among non-substitutable elements, and so should be used in conjunction with explicit recognition and evaluation of trade-offs and synergies.

Reforming policies with perverse outcomes

As described above for the Sahel, agricultural and forest policies, even if well intended, may be barriers to the adoption of agroecological practices. Forest policy limits farmers' ability to benefit from trees on their land, as does insecure or skewed distribution of land tenure and fertilizer subsidies (that may constrain investment in agroecological practices discussed above). In addition, many other policies and institutional arrangements, at a range of scales, may affect performance of agroecological practices and, therefore, decisions to adopt at field and farm level. Free movement of animals at landscape scale, for example, may make it very difficult to establish trees through FMNR at field level, a problem that may be overcome either by enclosing land or instituting regulations to control animal movement at village level (social fencing)[172] or at regional scales, depending on the scale of movement involved. The key requirement is to review policies regarding negative consequences for adoption of agroecological practices and reform as necessary, coupled with positive development of policies that encourage adoption of agroecological practices (as discussed below with respect to integration across sectors and scales).

Improving the evidence base

Despite their potential for providing both adaptation and mitigation benefits, there has been much lower investment in research about, and support for, implementation of agroecological approaches when compared with alternatives. For example, research and development spending in the U.S. related to diversified systems rather than monoculture makes up <2 percent of public agricultural research funding,[173] the FAO estimates that only 8 percent of their 2018–19 work contributes to agroecological transitions,[174] and the UK aid for agroecological projects is <5 percent of agricultural aid and <0.5 percent of the total aid budget since 2010.[175] Not surprisingly, there is much less evidence relating to the performance of agroecological practices compared to alternatives, making it inherently more risky to embark upon new ventures. Increased public and private investment in research and promotion of agroecological practices are required to raise the level of knowledge about agroecological practices to that of competing alternative approaches.

5.2 Embracing Complexity

As discussed in Section 2.4, agroecological practices occur where farmers apply agroecological principles to their local circumstances, rather than there being a prescribed set of agroecological practices. This generates a vast array of locally adapted agroecological practices, based as much on local knowledge as on science. It also challenges linear scaling models that assume discovery of new technology happens in research projects led by scientists, followed by pilots that test and refine the technologies across representative sites or farmers or both, before being widely disseminated through scaling up and out.[176] In addition, it challenges the *de facto* prioritization of scientific knowledge over that of farmers, extension staff, private sector actors, or proponents of agroecological practices in social movements. Agroecological approaches, therefore, fit with recent understanding of agricultural innovation systems in which a diverse range of actors shape innovation processes,[177] conditioned by the historical, political, social, and cultural context of a given place.[178] This indicates a need for a fundamental reconfiguration of international, national, and local research and extension systems so that they are fit for the purpose of supporting local innovation, rather than geared towards transfer of externally generated technology. There are three key dimensions to this configuration that merit attention.

Options by context

It is clear that rather than promoting one or two silver bullet technologies, agroecological practices need to be a locally adapted application of generic principles. Farmers' social, economic, and ecological contexts all vary at fine scale, so that practices need to be developed and tested across a prodigious range of contexts to generate knowledge about what is likely to work where and for whom.[179] Methods for doing this by embedding planned comparisons within the scaling up activities of development initiatives, working through farmer networks, and utilizing citizen science have been developed and successfully applied at scale. They now need to be mainstreamed to support agroecological innovation more widely.[180] Stakeholder engagement, structured on the basis of local knowledge, has been found effective for generating diverse and inclusive agroecological options suited to variable local contexts.[181]

Co-learning and horizontal knowledge sharing

It is well established that farmers have detailed and explanatory local knowledge about agroecological practices, how to manage them, and what determines their performance.[182] It is also well established that the knowledge of extension staff is often a rich, untapped knowledge repository about suitability of options across contexts.[183] Shifting from a technology-transfer paradigm to embrace the co-creation of knowledge principle of agroecology (No. 8 in Box 2 and central in Figure 1) requires working through some form of multistakeholder innovation platform that brings actors together in a participatory forum (Principle 13 in Box 2) where knowledge can be shared, collaboratively generated, and collectively owned. This requires the science supporting the development and spread of agroecological practices to become transdisciplinary (see Section 2.1). It needs to go beyond integrating disciplines around solving real-world problems to also embrace the knowledge of all stakeholders and the development of methods based on iterative reflection on progress. Supporting local innovation also involves encouraging farmer-to-farmer dissemination of successful practices, rather than the use of hierarchical technology transfer modalities.

Social movements and science

As seen in the case of ZBNF in India in Section 4.1, it is often social movements, rather than scientists or conventional extension approaches, that are critical for achieving rapid spread of agroecological practices among large numbers of farmers. This may be partly because messages are delivered in culturally relevant ways that foster behavior change, rather than as objective and dispassionate science. Differences in outlook and ways of working can lead to tensions between social movements and science, which can undermine progress in developing and scaling out agroecological practices. This makes efforts to bridge between knowledge cultures in social movements and among scientists a vital component of successful implementation of agroecological approaches at scale, combining scientific rigor with practical and cultural relevance.

5.3 Enabling Integration

The final barrier to achieving adoption of agroecological practices at scale is the fragmentation of actors in policy formation and implementation across sectors, and missing links in the implementation of policy over layers of governance at different scales when moving from national commitments to local action. Addressing these two issues requires developing means to achieve integration horizontally (across sectors) and vertically (across scales).

Integration across sectors

Agroecological practices often involve integration of components that, in many countries, are the responsibility of different ministries. This may be the case for the integration of agriculture and environment, as well as for trees and agriculture, livestock, water, and energy. This means that it may be necessary to develop instruments that enable inter-ministerial cooperation to develop and implement appropriate policies to support widespread adoption of agroecological practice. Horizontal integration may involve different mechanisms, such as discussion of Prime Ministerial Orders to implement a national agroforestry strategy and action plan in Rwanda. This is in contrast to the establishment of a delivery unit in the ministry of agriculture, but linking to other ministries, to deliver a national agroforestry scaling strategy in Ethiopia.[184]

Despite difficulties in reconciling overlapping responsibilities with inter-ministerial cooperation, several countries now have national agroforestry strategies, or policy processes, or provisions, including India, Nepal, Peru, Ethiopia, and Rwanda. There are ongoing processes to develop national instruments in Uganda, Vietnam (where there already are incentives for farmers to adopt agroforestry at a provincial level), and Indonesia. Agroforestry is now explicit in the EU common agricultural policy.[185] These examples illustrate how it is possible to develop innovative cross-sector policy processes where there is sufficient inclination to do so. As intimated in Section 3.3, agroecological practices, particularly agroforestry, have been identified within many Nationally Determined Contributions (NDCs) of the Paris Agreement on climate change.

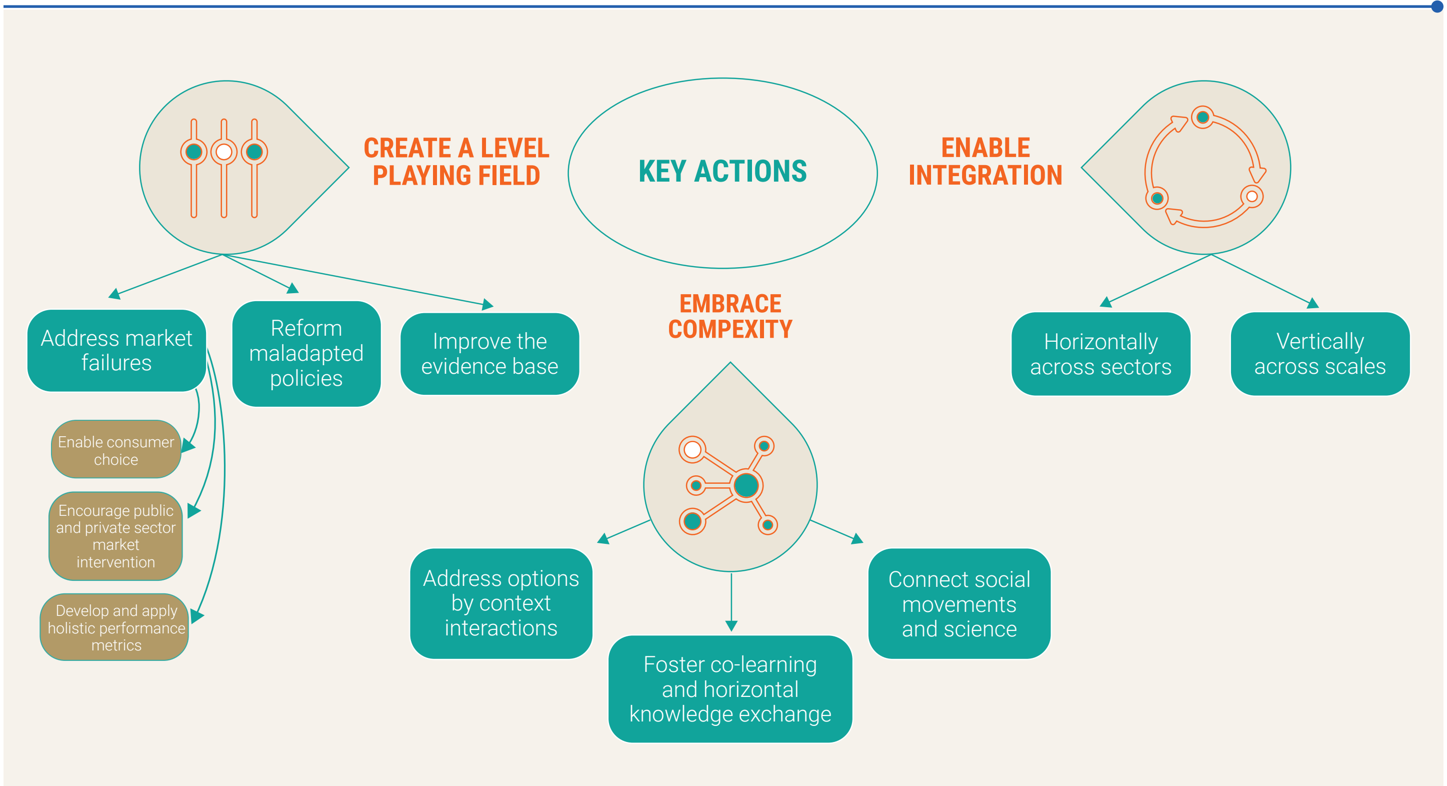
Integration across scales

While there are prodigious national and regional commitments to restoration that invoke agroecological practices responding to the Bonn Challenge, AFR100 in Africa and the 20 x 20 initiative in Latin America (already referred to in Section 4.4), translating these to actions on the ground is more challenging. A key bottleneck in implementing policy to manage trade-offs among impacts of adopting changes in land use practice on ES provision is the lack of policy structures, instruments, processes, or social capital at the local landscape scale (10–1000 km^2), at which many ES first manifest and so can be managed.[186] Developing policy implementation arrangements at local landscape scales is critical for creating incentives for more environmentally friendly and sustainable land use practices that include agroecological practices.

