Agroforestry: Realising the promise of an agroecological approach

Prabhu, Ravi ; Barrios, Edmundo ; Bayala, Jules; Diby, Lucien ; Donovan, Jason ; Gyau, Amos; Graudal, Lars; Jamnadass, Ramni; Kahia, Jane ; Kehlenbeck, Katja ; Kindt, Roeland; Kouame, Christophe; McMullin, Stepha ; van Noordwijk, Meine; Shepherd, Keith ; Sinclair, Fergus; Vaast, Philippe; Vågen, Tor Gunnar ; Xu, Jianchu

Published in:
Agroecology for food security and nutrition

Publication date:
2015

Citation for published version (APA):
Prabhu, R., Barrios, E., Bayala, J., Diby, L., Donovan, J., Gyau, A., ... Xu, J. (2015). Agroforestry: Realising the promise of an agroecological approach. In *Agroecology for food security and nutrition: Proceedings of the FAO International Symposium* (pp. 201-224). Rome: Food and Agriculture Organization of the United Nations.

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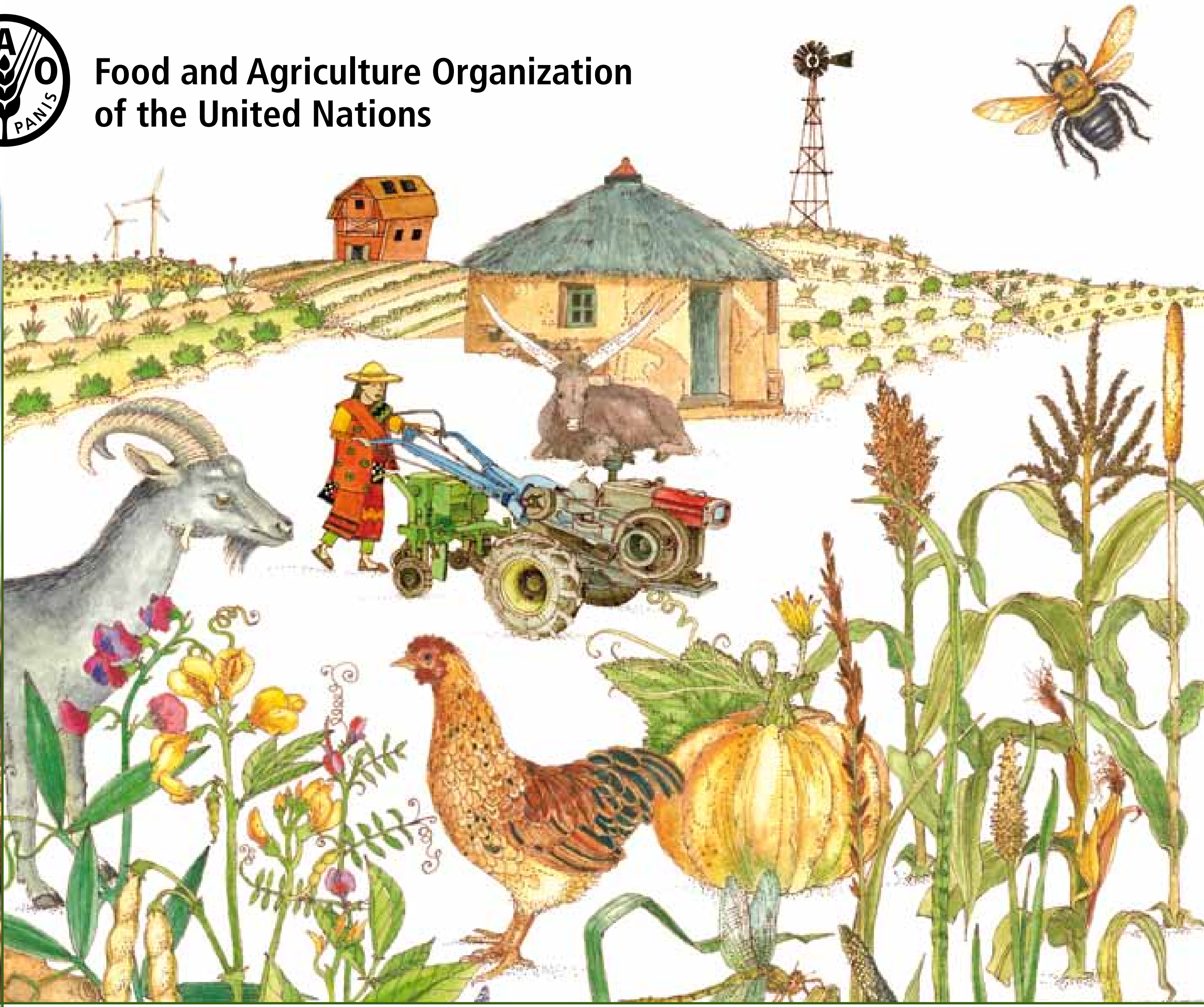
of the United Nations



