Agroforestry: Essential for Sustainable and Climate-Smart Land Use?

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Contents

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Abstract

Over the past four decades, a solid body of research has revealed the potential of agroforestry for increasing or maintaining system productivity while protecting natural resources and providing environmental services, including pollination, pest control/prevention, carbon sequestration, and the conservation of soil health, water quality, and biodiversity. Thus, agroforestry is well suited as a central tool for "sustainable intensification" within a land use paradigm that should be based, in alignment with a recent call by FAO, much more on biology and agroecology, rather than on chemistry and fossil fuels. With success stories from around the world and new methodological tools for valuing also environmental services, we can now apply these tools to design practices and systems that match the outputs of sustainable crop, tree, and animal agroforestry systems to the local needs. To custom-tailor the systems to the respective environmental and socioeconomic conditions, and rise to the challenge of sustainably producing more food that is less contaminated and less contaminating, we should advance in the following directions: (i) expand the species characterizations, (ii) widen the scope of plants and animals used and include "neglected and underutilized species" (NUS), (iii) intensify work on "using" beneficial soil organisms for soil and plant health, (iv) optimize the system design and management to maximize resource use efficiency and minimize pest incidence,

(v) create climate-smart and pest-suppressive landscapes, and, finally, (vi) advance toward more holistic socioeconomic assessments including an improved valuation of environmental services. A call is made to apply also relevant experiences from other fields such as biointensive or organic production, urban agriculture, and permaculture.

Keywords
Adaptation • Agrobiodiversity • Agroecology • Agroforestry • Alley cropping • Animal husbandry • Biochar • Biodiversity conservation • Biological control • Biointensive agriculture • Bird-friendly coffee • Cacao • Carbon sequestration • Climate-smart landscape • Certification • Coffee • Design • Diversification • Ecosystem service • Environmental service • Food security • Homegarden • Improved fallow • Living fences • Microclimate management • Mitigation • Modeling • Monocultures • Multifunctional agriculture • Multipurpose trees • Mycorrhizae • Neglected and underutilized crops (NUS) • N-fixation • Nutrition • Nutrient cycling • Organic production • PES (payment for environmental services) • Pest suppressiveness • Plantation crops • Polycultures • Rehabilitation • Shade management • Shelterbelt • Silvopastoral system • Soil conservation • Soil degradation • Soil fertility • Soil health • Sustainability • Sustainable intensification • Symbiosis • Taungya • Training materials • Tree domestication • Urban agriculture • Windbreaks

Setting the Stage for Agroforestry: Lessons from Monocultures

Since the dawn of agriculture, humans have used trees in combination with crops and livestock. Most early land use systems evolved under trees or in savannas, with more or less drastic modification of the tree component. With the evolution of agriculture and forestry as professional sciences since the 1800s, the production of crops and trees became increasingly separated, driven by the observation that their individual productivity could be maximized for most crops, at least in the short term, by excluding any other competing or harmful organism. As a consequence, monocultures of crops or trees began to expand and, ultimately, rise to predominance in many environments. Driven by the development of specialized machinery for planting and harvesting, plus the increasing use of agrochemicals to improve plant growth, this tendency accelerated greatly since the 1940s. For some time, impressive productivity gains often multiplied former yields, fueling the massive expansion of monocultures of corn, wheat, and soy in the vast plains of North America, substituting deep-rooted grasslands and forests. Elsewhere, particularly pronounced in Latin America, the Caribbean, and Asia, expanding monocultures of bananas, coffee, sugarcane, rubber, oil palm, rice, and soy began to engulf formerly biodiverse biomes (Kimbrell 2002).

However, after only a few decades, first cracks started to appear in the "get big or get out" paradigm of ever larger monocultures able to provide apparently unlimited productivity gains. One of the earliest indicators was that soil erosion by water and

Fig. 1 Soil degradation as a global problem of the past and present. *Top*: a dust storm in Texas in 1935 and the result of the "Dust Bowl" in South Dakota, USA, in 1936. The elimination of vegetation, particularly perennial grasses, but also trees and shrubs, and years of extreme drought have left the soil unprotected and vulnerable to wind erosion. *Bottom*: plowing and lack of protection disposes volcanic soils for vegetable production in Costa Rica to massive soil erosion even in the present. The long-term result can be seen as degraded slopes stripped of all fertile topsoil in Haiti (Photo credits: *top*, Wikimedia Commons; *bottom*, R. Muschler)

wind became ever more prevalent, illustrated in its extreme by the US "Dust Bowl" in the 1930s (Fig. 1) followed by similar events. The response gave rise to the establishment of the US Soil Conservation Service and its homologues in many other countries. As an immediate measure in the USA, shelterbelts and windbreaks were established to curb the effects of wind and protect the soil. This was an early widespread application of agroforestry. Lesson learnt: unprotected soil can neither be stable nor productive in the long run. Up to 10 cm and more of unprotected soil can be lost in just a single year (Montgomery 2012). And losses of more than 1 cm per year, a multiple of the rates of soil formation, are common in many regions around the world today (Amundson et al. 2015), including carelessly plowed fertile volcanic lands in Costa Rica or poor calcareous soils in Haiti (Fig. 1, bottom). Unfortunately, replicas of these examples are almost ubiquitous in many topographically similar situations around the tropics.