6. Outlook for the Widespread Use of Agroecological Practices to Enhance Adaptation

Locally appropriate agroecological practices clearly have potential to increase the resilience of livelihoods and enhance adaptation to climate change at field and farm levels across a wide range of contexts, often with significant mitigation co-benefits that might help to finance their establishment. Their potential will only be realized, however, if action is taken across hierarchical levels to remove barriers to their adoption (Figure 7). These need to address market failures and reform policies that create perverse incentives, at the same time as adopting comprehensive performance metrics for agricultural systems that factor in social and environmental externalities. A reconfiguration of the relationship between formal science and local knowledge, including bridging differences in outlook and emphasis between social movements and the scientific establishment, is required to foster co-learning among the diverse range of stakeholders involved in development and promotion of agroecological practice. Finally, integration of policy processes across sectors and scales is required to create an enabling environment that encourages adoption of agroecological practices.

FIGURE 7 Key Actions Required to Enable Adoption of Agroecological Practices at Scale to Build Resilience of Farming and Food Systems



Source: Developed by the authors.

While these are far-reaching requirements that demand joined up thinking and action, the recent change in outlook that is shifting public perception toward recognition of a climate emergency might create the pressure required to nudge decision-makers in the public and private sectors, scientists, consumers, and farmers to take the necessary actions required to put agroecological practices on a par with alternatives, which is a prerequisite for their more widespread adoption.

ENDNOTES

1. Campbell, B.M., D.J. Beare, E.M. Bennett, J.M. Hall-Spencer, J.S.I. Ingram, F. Jaramillo, et al. 2017. "Agriculture Production as a Major Driver of the Earth System Exceeding Planetary Boundaries." *Ecology and Society* 22 (4). https://doi.org/10.5751/ES-09595-220408.

2. Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, et al. 2015. "Planetary Boundaries: Guiding Human Development on a Changing Planet." *Science* 347 (6223): 1259855. https://doi.org/10.1126/science.1259855.

3. Tansley, A.G. 1935. "The Use and Abuse of Vegetational Concepts and Terms." *Ecology* 16 (3): 284–307. https://doi.org/10.2307/1930070.

4. Sills, D.L. 1975. "The Environmental Movement and Its Critics." *Human Ecology* 3 (1): 1–41. https://doi.org/10.1007/BF01531771

5. Spedding, C.R.W. 1996. *Agriculture and the Citizen*. London: Chapman and Hall.

6. Forsyth, T. 2003. *Critical Political Ecology: The Politics of Environmental Science*. London: Routledge; Robbins, P. 2004. Political Ecology: A Critical Introduction. Blackwell Publishing.

7. Thompson, J., and I. Scoones. 2009. "Addressing the Dynamics of Agri-Food Systems: An Emerging Agenda for Social Science Research." *Environmental Science & Policy,* Special Issue: Food Security and Environmental Change, 12 (4): 386–97. https://doi.org/10.1016/j.envsci.2009.03.001.

8. Jones, J.G.W., and P.R. Street, eds. 1990. *Systems Theory Applied to Agriculture and the Food Chain.* London: Elsevier Applied Science.

9. Caron, P., E. Reig, D. Roep, W. Hediger, T. Le Cotty, D. Barthelemy, et al. 2008. "Multifunctionality: Refocusing a Spreading, Loose and Fashionable Concept for Looking at Sustainability?" *International Journal of Agricultural Resources, Governance and Ecology* 7 (4–5): 301–18. https://doi.org/10.1504/IJARGE.2008.020078; IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development). 2009. *Agriculture at a Crossroads: Global Report.* Edited by B. D. McIntyre, H. R. Herren, J. Wakhungu, and R.T. Watson. Washington, DC: Island Press.

10. Berkes, F., and C. Folke, eds. 1998. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge, UK: Cambridge University Press.

11. Caron, P., E. Biénabe, and E. Hainzelin. 2014. "Making Transition towards Ecological Intensification of Agriculture a Reality: The Gaps in and the Role of Scientific Knowledge." *Current Opinion in Environmental Sustainability,* SI: Sustainability governance and transformation, 8 (October): 44–52. https://doi.org/10.1016/j.cosust.2014.08.004.

12. Wezel, A., S. Bellon, T. Doré, C. Francis, D. Vallod, and C. David. 2009. "Agroecology as a Science, a Movement and a Practice. A Review." *Agronomy for Sustainable Development* 29 (4): 503–15.

13. Bensin, B.M. 1930. "Possibilities for International Cooperation in Agroecological Investigations" *Int. Rev. Agr. Mo. Bull. Agr. Sci. Pract.* 21: 277–84.

14. Tischler, W. 1965. *Agrarökologie.* Jena, Germany: Gustav Fischer Verlag.

15. Odum, E.P. 1969. "The Strategy of Ecosystem Development." *Science* 164 (3877): 262–70. https://doi.org/10.1126/science.164.3877.262.

16. Altieri, M.A. 1987. A*groecology: The Scientific Basis of Alternative Agriculture.* Boulder, USA: Westview Press.

17. Hernández Xolocotzi, E. 1977. *Agroecosistemas de México: Contribuciones a La Enseñanza, Investigación y Divulgación Agrícola.* Chapingo, Mexico: Colegio de Postgraduados.

18. Altieri, M.A. 1995. *Agroecology: The Science of Sustainable Agriculture.* Boulder, USA: Westview Press.

19. FAO (Food and Agriculture Organization) Committee on Agriculture. 2016. "Achieving Sustainable Rural Development through Agricultural Innovation: COAG/2016/6." Rome: FAO. http://www.fao.org/3/a-mr236e.pdf.

20. Francis, C., G. Lieblein, S. Gliessman, T.A. Breland, N. Creamer, R. Harwood, et al. 2003. "Agroecology: The Ecology of Food Systems." *Journal of Sustainable Agriculture* 22 (3): 99–118. https://doi.org/10.1300/J064v22n03_10.; Gliessman, S.R. (2007) 2015. *Agroecology: The Ecology of Sustainable Food Systems.* Third edition. New York, USA: CRC Press. https://www.crcpress.com/Agroecology-The-Ecology-of-Sustainable-Food-Systems-Third-Edition/Gliessman/p/book/9781439895610.

21. Dalgaard, T., N.J. Hutchings, and J.R. Porter. 2003. "Agroecology, Scaling and Interdisciplinarity." *Agriculture, Ecosystems and Environment* 100: 39–51.

22. Wezel, A., P. Fleury, C. David, and P. Mundler. 2015. "The Food System Approach in Agroecology Supported by Natural and Social Sciences: Topics, Concepts, Applications." In *Agroecology, Ecosystems and Sustainability,* edited by N. Benkeblia, 181–99. Boca Raton, USA: CRC Press.

23. Méndez, V.E., C.M. Bacon, and R. Cohen. 2013. "Agroecology as a

Transdisciplinary, Participatory, and Action-Oriented Approach." *Agroecology and Sustainable Food Systems* 37 (1): 3–18.

24. HLPE (High Level Panel of Experts on Food Security and Nutrition). 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security." Rome.

25. Russell, A Wendy, Fern Wickson, and Anna L Carew. 2008. "Transdisciplinarity: Context, Contradictions and Capacity." *Futures* 40 (5): 460–72.

26. Carson, Rachel. 1962. *Silent Spring*. New York and Boston, USA: Houghton Mifflin.

27. Rosset, P.M, and M.A. Altieri. 1997. "Agroecology versus Input Substitution: A Fundamental Contradiction of Sustainable Agriculture." *Society & Natural Resources* 10 (3): 283–95; Wezel et al. 2009. "Agroecology as a Science, a Movement and a Practice. A Review"; IPES-Food (International Panel of Experts on Sustainable Food Systems). 2016. "From University to Diversity. A Paradigm Shift from Industrial Agriculture to Diversified Agroecological Systems. International Panel of Experts on Sustainable Food Systems." Louvain-la-Neuve, Belgium: International Panel of Experts on Sustainable Food Systems (IPES-Food). http://www.ipes-food.org/images/Reports/UniformityToDiversity_FullReport.pdf.

28. Altieri, M.A. 2002. "Agroecology: The Science of Natural Resource Management for Poor Farmers in Marginal Environments." *Agriculture, Ecosystems & Environment* 93 (1–3): 1–24.