AGROECOLOGY FOR FOOD SECURITY AND NUTRITION

PROCEEDINGS OF THE FAO INTERNATIONAL SYMPOSIUM

18-19 September 2014, Rome, Italy

BIODIVERSITY & ECOSYSTEM SERVICES IN AGRICULTURAL PRODUCTION SYSTEMS

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ISBN 978-92-5-108807-4
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Back cover reference:
* Gliessman, S.R. 2007. *Agroecology: the Ecology of Sustainable Food Systems*. 2nd Edition. Boca Raton, FL, USA, CRC Press, Taylor & Francis Group.

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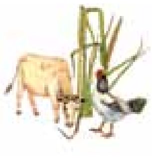

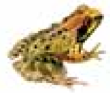

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AGROFORESTRY:
REALIZING THE PROMISE OF AN AGROECOLOGICAL APPROACH

Ravi Prabhu[1], Edmundo Barrios, Jules Bayala, Lucien Diby, Jason Donovan, Amos Gyau, Lars Graudal, Ramni Jamnadass, Jane Kahia, Katja Kehlenbeck, Roeland Kindt, Christophe Kouame, Stepha McMullin, Meine van Noordwijk, Keith Shepherd, Fergus Sinclair, Philippe Vaast, Tor Gunnar Vågen, Jianchu Xu

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Abstract

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

INTRODUCTION

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

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

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

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

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

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

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

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

FOUNDATIONS FOR OPTIMISM

Diversity as a resource and as an essential outcome

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

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

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

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

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

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

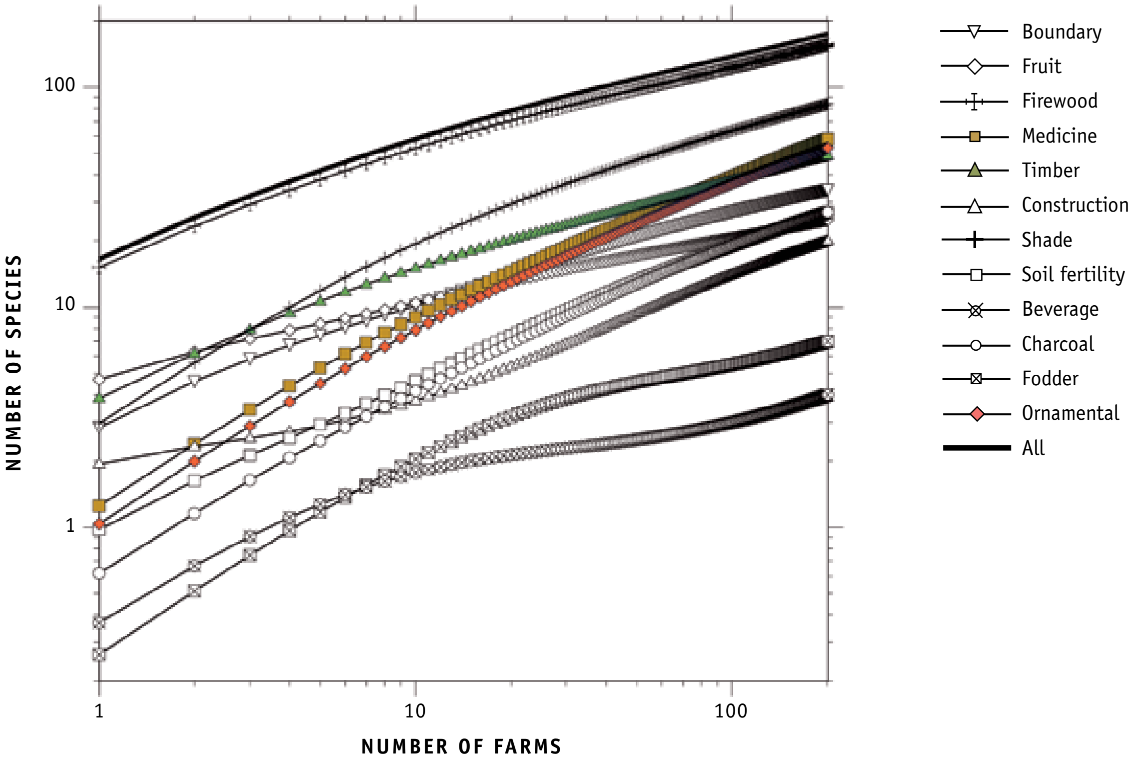
Regions are classified according to www.wikipedia.org/wiki/List_of_sovereign_states_and_dependent_territories_by_continent for Africa, Oceania and South America, and www.nationsonline.org/oneworld/asia.htm for Central Asia, Southeast Asia, and Western Asia and the Middle East. The greater number of total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