Some years later, on the chemical front, Rachel Carson's *Silent Spring* provided 1962 an eye-opening account of the negative and long-term impact of depending on agrochemicals for pest and disease control. Although these products had been hailed as the solution to almost all problems of plant nutrition and protection, the painful lessons about the bioaccumulation and long-term toxicity of persistent pesticides, plus their inevitable side effects like groundwater contamination and the loss of beneficial organisms such as insects, birds, or symbiotic soil microbes (Bardgett and van der Putten 2014; Stamets 2005; Kimbrell 2002), have shown that an overly dependence on agrochemicals and fossil-fuel-driven machinery is a dead-end road (IASS 2015). Recent information about their effects on human health raise concerns only more (Leu 2014; Samsel and Seneff 2013).

Clearly, even though this approach has been effective in some cases (ignoring its externalities) and for a short time, it cannot be sustained in the long run in the face of increasing prices of the external inputs and mounting evidence of their massive side effects on natural resources and human health (Colburn et al. 1997; Conway and Pretty 1991). The accelerating loss of biodiversity; the drastic decline of bee populations (Pilatic 2012); the contamination with fertilizers and pesticides of most water bodies, including the Gulf of Mexico and the great lakes of the USA; and the groundwater in so many regions of Europe, Asia, and Latin America provide ample evidence of this (IASS 2015; Kimbrell 2002). Obviously, the business-as-usual model cannot be sustained.

Learning from past mistakes, acceptance is growing that the only truly sustainable long-term options depend on using an effective agroecological design for linking productive units embedded in a biodiverse and functional landscape (FAO 2013; Trumper et al. 2009). The judicious distribution and integration of appropriately sized patches of agricultural, agroforestry, and forestry systems allows maximizing agroecological benefits, both in terms of products and services (Fig. 2). The functional outputs of such a system include (1) the mutual stimulation of growth rates of compatible components, (2) the prevention and control of pests and diseases, (3) the protection and enrichment of soils, (4) the maintenance of water flow and quality, and (5) the support of (functional) biodiversity to provide essential products and services including pollination, biological pest control, and adaptation/mitigation to climate change (Nicholls et al. 2013).

Figure 2 illustrates how the spatial dimensions and distribution of agricultural, agroforestry, and forestry systems modify a landscape and, therefore, determine, to a large extent, the products and environmental services that can be provided. A treeless barren landscape cannot protect the soil or water resources. Beyond these geometric factors, obviously, also the density and arrangement of trees and crops; their characteristics, as well as their temporal sequence; and the interactions among all components contribute to mold the overall benefits that can be derived from such a landscape. Reversely, if the goal is rehabilitation of a degraded landscape like in Fig. 1, it is imperative to include a substantial number of trees. Ideally, the local site conditions will define the species and their best arrangements and management. In all cases, agroforestry, with its multiple products and services, is at the heart of sustainable landscape design (Nicholls et al. 2013; Trumper et al. 2009; Muschler and Bonnemann 1997). This chapter presents the potential of agroforestry as an essential component of truly sustainable climate-smart land use.