29. Wezel, A. 2017. *Agroecological Practices for Sustainable Agriculture: Principles, Applications, and Making the Transition.* New Jersey, USA: World Scientific.

30. Reijntjes, C., B. Haverkort, and A. Waters-Bayer. 1992. *Farming for the Future: An Introduction to Low-External-Input and Sustainable Agriculture.* London: Macmillan Press; Altieri. 1995. "Agroecology: The Science of Sustainable Agriculture"; Wezel, A., M. Casagrande, F. Celette, J.-F. Vian, A. Ferrer, and J. Peigné. 2014. "Agroecological Practices for Sustainable Agriculture. A Review." *Agronomy for Sustainable Development* 34 (1): 1–20.

31. Wezel et al. 2014. "Agroecological Practices for Sustainable Agriculture. A Review"; Wezel, A., and E. Silva. 2017. "Agroecology and Agroecological Cropping Practices." In *Agroecological Practices for Sustainable Agriculture: Principles, Applications, and Making the Transition*, edited by A. Wezel, 19–51. New Jersey, USA: World Scientific.

32. Altieri, M.A. 2004. "Agroecology versus Ecoagriculture: Balancing Food Production and Biodiversity Conservation in the Midst of Social Inequity." Issue 3. Commission on Environmental, Economic and Social Policy Occasional Papers. Gland, Switzerland: International Union for the Conservation of Nature; Wibbelmann, M., U. Schmutz, J. Wright, D. Udall, F. Rayns, M. Kneafsey, et al. 2013. "Mainstreaming Agroecology: Implications for Global Food and Farming Systems." Centre for Agroecology and Food Security Discussion Paper. Coventry, UK: Centre for Agroecology and Food Security (CAFS); van der Ploeg, J.D., and F. Ventura. 2014. "Heterogeneity Reconsidered." *Current Opinion in Environmental Sustainability,* SI: Sustainability governance and transformation, 8: 23–28. https://doi.org/10.1016/j.cosust.2014.07.001.

33. Mier y Terán Giménez Cacho, M., O.F. Giraldo, M. Aldasoro, H. Morales, B.G. Ferguson, P. Rosset, et al. 2018. "Bringing Agroecology to Scale: Key Drivers and Emblematic Cases." *Agroecology and Sustainable Food Systems* 42 (6): 637–65. https://www.tandfonline.com/doi/full/10.1080/21683565.2018.1443313.

34. Anderson, K., M. Pimbert, and C. Kiss. 2015. "Building, Defining and Strengthening Agroecology." Coventry University, UK: ILEIA and Centre for Agroecology, Water and Resilience. http://www.agroecologynow.com/wp-content/uploads/2015/05/Farming-Matters-Agroecology-EN.pdf; CNOP (Coordination Nationale des Organisations Paysannes), and IPC (International Planning Committee for Food Sovereignty). 2015. "International Forum for Agroecology." Nyéléni Center, Sélingué, Mali. http://www.foodsovereignty.org/wp-content/uploads/2015/10/NYELENI-2015-ENGLISH-FINAL-WEB.pdf.

35. CNOP and IPC. 2015. "International Forum for Agroecology."

36. Hensby, A. 2019. "Extinction Rebellion: Disruption and Arrests Can Bring Social Change." The Conversation. Accessed June 8, 2019. http://theconversation.com/extinction-rebellion-disruption-and-arrestscan- bring-social-change-115741.

37. Natalini, D. 2019. "Gilets Jaunes May Be the Start of a Worldwide Revolt against Climate Action." The Conversation. Accessed August 6, 2019. http://theconversation.com/gilets-jaunes-may-be-the-start-of-a-worldwide-revolt-against-climate-action-112636.

38. Nicholls, C.I, M.A. Altieri, and L. Vazquez. 2016. "Agroecology: Principles for the Conversion and Redesign of Farming Systems." *Journal of Ecosystem and Ecography* S5: 10. https://doi.org/10.4172/2157-7625; FAO. 2018. "Agroecology Knowledge Hub. 10 Elements." Food and Agriculture Organization of the United Nations. http://www.fao.org/agroecology/knowledge/10-elements/en/; CIDSE (Coopération Internationale pour le Développement et la Solidarité). 2018. "The Principles of Agroecology. Towards Just,

Resilient and Sustainable Food Systems." Brussels, Belgium: CIDSE. https://www.cidse.org/publications/just-food/food-and-climate/the-principles-of-agroecology.html

39. HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition."

40. FAO. 2018. "Agroecology Knowledge Hub. 10 Elements."

41. HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition;" Nicholls et al. 2016. "Agroecology: Principles for the Conversion and Redesign of Farming Systems,"; CIDSE. 2018. "The Principles of Agroecology. Towards Just, Resilient and Sustainable Food Systems"; FAO. 2018. "Agroecology Knowledge Hub. 10 Elements."

42. Sinclair, F., and R. Coe. 2019. "The Options by Context Approach: A Paradigm Shift in Agronomy." *Experimental Agriculture* 55 (S1): 1–13. https://doi.org/10.1017/S0014479719000139.

43. Sinclair, F., T.S. Rosenstock, V. Gitz, and L. Wollenberg. 2017. "Agroforestry to Diversify Farms and Enhance Resilience." In *10 Best Bet Innovations for Adaptation in Agriculture: A Supplement to the UNFCCC NAP Technical Guidelines,* edited by D. Dinesh, B. Campbell, O. Bonilla-Findji, and M. Richards, 14–19. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). http://www.cifor.org/nc/online-library/browse/view-publication/publication/7155.html.

44. Coe, R., J. Njoloma, and F. Sinclair. 2019. "Loading the Dice in Favour of the Farmer: Reducing the Risk of Adopting Agronomic Innovations." *Experimental Agriculture* 55 (S1): 67–83. https://doi.org/10.1017/S0014479716000181.

45. Sinclair and Coe. 2019. "The Options by Context Approach."

46. Gliessman. (2007) 2015. "Agroecology: The Ecology of Sustainable Food Systems."

47. Gliessman, S. 2016. "Transforming Food Systems with Agroecology." Agroecology and Sustainable Food Systems 40 (3): 187–89. https://doi.org/10.1080/21683565.2015.1130765; HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition."

48. Gliessman. 2016. "Transforming Food Systems with Agroecology." HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security."

49. IPCC (Intergovernmental Panel on Climate Change). 2014. "Annex II: Glossary." *In Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartB_FINAL.pdf.

50. IPCC. 2014. "Annex II: Glossary."

51. Spanger-Siegfried, E., J. Funk, R. Cleetus, M. Deas, and J. Christian-Smith. 2016. "Toward Climate Resilience: A Framework and Principles for Science-Based Adaptation." Cambridge, MA: Union of Concerned Scientists (UCS). https://www.ucsusa.org/sites/default/files/attach/2016/06/climate-resilience-framework-and-principles.pdf.

52. Meridian Institute. 2011. "Agriculture and Climate Change Policy Brief: Main Issues for the UNFCCC and Beyond." Adapted from "Agriculture and Climate Change: A Scoping Report" by B. Campbell, W. Mann, R. Meléndez-Ortiz, C. Streck, T. Tennigkeit, and S. Vermeulen. www.climate-agriculture.org.

53. Spanger-Siegfried et al. 2016. "Toward Climate Resilience: A Framework and Principles for Science-Based Adaptation."

54. Meridian Institute. 2011. "Agriculture and Climate Change Policy Brief: Main Issues for the UNFCCC and Beyond."

55. Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, et al. 2007. "Food, Fibre and Forest Products. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge, U.K: Cambridge University Press.

56. HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition.

57. Tiwari, T.P., D.S. Virk, and F.L. Sinclair. 2009. "Rapid Gains in Yield and Adoption of New Maize Varieties for Complex Hillside Environments through Farmer Participation: I. Improving Options through Participatory Varietal Selection (PVS)." *Field Crops Research* 111 (1): 137–43. https://doi.org/10.1016/j.fcr.2008.11.008.

58. Tiwari, T.P., R.M. Brook, P. Wagstaff, and F.L. Sinclair. 2012. "Effects of Light Environment on Maize in Hillside Agroforestry Systems

of Nepal." *Food Security* 4 (1): 103–14. https://doi.org/10.1007/s12571012-0165-4.

59. Orozco-Ramírez, Q., G. Bocco, and B. Solís-Castillo. 2019. "Cajete Maize in the Mixteca Alta Region of Oaxaca, Mexico: Adaptation, Transformation, and Permanence." *Agroecology and Sustainable Food Systems* 0 (0): 1–23. https://doi.org/10.1080/21683565.2019.1646374.

60. Debray, V., A. Wezel, A. Lambert-Derkimba, K. Roesch, G. Lieblein, and C.A. Francis. 2019. "Agroecological Practices for Climate Change Adaptation in Semiarid and Subhumid Africa." *Agroecology and Sustainable Food Systems* 43 (4): 429–56. https://doi.org/10.1080/21683565.2018.1509166; Mbow, C., M. van Noordwijk, E. Luedeling, H. Neufeldt, P.A. Minang, and G. Kowero. 2014. "Agroforestry Solutions to Address Food Security and Climate Change Challenges in Africa." *Current Opinion in Environmental Sustainability*, Sustainability challenges, 6: 61–67. https://doi.org/10.1016/j.cosust.2013.10.014.

61. Rahn, E., P. Vaast, P. Läderach, P. van Asten, L. Jassogne, and J. Ghazoul. 2018. "Exploring Adaptation Strategies of Coffee Production to Climate Change Using a Process-Based Model." *Ecological Modelling* 371: 76–89. https://doi.org/10.1016/j.ecolmodel.2018.01.009.