Source: Dawson *et al.*, 2014b

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

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

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



Source: Kindt *et al.*, 2006a

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

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

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

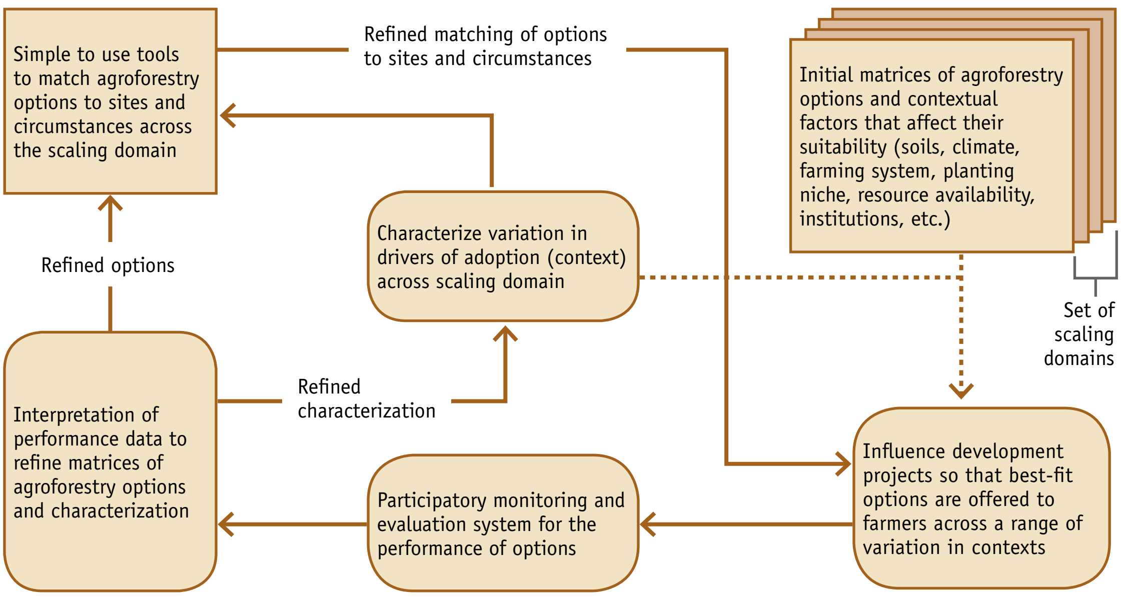
From an ecological standpoint, different tree species grow spontaneously in different places and segregation around these ecologies to promote tree-based systems may appear to be appealing. For instance, characterizations of the Sahelian 'parkland' systems (and to some extent agroforestry systems) have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

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

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

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

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



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

Economic benefits of agroforestry

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

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

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

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

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

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

Land health is a key outcome

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

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

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

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

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

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

CASE STUDIES

Food trees for improved nutrition in smallholder agricultural systems

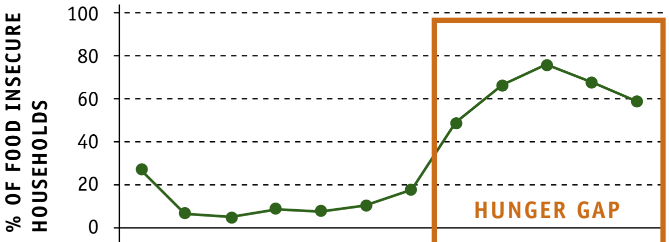
In 2010, about 104 million children under the age of five were underweight and 171 million were stunted worldwide (i.e. they show low height for their age because of chronic undernutrition), particularly in sub-Saharan Africa and Southern Asia (WHO, 2015). One of the reasons for high stunting rates is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