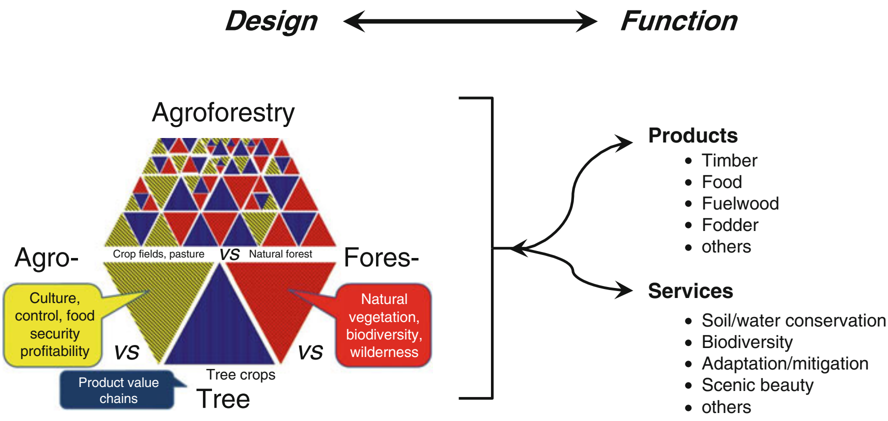

Fig. 2 Multifunctionality of agroforestry. Agroforestry allows combining agricultural and forestry production on the same plot of land. Furthermore, it serves as a biological corridor to link agricultural and forest lands in the landscape. As indicated by the *two-directional arrow* on *top*, there is a two-way relationship between the "design" of the landscape mosaic and its "functions" in the form of products and services. While a given landscape design determines largely the functions that can be met, the opposite also holds true: the definition of expected functions determines largely the most appropriate design (Source: the mosaic graph is from van Nordwijk 2014)

Agroforestry: Evolution, Definition, Practices, and Systems

Evolution of Agroforestry

Although its practice dates back to the beginning of human land use, agroforestry, the purposeful combination of trees with crops and/or animals, emerged only in the 1970s as a professional field of its own. This new discipline emerged when it was realized that it held great potential for combining production with protection purposes. The official start for the evolution of agroforestry as a stand-alone discipline is commonly cited with the establishment in 1977 of the "International Council for Research in Agroforestry" (ICRAF), headquartered in Nairobi, as the global lead institution under the umbrella of the "Consultative Group for International Agricultural Research" (CGIAR). Interestingly, in Latin America, the beginning was marked at the same time by a series of German-funded projects at the Center for Research and Higher Education in Tropical Agriculture (CATIE), a spin-off institution of the "Inter-American Institute for Cooperation on Agriculture" (IICA), headquartered in Costa Rica. With German core funding from 1976 to 2003 for the study of Central American silvopastoral systems with cows, goats, and, later, agroforestry systems with cacao and coffee, CATIE converted itself into the pioneer institution that led the way of agroforestry development in Latin America (CATIE 2001, 1999; Beer 2000; Beer et al. 1987). In Africa and Asia, ICRAF has led the way. Today, ICRAF (now under the name "World Agroforestry Centre"), with its global mandate, has a regional office at CATIE, and there is increasing cooperation between these two lead organizations.

The initial geographic focus for the evolution of agroforestry was on the tropics, since the issues to be addressed there are particularly urgent. After the first two decades dedicated largely to definitions, descriptions, and characterizations of the different types of agroforestry (Nair 1993; MacDicken and Vergara 1990; Steppler and Nair 1987), the 1990s saw an increasing interest in studying functional aspects to improve the systems' productivity (tree-crop interactions, tree selection, pruning regimes, shade management, input substitution, etc.; see Huxley 1999; Rao et al. 1998; Ong and Huxley 1996) and to explore the potential of agroforestry for addressing the increasingly more urgent issues linked to natural resource degradation and contamination, biodiversity loss, and the deterioration of family farms. Today, the solid research about the production and protection functions of agroforestry[1] has established this field as a central pillar for truly sustainable land use systems, that is, systems, which can be sustained indefinitely. The outburst of scientific publications over the past 40 years on the many ecological, economic, and social benefits that agroforestry can provide in many environments around the world provide a solid justification for the well-chosen title of a recent global review "Agroforestry – the Future of Global Land Use" (Nair and Garrity 2012). In the USA, in recognition of the potential of agroforestry for enhancing agricultural landscapes, watersheds, and rural communities, the USDA released in 2011 its "Agroforestry Strategic Framework." While agroforestry is not a magic bullet for solving all problems, it clearly provides many of the central tenets for developing productive and climate-smart agricultural systems which, at the same time, can provide essential environmental services for maintaining a healthy and sustainable landscape (FAO 2013). This takes us to the definition of agroforestry.

Definition and Classification: What Is Agroforestry?

One of the shorter yet most comprehensive definitions of agroforestry states that it is "the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits" (USDA). As such, it encompasses a wealth of different land use systems at the interface of agricultural, livestock, and forestry systems. A widely accepted structural classification of agroforestry systems is based on the type of components present in a system (Fig. 3; Nair 1993). According to this classification, there are four main groups that combine trees or woody shrubs with:

- Annual or perennial crops (agrisilvicultural systems)
- Pastures and grazing animals (silvopastoral systems)

[1]For the roles of agroforestry for biodiversity conservation, see Schroth et al. (2004), and for the provision of ecosystem services, see Rapidel et al. (2011).