62. Sida, T.S., F. Baudron, H. Kim, and K.E. Giller. 2018. "Climate-Smart Agroforestry: Faidherbia Albida Trees Buffer Wheat against Climatic Extremes in the Central Rift Valley of Ethiopia." *Agricultural and Forest Meteorology* 248: 339–47. https://doi.org/10.1016/j.agrformet.2017.10.013.

63. Harrison, R.D., C. Thierfelder, F. Baudron, P. Chinwada, C. Midega, U. Schaffner, et al. 2019. "Agro-Ecological Options for Fall Armyworm (Spodoptera Frugiperda JE Smith) Management: Providing Low-Cost, Smallholder Friendly Solutions to an Invasive Pest." *Journal of Environmental Management* 243: 318–30. https://doi.org/10.1016/j.jenvman.2019.05.011; Midega, C.A.O., J.O. Pittchar, J.A. Pickett, G.W. Hailu, and Z.R. Khan. 2018. "A Climate-Adapted Push-Pull System Effectively Controls Fall Armyworm, Spodoptera Frugiperda (J E Smith), in Maize in East Africa." *Crop Protection* 105: 10–15. https://doi.org/10.1016/j.cropro.2017.11.003

64. Minasny, B, and A.B. McBratney. 2018. "Limited Effect of Organic Matter on Soil Available Water Capacity." *European Journal of Soil Science* 69 (1): 39–47. https://doi.org/10.1111/ejss.12475; Minasny, B, and A.B. McBratney. 2018. "Rejoinder to the Comment on: B. Minasny & A.B. McBratney. 2018. Limited Effect of Organic Matter on Soil Available Water Capacity." *European Journal of Soil Science* 69 (1): 155–57. https://doi.org/10.1111/ejss.12526.

65. Sickles, R.C., and V. Zelenyuk. 2019. *Measurement of Productivity and Efficiency: Theory and Practice.* Cambridge University Press. https://doi.org/10.1017/9781139565981.

66. van Noordwijk, M., L.A. Duguma, S. Dewi, B. Leimona, D.C. Catacutan, B. Lusiana, et al. 2018. "SDG Synergy between Agriculture and Forestry in the Food, Energy, Water and Income Nexus: Reinventing Agroforestry?" *Current Opinion in Environmental Sustainability,* Sustainability Science, 34: 33–42. https://doi.org/10.1016/j.cosust.2018.09.003.

67. Pagella, T.F, and F.L. Sinclair. 2014. "Development and Use of a Typology of Mapping Tools to Assess Their Fitness for Supporting Management of Ecosystem Service Provision." *Landscape Ecology* 29 (3): 383–99. https://doi.org/10.1007/s10980-013-9983-9.

68. Crossland, M., L. Winowiecki, T. Pagella, K. Hagdu, and F. Sinclair. 2018. "Implications of Variation in Local Perception of Degradation and Restoration Processes for Implementing Land Degradation Neutrality." *Environmental Development* 28: 42–54.

69. Carroll, Z.L., S.B. Bird, B.A. Emmett, B. Reynolds, and F. L. Sinclair. 2004. "Can Tree Shelterbelts on Agricultural Land Reduce Flood Risk?" *Soil Use and Management* 20 (3): 357–59. https://doi.org/10.1111/j.1475-2743.2004.tb00381.x

70. Jackson, B., T. Pagella, F. Sinclair, B. Orellana, A. Henshaw, B. Reynolds, et al. 2013. "Polyscape: A GIS Mapping Framework Providing Efficient and Spatially Explicit Landscape-Scale Valuation of Multiple Ecosystem Services." *Landscape and Urban Planning* 112: 74–88. https://doi.org/10.1016/j.landurbplan.2012.12.014

71. Galli, A. 2015. "On the Rationale and Policy Usefulness of Ecological Footprint Accounting: The Case of Morocco." *Environmental Science & Policy* 48: 210–24. https://doi.org/10.1016/j.envsci.2015.01.008; HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition."

72. van Noordwijk et al. 2018. "SDG Synergy between Agriculture and Forestry in the Food, Energy, Water and Income Nexus."

73. Debray et al. 2019. "Agroecological Practices for Climate Change Adaptation in Semiarid and Subhumid Africa."

74. IPCC (Intergovernmental Panel on Climate Change). 2014. *Climate Change 2014: Synthesis Report.* Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.). Geneva: IPCC. https://www.ipcc.ch/report/ar5/wg2/

75. Schellnhuber, H.J., B. Hare, O. Serdeczny, M. Schaeffer, S. Adams,

F. Baarsch, et al. 2013. "Turn down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics." Washington DC.

76. Debray et al. 2019. "Agroecological Practices for Climate Change Adaptation in Semiarid and Subhumid Africa."

77. Sinclair and Coe. 2019. "The Options by Context Approach."

78. Mapfumo, P., S.Adjei-Nsiah, F. Mtambanengwe, R. Chikowo, and K.E. Giller. 2013. "Participatory Action Research (PAR) as an Entry Point for Supporting Climate Change Adaptation by Smallholder Farmers in Africa." *Environmental Development,* Thematic Issue - Climate change risk management in Africa, 5: 6–22. https://doi.org/10.1016/j.envdev.2012.11.001

79. Debray et al. 2019. "Agroecological Practices for Climate Change Adaptation in Semiarid and Subhumid Africa."

80. Debray et al. 2019. "Agroecological Practices for Climate Change Adaptation in Semiarid and Subhumid Africa."

81. Aune, J.B. 2011. "Agro-Sahel. Une Collection de Techniques et d'approches Pratiques Pour l'amélioration de l'agriculture Dans Le Sahel." Oslo, Norway: Groupe de Coordination des Zones Arides; Basquin, H., F. Charhon, M. Cissokho, G. Le Gauyer, H. Rouillé d'Orfeuil, and J.-L. Vielajus. 2014. "Nourrir les villes, défi de l'agriculture familiale. Des innovations locales et paysannes en Afrique de l'Ouest." Paris, France: CFSI et la Fondation de France; Bilgo, A., A.K. Sangare, D. Bambara, and V. Hien. 2013. "Lutte Contre La Désertification Au Burkina Faso: Opportunités et Contraintes." Grain de Sel 63–66: 11–13; CILSS (Comite permanente Inter-estados de Luta contra a Seca no Sahel). 2009. "Récupération des glacis dénudés à des fins sylvo-pastorales." Ouagadougou, Burkina Faso: CILSS; De Witte, C. 2013. "Fiches Techniques d'agroécologie." Paris, France: Agronomes et Vétérinaires Sans (AVSF); Dorlöchter, S, and D. Nill. 2012. "Bonnes Pratiques de CES/DRS. Contribution à l'adaptation Au Changement Climatique et à La Résilience Des Producteurs. Les Expériences de Quelques Projets Au Sahel." Eschborn, Germany: GTZ; Leroy, M. 2015. "Fiches techniques GTD/RéSaD." CARI. http://www.gtdesertification.org; Scholle, J. 2015. "Livret de Vulgarisation de Pratiques Agroécologiques et Agroforestières. Techniques Développées Dans Le Cadre Du Projet DEFIV-DAFOMA Dans Le Mayanda, Bas Congo, RDC (2010–2015)." France; Wezel, A., and T. Rath. 2002. "Resource Conservation Strategies in Agro-Ecosystems of Semi-Arid West Africa." *Journal of Arid Environments* 51 (3): 383–400. https://doi.org/10.1006/jare.2001.0968.

82. Berton, S., R. Billaz, P. Burger, and A. Lebreton. 2013. "Agroécologie, Une Transition Vers Des Modes de Vie et de Développement Viables. Paroles d'acteurs." Viols Le Fort, France: AVSF, CARI, GTD; Bilgo et al. 2013. "Lutte Contre La Désertification Au Burkina Faso: Opportunités et Contraintes"; De Witte. 2013. "Fiches Techniques d'agroécologie"; Diguingue, D. 2010. "Rapport de Capitalisation: Les Cordons Pierreux Une Expérience à l'Est Du Tchad." Germany; Dorlöchter and Nill. 2012. "Bonnes Pratiques de CES/DRS. Contribution à l'adaptation Au Changement Climatique et à La Résilience Des Producteurs. Les Expériences de Quelques Projets Au Sahel"; Leroy. 2015. "Fiches techniques GTD/RéSaD"; Mwanyoka, I. 2015. "Lesson Learned from Implementation of the 'Where the Rain Falls - Community Based Adaptation' Project." Tanzania: CARE; Scholle. 2015. "Livret de Vulgarisation de Pratiques Agroécologiques et Agroforestières. Techniques Développées Dans Le Cadre Du Projet DEFIV-DAFOMA Dans Le Mayanda, Bas Congo, RDC (2010–2015)"; Tumbo, S.D., B.P. Mbilinyi, F.B. Rwehumbiza, and K.D. Mutabazi. 2010. "Economics of Climate Change for Agriculture Sector in Tanzania. Adaptation Options and Their Costs." Tanzania: Soil Water Management Group, Sokoine University of Agriculture. http://economics-of-cc-in-tanzania.org/images/Final_Corrected_Version_1_v2.pdf.

83. Dorlöchter and Nill. 2012. "Bonnes Pratiques de CES/DRS. Contribution à l'adaptation Au Changement Climatique et à La Résilience Des Producteurs. Les Expériences de Quelques Projets Au Sahel"; Roesch, K., and M. Chapon. 2014. "Des unités de méthanisation au Mali." Paris and Lyon, France: AVSF; Scholle. 2015. "Livret de Vulgarisation de Pratiques Agroécologiques et Agroforestières. Techniques Développées Dans Le Cadre Du Projet DEFIV-DAFOMA Dans Le Mayanda, Bas Congo, RDC (2010–2015)."