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

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

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

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



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

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

Revitalising cocoa systems in Côte d'Ivoire

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

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

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

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

Agroforestry and shade trees as adaptation mechanisms in coffee systems

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

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

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

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

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

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

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

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

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

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

CONCLUSIONS

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

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

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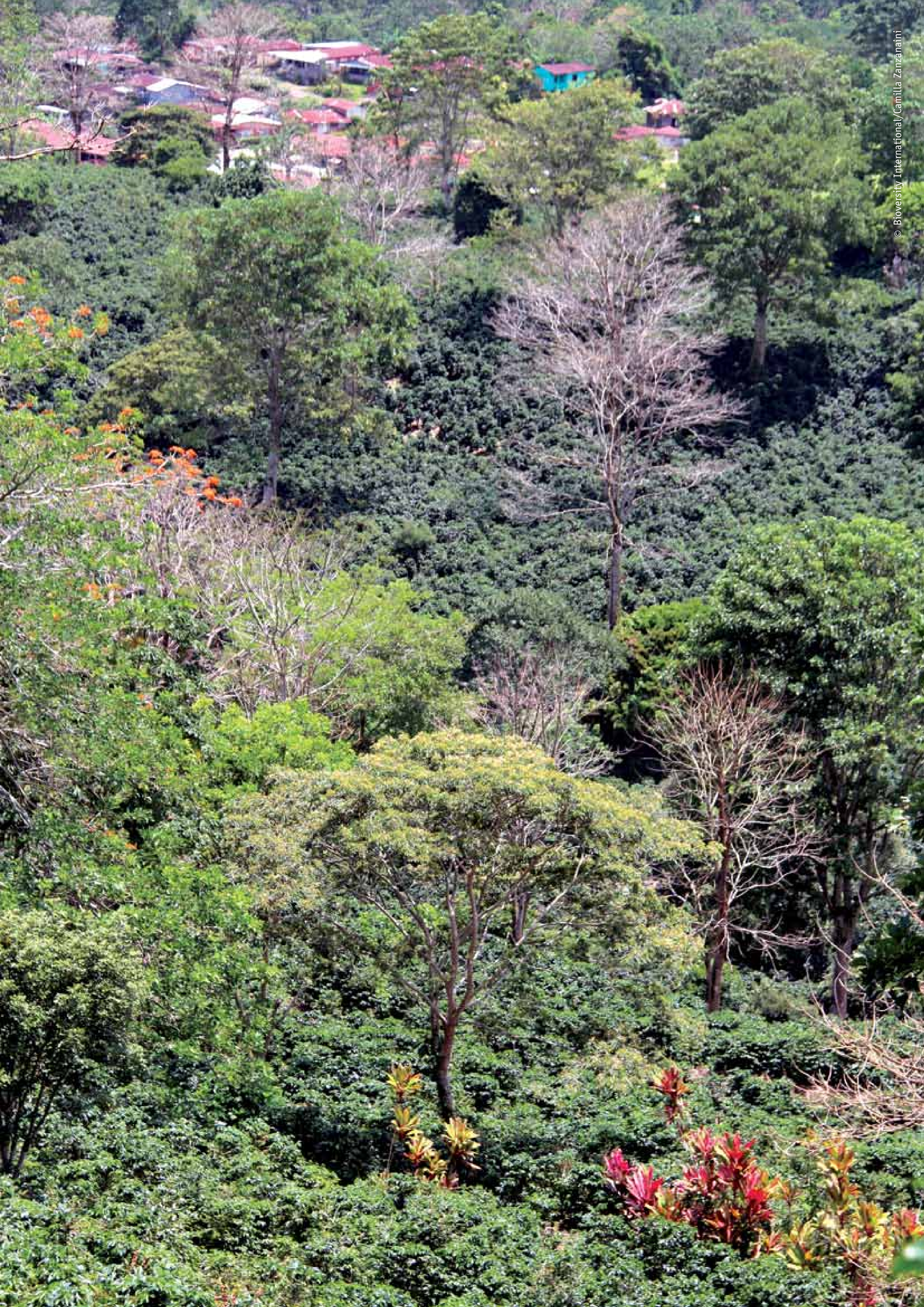

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AGROECOLOGY is the science of applying ecological concepts and principles to the design and management of sustainable food systems.* It focuses on the interactions between plants, animals, humans and the environment. Agroecological practices work in harmony with these interactions, applying innovative solutions that harness and conserve biodiversity. Agroecology is practised in all corners of the world, with the traditional and local knowledge of family farmers at its core. Through an integrative approach, agroecology is a realm where science, practice and social movements converge to seek a transition to sustainable food systems, built upon the foundations of equity, participation and justice.

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ISBN 978-92-5-108807-4

9 789251 088074

I4729E/1/06.15