84. Aune. 2011. "Agro-Sahel. Une Collection de Techniques et d'approches Pratiques Pour l'amélioration de l'agriculture Dans Le Sahel."; Lheriteau, F, and A. Rakotondramanana Ratrimo. 2014. "Stock Taking of CTAS Scheme of Lead Farmers' Experiences for the Dissemination of Innovative Good Practices." France: GRET.

85. Bachar, A.I. 2011. "Seuil d'épandage Du PROBADO: Un Ouvrage à Usages Multiples." Germany: Coopération Tchado-Allemande; Bender, H. 2009. "Mesures de réhabilitation et d'aménagement des bas-fonds. Seuils d'épandage. Gestion optimale et durable des eaux et des sols." Abéché, Tchad: GTZ, KFW.; BERCEF (Bureau d'Encadrement Rural, de Conseils d'Etudes et de Formations). 2007. "Etude de Faisabilité Socio-Économique et Impact Environnemental de Seuils d'épandage de Ouadi Chaou. Rapport II: Etude Socio-Économique." Germany: Coopération Tchado-Allemande.; De Witte. 2013. "Fiches Techniques d'agroécologie"; Dorlöchter and Nill. 2012. "Bonnes Pratiques de CES/DRS. Contribution à l'adaptation Au Changement Climatique et à La Résilience Des Producteurs. Les Expériences de Quelques Projets Au Sahel"; Orlhac, M. 2013. "Local Governance of Water Management in Luale Ward, Uluguru Mountains, Tanzania: Innovations and Collective

Actions." Montpellier, France: SupAgro; URD (Urgence Réhabilitation Développement). 2009. "La pompe à corde. Expérience au Tchad. Une solution alternative pour l'eau potable." Plaisians, France: URD; Stroesser, L. 2015. "Fiches Techniques GTD/RéSaD." CARI. http://www.gtdesertification.org; Cornu, F. 2011. "La Gestion Concertée Des Ressources En Eau Au Mali: Une Expérience Originale à l'épreuve Des Pratiques Locales." Lyon, France: AVSF, ICD.

86. Aune. 2011. "Agro-Sahel. Une Collection de Techniques et d'approches Pratiques Pour l'amélioration de l'agriculture Dans Le Sahel."; Tumbo et al. 2010. "Economics of Climate Change for Agriculture Sector in Tanzania. Adaptation Options and Their Costs."

87. Aune. 2011. "Agro-Sahel. Une Collection de Techniques et d'approches Pratiques Pour l'amélioration de l'agriculture Dans Le Sahel."

88. Aune. 2011. "Agro-Sahel. Une Collection de Techniques et d'approches Pratiques Pour l'amélioration de l'agriculture Dans Le Sahel."; AVSF (Agronomes et vétérinaires sans frontières). 2011. "Étude Sur Les Adaptations Des Exploitations Paysannes Au Changement Climatique." Paris, France: AVSF; Liwenga, E.T., L.K., and T. Afifi. 2012. "Rainfall, Food Security, and Human Mobility. Case Study: Tanzania." Bonn, Germany.

89. Basquin et al. 2014. "Nourrir les villes, défi de l'agriculture familiale. Des innovations locales et paysannes en Afrique de l'Ouest"; Bouziane, M., C. Brosse, J.B. Cheneval, N. Diop, A. Issa, K. Christine, et al. 2013. "Intégrer Les Contraintes Climatiques et Énergétiques Dans Les Pratiques de Développement. De La Bonne Pratique à La Politique Publique: Recommandations Du Réseau Climat et Développement." Montreuil, France: RAC-France; Comoé, H., and M. Siegrist. 2015. "Relevant Drivers of Farmers' Decision Behavior Regarding Their Adaptation to Climate Change: A Case Study of Two Regions in Côte d'Ivoire." *Mitigation and Adaptation Strategies for Global Change* 20 (2): 179–99. https://doi.org/10.1007/s11027-013-9486-7; GRET (Groupe de Recherches et d'Echanges Technologiques). 2011. "Développement agricole. Projet de sécurisation de l'approvisionnement en semences dans la région Androy à Madagascar." France: GRET; Liwenga et al. 2012. "Rainfall, Food Security, and Human Mobility. Case Study: Tanzania."

90. Stroesser. 2015. "Fiches Techniques GTD/RéSaD."

91. GRET. 2011. "Développement agricole. Projet de sécurisation de l'approvisionnement en semences dans la région Androy à Madagascar"; Aune. 2011. "Agro-Sahel. Une Collection de Techniques et d'approches Pratiques Pour l'amélioration de l'agriculture Dans Le Sahel; Franzel, S., S. Carsan, B. Lukuyu, J. Sinja, and C. Wambugu. 2014. "Fodder Trees for Improving Livestock Productivity and Smallholder Livelihoods in Africa." *Current Opinion in Environmental Sustainability,* Sustainability challenges, 6: 98–103. https://doi.org/10.1016/j.cosust.2013.11.008.; Leroy. 2015. "Fiches techniques GTD/RéSaD"; Scholle. 2015. "Livret de Vulgarisation de Pratiques Agroécologiques et Agroforestières. Techniques Développées Dans Le Cadre Du Projet DEFIV-DAFOMA Dans Le Mayanda, Bas Congo, RDC (2010–2015)."; Stroesser. 2015. "Fiches Techniques GTD/RéSaD."

92. Stroesser. 2015. "Fiches Techniques GTD/RéSaD."

93. Liwenga et al. 2012. "Rainfall, Food Security, and Human Mobility. Case Study: Tanzania."

94. Harris, D., and A. Orr. 2014. "Is Rainfed Agriculture Really a Pathway from Poverty?" *Agricultural Systems* 123: 84–96. https://doi.org/10.1016/j.agsy.2013.09.005.

95. Rusere, F., O. Crespo, L. Dicks, S. Mkuhlani, J. Francis, and L. Zhou. 2019. "Enabling Acceptance and Use of Ecological Intensification Options through Engaging Smallholder Farmers in Semi-Arid Rural Limpopo and Eastern Cape, South Africa." *Agroecology and Sustainable Food Systems.* https://doi.org/10.1080/21683565.2019.1638336.

96. Pretty, J., T.G. Benton, Z. Pervez Bharucha, L.V. Dicks, C. Butler Flora, H.C.J. Godfray, et al. 2018. "Global Assessment of Agricultural System Redesign for Sustainable Intensification." *Nature Sustainability* 1 (8): 441–46. https://doi.org/10.1038/s41893-018-0114-0.

97. Sinclair, F.L. 2017. "Systems Science at the Scale of Impact: Reconciling Bottom up Participation with the Production of Widely Applicable Research Outputs." In *Sustainable Intensification in Smallholder Agriculture: An Integrated Systems Research Approach*, 43–57. London, UK: Routledge. http://dx.doi.org/10.4324/9781315618791.

98. Franzel et al. 2014. "Fodder Trees for Improving Livestock Productivity and Smallholder Livelihoods in Africa."

99. Duguma, L.A., P.A. Minang, O.E. Freeman, and H. Hager. 2014. "System Wide Impacts of Fuel Usage Patterns in the Ethiopian Highlands: Potentials for Breaking the Negative Reinforcing Feedback Cycles." *Energy for Sustainable Development* 20: 77–85.

100. Barrios, E., G.W. Sileshi, K. Shepherd, and F. Sinclair. 2012. "Agroforestry and Soil Health: Linking Trees, Soil Biota and Ecosystem Services." In *Soil Ecology and Ecosystem Services*, edited by D.H. Wall, R.D. Bardgett, V. Behan-Pelletier, J.E. Herrick, T.H. Jones, et al. 315–30. Oxford, UK: Oxford University Press.

ENDNOTES

101. Minasny, B., B.P. Malone, A.B. McBratney, D.A. Angers, D. Arrouays, A. Chambers, et al. 2017. "Soil Carbon 4 per Mille." *Geoderma* 292: 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

102. Zomer, R.J., H. Neufeldt, J. Xu, A. Ahrends, D. Bossio, A. Trabucco, M.van Noordwijk, et al. 2016. "Global Tree Cover and Biomass Carbon on Agricultural Land: The Contribution of Agroforestry to Global and National Carbon Budgets." *Scientific Reports* 6: 29987. https://doi.org/10.1038/srep29987.

103. Minasny, B., D. Arrouays, A.B McBratney, D.A. Angers, A. Chambers, V. Chaplot, et al. 2018. "Rejoinder to Comments on Minasny et al., 2017 Soil Carbon 4 per Mille *Geoderma* 292, 59-86." Geoderma 309: 124–29.

104. Zomer et al. 2016. "Global Tree Cover and Biomass Carbon on Agricultural Land."

105. Mbow, C., P. Smith, D. Skole, L. Duguma, and M. Bustamante. 2014. "Achieving Mitigation and Adaptation to Climate Change through Sustainable Agroforestry Practices in Africa." *Current Opinion in Environmental Sustainability,* Sustainability challenges, 6: 8–14. https://doi.org/10.1016/j.cosust.2013.09.002

106. Pimbert, M. 2015. "Agroecology as an Alternative Vision to Conventional *Development* and Climate-Smart Agriculture." Development 58 (2-3): 286–98. https://doi.org/10.1057/s41301-016-0013-5.

107. Debray et al. 2019. "Agroecological Practices for Climate Change Adaptation in Semiarid and Subhumid Africa."

108. Glover, J.D, J.P. Reganold, and C.M. Cox. 2012. "Agriculture: Plant Perennials to Save Africa's Soils." *Nature* 489: 359–61; Schroth, G., and F.L. Sinclair. 2003. *Trees, Crops, and Soil Fertility: Concepts* and *Research Methods*. Wallignford, UK and Cambridge, USA: CABI Publishing.; van Noordwijk, M., G. Cadisch, and C.K. Ong, eds. 2004. *Below-Ground Interactions in Tropical Agroecosystems: Concepts and Models with Multiple Plant Components.* Wallingford, UK and Cambridge, USA: CABI Publishing; Sileshi, G.W., P.L. Mafongoya, F.K. Akinnifesi, E. Phiri, P. Chirwa, T. Beedy, et al. 2014. "Agroforestry: Fertilizer Trees." In *Encyclopedia of Agriculture and Food Systems,* edited by N.K. Van Alfen, 222–34. London, UK, Waltham, USA, San Diego, USA: Elsevier; Ng, S.L., Q.G. Cai, S.W. Ding, K.C. Chau, and J. Qin. 2008. "Effects of Contour Hedgerows on Water and Soil Conservation, Crop Productivity and Nutrient Budget for Slope Farmland in the Three Gorges Region (TGR) of China." *Agroforestry Systems* 74 (3): 279–91. https://doi.org/10.1007/s10457-008-9158-x.

109. Barrios. 2012. "Agroforestry and Soil Health: Linking Trees, Soil Biota and Ecosystem Services."; Orgiazzi, A., R.D. Bardgett, E. Barrios, V. Behan-Pelletier, M.J.I. Briones, Jean-Luc Chotte, et al., eds. 2016. *Global Soil Biodiversity Atlas*. Luxembourg: European Commission, Publications Office of the European Union.

110. Ilstedt, U., A. Bargués Tobella, H.R. Bazié, J. Bayala, E. Verbeeten, G. Nyberg, et al. 2016. "Intermediate Tree Cover Can Maximize Groundwater Recharge in the Seasonally Dry Tropics." *Scientific Reports* 6: 21930; Bayala, J., and J.S. Wallace. 2015. "The Water Balance of Mixed Tree-Crop Systems." In *Tree-Crop Interactions: Agroforestry in a Changing Climate*, edited by Chin K. Ong, Colin Black, and Julia Wilson, 2nd edition, 140–90. Wallingford, UK and Boston, USA: CABI Publishing; Carroll et al. 2004. "Can Tree Shelterbelts on Agricultural Land Reduce Flood Risk?"

111. Bayala, J., J. Sanou, Z. Teklehaimanot, and F. Sinclair. 2015. "Adaptation of Crops to Partial Shade in Mixed Cropping Systems." In *Tree-Crop Interactions: Agroforestry in a Changing Climate,* edited by C.K. Ong, C. Black, and J. Wilson, 2nd edition, 309–25. Wallingford, UK and Boston, USA: CABI Publishing; Ovalle-Rivera, O., P. Läderach, C. Bunn, M. Obersteiner, and G. Schroth. 2015. "Projected Shifts in Coffea Arabica Suitability among Major Global Producing Regions Due to Climate Change." *PloS One* 10 (4): e0124155; Key, N., S. Sneeringer, and D. Marquardt. 2014. "Climate Change, Heat Stress, and U.S. Dairy Production." *USDA-ERS Economic Research Report* Number 175, September. https://papers.ssrn.com/abstract=2506668; Sida et al. 2018. "Climate-Smart Agroforestry."

112. Franzel et al. 2014. "Fodder Trees for Improving Livestock Productivity and Smallholder Livelihoods in Africa"; Mishra, S., and P. Pathak. 2015. "Fodder Production and Conservation: A Potential Source of Livelihood for Women." In *Women, Technology and Development,* edited by P. Vasudevan, S. Sharma, V.P. Sharma, and M. Verma, 136–50. New Delhi: Narosa Publishing House; Place, F., R. Roothaert, L. Maina, S. Franzel, J. Sinja, and J. Wanjiku. 2009. "The Impact of Fodder Trees on Milk Production and Income among Smallholder Dairy Farmers in East Africa and the Role of Research." World Agroforestry Centre Occasional Paper. Nairobi: World Agroforestry Center. http://old.worldagroforestry.org/downloads/Publications/PDFS/OP16490.pdf.

113. Dawson, I.K., P. Place, E. Torquebiau, E. Malézieux, M. Iiyama, G.W. Sileshi, et al. 2013. "Agroforestry, Food and Nutritional Security." Background Paper for the International Conference on Forests for Food Security and Nutrition. Rome: FAO. http://www.fao.org/forestry/37082-04957fe26afbc90d1e9c0356c48185295.pdf; Duguma et al. 2014. "System Wide Impacts of Fuel Usage Patterns in the Ethiopian Highlands"; Mosa, A., K. Siddig, and H. Grethe. 2016. "Time Use for Home Activities, Market Activities and

Leisure in Ethiopia: Economy-Wide Effects of Improved Efficiency." Paper prepared for the 19th Annual Conference n Global Economic Ananlysis, June 15–17, 2016. Washington, DC, USA: Global Trade Analysis Project (GTAP).

114. ICRAF (World Agroforestry). n.d. "Developing and Promoting Market-Based Agroforestry and Forest Rehabilitation Options for Northwest Vietnam – AFLI-II." World Agroforestry. https://www.worldagroforestry.org/project/developing-and-promoting-market-based-agroforestry-and-forest-rehabilitation-options.

115. ICRAF (World Agroforestry). n.d. "Kanoppi 2: Developing and Promoting Market-Based Agroforestry Options and Integrated Landscape Management for Smallholder Forestry in Indonesia." https://www.worldagroforestry.org/project/kanoppi-2-developing-and-promoting-market-based-agroforestry-options-and-integrated.

116. Binam, J.N., F. Place, A. Kalinganire, S. Hamade, M. Boureima, A. Tougiani, et al. 2015. "Effects of Farmer Managed Natural Regeneration on Livelihoods in Semi-Arid West Africa." Environmental Economics and Policy Studies 17 (4): 543–75. https://doi.org/10.1007/s10018-015-0107-4; Vaast, Philippe, and Eduardo Somarriba. 2014. "Trade-Offs between Crop Intensification and Ecosystem Services: The Role of Agroforestry in Cocoa Cultivation." Agroforestry Systems 88 (6): 947–56. https://doi.org/10.1007/s10457-014-9762-x; Angelsen, A., P. Jagger, R. Babigumira, B. Belcher, N.J. Hogarth, S. Bauch, J. Börner, C. Smith-Hall, and S. Wunder. 2014. "Environmental Income and Rural Livelihoods: A Global-Comparative Analysis." World Development, Forests, Livelihoods, and Conservation, 64: S12–28. https://doi.org/10.1016/j.worlddev.2014.03.006; Dawson et al. 2013. "Agroforestry, Food and Nutritional Security."

117. Sileshi, G., F.K. Akinnifesi, O.C. Ajayi, and F. Place. 2008. "Meta-Analysis of Maize Yield Response to Woody and Herbaceous Legumes in Sub-Saharan Africa." *Plant and Soil* 307 (1): 1–19. https://doi.org/10.1007/s11104-008-9547-y; Ajayi, O.C., F. Place, F.K. Akinnifesi, and G. W. Sileshi. 2011. "Agricultural Success from Africa: The Case of Fertilizer Tree Systems in Southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe)." *International Journal of Agricultural Sustainability* 9 (1): 129–36. https://doi.org/10.3763/ijas.2010.0554; Garrity, D.P., F.K. Akinnifesi, O.C. Ajayi, S.G. Weldesemayat, J.G. Mowo, A. Kalinganire, et al. 2010. "Evergreen Agriculture: A Robust Approach to Sustainable Food Security in Africa." *Food Security* 2 (3): 197–214. https://doi.org/10.1007/s12571-010-0070-7; Coe et al. 2019. "Loading the Dice in Favour of the Farmer: Reducing the Risk of Adopting Agronomic Innovations"; Bai, Z.G., D.L. Dent, L. Olsson, and M.E. Schaepman. 2008. "Proxy Global Assessment of Land Degradation." *Soil Use and Management* 24 (3): 223–34. https://doi.org/10.1111/j.1475-2743.2008.00169.x; Lal, R., U. Safriel, and B. Boer. 2012. "Zero Net Land Degradation: A New Sustainable Development Goal for Rio+ 20. A Report Prepared for the Secretariat of the United Nations Convention to Combat Desertification." Bonn; Stavi, I., and R. Lal. 2015. "Achieving Zero Net Land Degradation: Challenges and Opportunities." *Journal of Arid Environments* 112: 44–51. https://doi.org/10.1016/j.jaridenv.2014.01.016.

118. Binam et al. 2015. "Effects of Farmer Managed Natural Regeneration on Livelihoods in Semi-Arid West Africa"; Dawson et al. 2013. "Agroforestry, Food and Nutritional Security."; Kehlenbeck, K., and S. McMullin. 2015. Fruit Tree Portfolios for Improved Diets and Nutrition. How to Use the Diversity of Different Fruit Tree Species Available in Machakos County to Provide Better Nutrition for Smallholder Farming Families. Nairobi: World Agroforestry Centre (ICRAF); Ickowitz, A., B. Powell, M.A. Salim, and T.C.H. Sunderland. 2014. "Dietary Quality and Tree Cover in Africa." *Global Environmental Change* 24: 287–94. https://doi.org/10.1016/j.gloenvcha.2013.12.001; Sunderland, T., B. Powell, A. Ickowitz, S. Foli, M. Pinedo-Vasquez, R. Nasi, et al. 2013. "Food Security and Nutrition: The Role of Forests." Discussion paper. Bogor, Indonesia: CIFOR. http://www.cifor.org/publications/pdf_files/WPapers/DPSunderland1301.pdf.

119. Khadse, A., P.M. Rosset, H. Morales, and B.G. Ferguson. 2018. "Taking Agroecology to Scale: The Zero Budget Natural Farming Peasant Movement in Karnataka, India." *The Journal of Peasant Studies* 45 (1): 192–219. https://doi.org/10.1080/03066150.2016.1276450.

120. Smart Indian Agriculture. n.d. "ICRISAT's DG Takes a Swipe at Subhash Palekar's Zero-Budget Natural Farming at NAAS Lecture." Smart Indian Agriculture. Accessed August 5, 2019. https://www.smartindianagriculture.com/icrisats-dg-takes-a-swipe-at-subhash-palekars-zero-budget-natural-farming-at-naas-lecture/.

121. Saldanha, L.F. 2018. "A Review of Andhra Pradesh's Climate Resilient Zero Budget Natural Farming." Environment Support Group; Sharma, D. 2019. "Zero-Budget Farming." The Tribune India News Service. July 22, 2019. https://www.tribuneindia.com/news/comment/zero-budget-farming/805658.html.

122. Khadse et al. 2018. "Taking Agroecology to Scale."

123. Kumar, V. 2018. "Engineering Transformation through Zero Budget Natural Farming (ZBNF)." The Second International Symposium on Agroecology: Scaling-up Agroecology to Achieve the Sustainable Development Goals, Rome, April 3–5, 2018. http://www.fao.org/3/BU710EN/bu710en.pdf; La Via Campesina. n.d. "Zero Budget Natural Farming in India. 52 Profiles on Agroecology." http://www.fao.org/3/a-bl990e.pdf; Khadse et al. 2018. "Taking Agroecology to Scale."

124. Smith Dumont, E., S. Bonhomme, T.F. Pagella, and F.L. Sinclair. 2019. "Structured Stakeholder Engagement Leads to Development of More Diverse and Inclusive Agroforestry Options." *Experimental Agriculture* 55 (S1): 252–74. https://doi.org/10.1017/S0014479716000788.

ENDNOTES

125. Harrison et al. 2019. "Agro-Ecological Options for Fall Armyworm (Spodoptera Frugiperda JE Smith) Management."

126. Goergen, G., P.L. Kumar, S.B. Sankung, A. Togola, and M. Tamo. 2016. "First Report of Outbreaks of the Fall Armyworm Spodoptera Frugiperda (JE Smith)(Lepidoptera, Noctuidae), a New Alien Invasive Pest in West and Central Africa." *PloS One* 11 (10): e0165632.

127. Abrahams, P., M. Bateman, T. Beale, V. Clottey, and M. Cock. 2017. Fall Armyworm: Impacts and Implications for Africa. CABI.

128. Abate, T., A. van Huis, and J.K.O. Ampofo. 2000. "Pest Management Strategies in Traditional Agriculture: An African Perspective." *Annual Review of Entomology* 45 (1): 631–59. https://doi.org/10.1146/annurev.ento.45.1.631; van Huis, A., and F. Meerman. 1997. "Can We Make IPM Work for Resource-Poor Farmers in Sub-Saharan Africa?" *International Journal of Pest Management* 43 (4): 313–20. https://doi.org/10.1080/096708797228636; Wyckhuys, K.A.G., and R.J. O'Neil. 2007. "Local Agro-Ecological Knowledge and Its Relationship to Farmers' Pest Management Decision Making in Rural Honduras." *Agriculture and Human Values* 24 (3): 307–21. https://doi.org/10.1007/s10460-007-9068-y.

129. Altieri, M.A., and C.I. Nicholls. 2003. "Soil Fertility Management and Insect Pests: Harmonizing Soil and Plant Health in Agroecosystems." *Soil and Tillage Research* 72 (2): 203–11. https://doi.org/10.1016/S0167-1987(03)00089-8.

130. Midega et al. 2018. "A Climate-Adapted Push-Pull System Effectively Controls Fall Armyworm, Spodoptera Frugiperda (J E Smith), in Maize in East Africa."

131. van Huis, A. 1981. "Integrated Pest Management in the Small Farmer's Maize Crop in Nicaragua." PhD Thesis, Wageningen.

132. Rivers, A., M. Barbercheck, B. Govaerts, and N. Verhulst. 2016. "Conservation Agriculture Affects Arthropod Community Composition in a Rainfed Maize–Wheat System in Central Mexico." *Applied Soil Ecology* 100: 81–90. https://doi.org/10.1016/j.apsoil.2015.12.004.

133. Maas, B., Y. Clough, and T. Tscharntke. 2013. "Bats and Birds Increase Crop Yield in Tropical Agroforestry Landscapes." *Ecology Letters* 16 (12): 1480–87. https://doi.org/10.1111/ele.12194; Meagher Jr, R.L., G.S Nuessly, R.N. Nagoshi, and M.M. Hay-Roe. 2016. "Parasitoids Attacking Fall Armyworm (Lepidoptera: Noctuidae) in Sweet Corn Habitats." *Biological Control* 95: 66–72. https://doi.org/10.1016/j.biocontrol.2016.01.006; Wyckhuys, K.A.G., and R.J. O'Neil. 2007. "Local Agro-Ecological Knowledge and Its Relationship to Farmers' Pest Management Decision Making in Rural Honduras." *Agriculture and Human Values* 24 (3): 307–21. https://doi.org/10.1007/s10460-007-9068-y.

134. Midega et al. 2018. "A Climate-Adapted Push-Pull System Effectively Controls Fall Armyworm, Spodoptera Frugiperda (J E Smith), in Maize in East Africa."

135. Thierfelder, C., S. Niassy, C. Midega, S. Sevgan, J. van den Burg, B.M. Prasanna, et al. 2018. "Low-Cost Agronomic Practices and Landscape Management Approaches to Control FAW." In Fall *Armyworm in Africa: A Guide for Integrated Pest Management,* 89–96. Mexico: CDMX: International Maize and Wheat Improvement Center (CIMMYT).

136. Harrison et al. 2019. "Agro-Ecological Options for Fall Armyworm (Spodoptera Frugiperda JE Smith) Management."

137. Hänke, H., L. Börjeson, K. Hylander, and E. Enfors-Kautsky. 2016. "Drought Tolerant Species Dominate as Rainfall and Tree Cover Returns in the West African Sahel." *Land Use Policy* 59: 111–20. https://doi.org/10.1016/j.landusepol.2016.08.023.

138. Boffa, J.-M. 1999. "Agroforestry Parklands in Sub-Saharan Africa." FAO Conservation Guide 34. Rome: Food and Agriculture Organization.

139. Lykke, A.M., M.K. Kristensen, and S. Ganaba. 2004. "Valuation of Local Use and Dynamics of 56 Woody Species in the Sahel." *Biodiversity & Conservation* 13 (10): 1961–90. https://doi.org/10.1023/B:BIOC.0000035876.39587.1a.

140. Sendzimir, J., C.P. Reij, and P. Magnuszewski. 2011. "Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger." *Ecology and Society* 16 (1). http://dx.doi.org/10.5751/ES-04198-160301.

141. Bayala, J., J. Sanou, H.R. Bazié, R. Coe, A. Kalinganire, and F.L. Sinclair. 2019. "Regenerated Trees in Farmers' Fields Increase Soil Carbon across the Sahel." *Agroforestry Systems*. https://doi.org/10.1007/s10457-019-00403-6.

142. Bayala, J., G.W. Sileshi, R. Coe, A. Kalinganire, Z. Tchoundjeu, F. Sinclair, et al. 2012. "Cereal Yield Response to Conservation Agriculture Practices in Drylands of West Africa: A Quantitative Synthesis." *Journal of Arid Environments* 78: 13–25. https://doi.org/10.1016/j.jaridenv.2011.10.011.

143. Coe et al. 2019. "Loading the Dice in Favour of the Farmer: Reducing the Risk of Adopting Agronomic Innovations."

144. Binam et al. 2015. "Effects of Farmer Managed Natural Regeneration on Livelihoods in Semi-Arid West Africa."

145. Baxter, J. 2018. "Challenging Gender Norms around Trees and Land Restoration in West Africa: Can Research Be Transformative?" Agroforestry World (blog). December 21, 2018. http://blog.worldagroforestry.org/index.php/2018/12/21/challenging-gender-

norms-around-trees-and-land-restoration-in-west-africa-can-research-be-transformative/.

146. Sendzimir et al. 2011. "Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger."

147. Tougiani, A., C. Guero, and T. Rinaudo. 2009. "Community Mobilisation for Improved Livelihoods through Tree Crop Management in Niger." *GeoJournal* 74 (December): 377–89. https://doi.org/10.1007/s10708-008-9228-7.

148. Dramé, Y.A., and F. Berti. 2008. "Les Enjeux Socio-Économiques Autour de l'agroforesterie Villageoise à Aguié (Niger)." *Tropicultura* 26 (3): 141–49.

149. Tougiani et al. 2009. "Community Mobilisation for Improved Livelihoods through Tree Crop Management in Niger."

150. Chomba, S., J. Kariuki, J.F. Friis Lund, and F. Sinclair. 2016. "Roots of Inequity: How the Implementation of REDD+ Reinforces Past Injustices." *Land Use Policy* 50: 202–13. https://doi.org/10.1016/j.landusepol.2015.09.021.

151. Robiglio, V., and M. Reyes. 2016. "Restoration through Formalization? Assessing the Potential of Peru's Agroforestry Concessions Scheme to Contribute to Restoration in Agricultural Frontiers in the Amazon Region." *World Development Perspectives* 3: 42–46. https://doi.org/doi.org/10.1016/j.wdp.2016.11.013.

152. WRI (World Resources Institute). 2016. "Initiative 20x20." World Resources Institute. 2016. https://www.wri.org/our-work/project/initiative-20x20.

153. Robiglio and Reyes. 2016. "Restoration through Formalization? Assessing the Potential of Peru's Agroforestry Concessions Scheme to Contribute to Restoration in Agricultural Frontiers in the Amazon Region."

154. IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2018. "Summary for Policymakers of the Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services." Bonn, Germany: IPBES Secretariat. http://www.db.zs-intern.de/uploads/1523006347-IBPESregionalsummaryEurope.pdf; Pe'er, G., L.V. Dicks, P. Visconti, R. Arlettaz, A. Báldi, T.G. Benton, et al. 2014. "EU Agricultural Reform Fails on Biodiversity." *Science* 344 (6188): 1090–92. https://doi.org/doi.org/10.1126/science.1253425;
Potts, S., K. Biesmeijer, R. Bommarco, T. Breeze, L. Carvalheiro, M. Franzén, et al. 2015. *Status and Trends of European Pollinators. Key Findings of the STEP Project.* Sofia, Bulgaria: Pensoft Publishers.

155. HLPE. 2019. "Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition.

156. OECD (Organisation for Economic Co-operation and Development). 2017. "Reforming Agricultural Subsidies to Support Biodiversity in Switzerland." *OECD Environment Policy Papers* No. 8. https://doi.org/10.1787/53c0e549-en.

157. Bellon, S., and G. Ollivier. 2018. "Institutionalizing Agroecology in France: Social Circulation Changes the Meaning of an Idea." *Sustainability* 10 (5): 1380. https://doi.org/10.3390/su10051380; Ajates Gonzalez, R., J. Thomas, and M. Chang. 2018. "Translating Agroecology into Policy: The Case of France and the United Kingdom." *Sustainability* 10 (8): 2930. https://doi.org/10.3390/su10082930.

158. Bellon and Ollivier. 2018. "Institutionalizing Agroecology in France: Social Circulation Changes the Meaning of an Idea"; Ajates Gonzalez et al. 2018. "Translating Agroecology into Policy: The Case of France and the United Kingdom."

159. Anderson, C.R., C. Maughan, and M.P. Pimbert. 2019. "Transformative Agroecology Learning in Europe: Building Consciousness, Skills and Collective Capacity for Food Sovereignty." *Agriculture and Human Values* 36 (3): 531–47. https://doi.org/10.1007/s10460-018-9894-0; Wezel, A., J. Goette, E. Lagneaux, G. Passuello, E. Reisman, C. Rodier, et al. 2018. "Agroecology in Europe: Research, Education, Collective Action Networks, and Alternative Food Systems." *Sustainability* 10 (4): 1214. https://doi.org/10.3390/su10041214.

160. Costanza, R., R. de Groot, L. Braat, I. Kubiszewski, L. Fioramonti, P. Sutton, et al. 2017. "Twenty Years of Ecosystem Services: How Far Have We Come and How Far Do We Still Need to Go?" *Ecosystem Services* 28: 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

161. Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, et al. 2019. "Food in the Anthropocene: The EAT–Lancet Commission on Healthy Diets from Sustainable Food Systems." *The Lancet* 393 (10170): 447–92. https://doi.org/10.1016/S0140-6736(18)31788-4.

162. Thaler, R.H., and C.R. Sunstein. 2009. Nudge: Improving Decisions about Health, Wealth, and Happiness. London: Penguin.

163. Si, T., and C. Weiping. 2018. "How to Build Consumers' Trust in Community Supported Agriculture: The Case of Four Seasons Share Organic Farm in Huizhou, Guangdong Province." *China Agricultural University Journal of Social Sciences Edition* 35 (4): 103–16.

164. Carolan, M. 2018. "Big Data and Food Retail: Nudging out Citizens by Creating Dependent Consumers." *Geoforum* 90: 142–50. https://doi.org/10.1016/j.geoforum.2018.02.006.

165. Chappell, M.J. 2018. Beginning to End Hunger. Berkeley, CA: University of California Press.

166. Sukhdev, P.,P. May, A. Müller, A. 2016. Fix food metrics. *Nature* 540 (7631): 33-34.

167. Shiming, L. 2018. "The Setting up of Institution for the Eco-Transition of Agriculture in China." *Democratic and Science* 173 (4): 15–17.

168. Olam International Limited. 2018. "Olam Living Landscapes Policy, April." https://www.olamgroup.com/content/dam/olamgroup/pdffiles/Olam-Living-Landscapes-Policy_English.pdf.

169. Mithöfer, D., V.E. Méndez, A. Bose, and P. Vaast. 2017. "Harnessing Local Strength for Sustainable Coffee Value Chains in India and Nicaragua: Reevaluating Certification to Global Sustainability Standards." *International Journal of Biodiversity Science, Ecosystem Services & Management* 13 (1): 471–96.

170. Lyngbæk, Anja E, Reinhold G Muschler, and F. L. Sinclair. 2001. "Productivity and Profitability of Multistrata Organic versus Conventional Coffee Farms in Costa Rica." *Agroforestry Systems* 53 (2): 205–13.

171. IFOAM (International Federation of Organic Agriculture Movements). 2018. "How Governments Can Recognize and Support Participatory Guarantee Systems (PGS)." IFOAM Policy Brief. IFOAM. https://www.ifoam.bio/sites/default/files/policybrief_how_governments_can_support_pgs.pdf.

172. Twomlow, S. 2014. "Social Fencing: A Community Barrier to Overgrazing and Degradation in Africa." IFAD social reporting blog. Social Fencing (blog). June 6, 2014. https://ifad-un.blogspot.com/2014/06/social-fencing-community-barrier-to.html.

173. Carlisle, L., and A. Miles. 2013. "Closing the Knowledge Gap: How the USDA Could Tap the Potential of Biologically Diversified Farming Systems." *Journal of Agriculture, Food Systems, and Community Development* 3 (4): 219–25.

174. FAO (Food and Agriculture Organization). 2018. "Transition towards Sustainable Food and Agriculture: An Analysis of FAO's 2018-2019 Work Plan."

175. Pimbert, M., and N. Moeller. 2018. "Absent Agroecology Aid: On UK Agricultural Development Assistance since 2010." *Sustainability* 10 (2): 505.

176. Wigboldus, S., L. Klerkx, C. Leeuwis, M. Schut, S. Muilerman, and H. Jochemsen. 2016. "Systemic Perspectives on Scaling Agricultural Innovations. A Review." *Agronomy for Sustainable Development* 36 (3): 46. https://doi.org/10.1007/s13593-016-0380-z.

177. Klerkx, L., N. Aarts, and C. Leeuwis. 2010. "Adaptive Management in Agricultural Innovation Systems: The Interactions between Innovation Networks and Their Environment." *Agricultural Systems* 103 (6): 390–400. https://doi.org/10.1016/j.agsy.2010.03.012.

178. Biggs, S. 2007. "Building on the Positive: An Actor Innovation Systems Approach to Finding and Promoting pro Poor Natural Resources Institutional and Technical Innovations." *International Journal of Agricultural Resources, Governance and Ecology* 6 (2): 144–64.

179. Coe, R., F. Sinclair, and E. Barrios. 2014. "Scaling up Agroforestry Requires Research 'in' Rather than 'for' Development." *Current Opinion in Environmental Sustainability,* Sustainability challenges, 6: 73–77. https://doi.org/10.1016/j.cosust.2013.10.013.

180. Sinclair and Coe. 2019. "The Options by Context Approach."

181. Smith Dumont et al. 2019. "Structured Stakeholder Engagement Leads to Development of More Diverse and Inclusive Agroforestry Options."

182. Cerdán, C.R., M.C. Rebolledo, G. Soto, B. Rapidel, and F.L. Sinclair. 2012. "Local Knowledge of Impacts of Tree Cover on Ecosystem Services in Smallholder Coffee Production Systems." *Agricultural Systems* 110: 119–30.

183. Walker, D.H., F.L. Sinclair, L. Joshi, and B. Ambrose. 1997. "Prospects for the Use of Corporate Knowledge Bases in the Generation, Management and Communication of Knowledge at a Frontline Agricultural Research Centre." *Agricultural Systems* 54 (3): 291–312.

184. Louppe, D., D. Depommier, M. Bizimana, F.L. Sinclair, A. Mukuralinda, and N.J. Damascene. 2018. "Rwanda Agroforestry Strategy and Action Plan 2018-2027." Rome: FAO.

185. EAFRD (European Agricultural Fund for Rural Development). 2013. Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on Support for Rural Development by the European Agricultural Fund for Rural Development (EAFRD) and Repealing Council Regulation (EC) No 1698/2005. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:347:0487:0548:en:PDF.

186. Pagella and Sinclair. 2014. "Development and Use of a Typology of Mapping Tools to Assess Their Fitness for Supporting Management of Ecosystem Service Provision."

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ABOUT THE AUTHORS' RESEARCH INSTITUTION

World Agroforestry (ICRAF) is a centre of science and development excellence that harnesses the benefits of trees for people and the environment. Leveraging the world's largest repository of agroforestry science we innovate to end hunger while protecting and restoring the environment. ICRAF does globally significant agroforestry research in and for all of the developing tropics. Knowledge produced by ICRAF enables governments, development agencies, and farmers to utilize the power of trees to make farming and livelihoods more environmentally, socially, and economically sustainable at scales from that of the farm to the whole planet. ICRAF and Bangor University partner in leading the Livelihood Systems Flagship of FTA that has agroecology as a research priority.

ABOUT THE GLOBAL COMMISSION ON ADAPTATION

The Global Commission on Adaptation seeks to accelerate adaptation action and support by elevating the political visibility of adaptation and focusing on concrete solutions. It is convened by 20 countries and guided by more than 30 Commissioners, and co-managed by the Global Center on Adaptation and World Resources Institute.