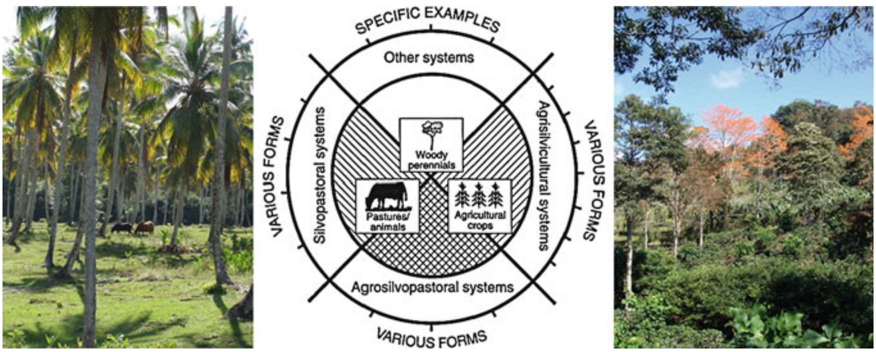

Fig. 3 Classification of agroforestry systems based on the type of components. The three main groups combine trees or woody shrubs, as the essential perennial component, either with (i) pastures and animals (silvopastoral systems; *left* photo, an example from the Dominican Republic), (ii) with annual or perennial crops (agrisilvicultural systems; *right*, coffee with timber and service trees), or (iii) all three (agrosilvopastoral systems). The forth segment ("other systems") collects other systems such as combinations of fish or shrimp farming or bee keeping with trees or shrubs providing habitat or fodder. For details see text (Graph from Nair 1993; Photo credits: R. Muschler)

- Crops and animals (agrosilvopastoral systems)
- Non-pastoral animal species ("other systems") such as combinations of fish, shrimp, or bees with trees or shrubs providing habitat or fodder

Besides this structural classification according to components and their products, other classifications are based on:

- The **tree cover in agricultural lands** with a minimum of 10 % for some systems and higher values for others (Zomer et al. 2014)
- The intended **functions or roles of the systems**, e.g., for soil protection, fodder production, or for providing microclimatic benefits as is the case of windbreaks
- **Socioeconomic aspects** such as the intensity of management, the type and level of inputs, or whether the production is for commercial or subsistence purposes
- **Biogeographic conditions** for which the systems are selected. For example, while a particular mix, arrangement, and management of species may be appropriate for dryland systems, these attributes would likely not be appropriate or sufficient for systems in the humid tropics. Similarly, the species mix and arrangement will differ depending on the desired products and biophysical attributes such as rainfall distribution and intensity, temperatures, topography, soil fertility, windiness, and even native pest and disease organisms. Details on these other classification systems can be found in Nair (1993) and in MacDicken and Vergara (1990). The latter authors have assembled the central aspects of agroforestry practices and systems in most of the major agroecological zones of the world, including the humid tropics, the semiarid tropics, tropical highlands, and temperate zones.

Agroforestry Practices and Systems

According to Nair (1993), an agroforestry "practice" refers to a "distinctive arrangement of components in space and time," while an agroforestry "system" is a specific local example of a practice. As such, a system is characterized by the site-specific selection of plant species, their arrangement, management, and socioeconomic performance. While there are only some 20 practices that can be found even in widely different settings around the world (see section "Principal Agroforestry Practices"), there is a multiple of site-specific systems. Table 1 summarizes the major agroforestry practices and their main characteristics. For detailed information about the diversity of agroforestry systems, the reader is referred to the agroforestry system inventory spearheaded by the World Agroforestry Centre (ICRAF) headquartered in Kenya. Its first comprehensive inventory was edited by Nair (1993), which still serves as a basic reference. This work has since then been complemented by ICRAF and agroforesters around the world, much of it published in "Agroforestry Systems," the principal scientific journal in the field. Further aspects on the definitions of agroforestry practices have been provided by Sinclair (1999). The following sections provide a brief characterization of the principal agroforestry practices.

Principal Agroforestry Practices

The combination of trees, crops, and animals predates the evolution of monocrop forestry or agriculture, which focuses largely on producing just a single or a few primary commodities. Until the Middle Ages, it was common even in Europe, as it still is in many parts of the world today, to thin or clear-cut forest patches, burn the slash, and, then, plant selected food crops and trees. As a result, more or less stable long-term arrangements of crops, trees, and, often, animals such as sheep, pigs, cattle, or fowl evolved with different emphases according to the local sociocultural context and markets. A particular arrangement of components, independent of the specific choice of locally adapted species, can be described under the term "agroforestry practice" (Nair 1993). Despite the evolution of monocultures of trees or crops as the ultimate simplification for ease of management and harvest, a trend that started in industrialized Europe and North America, followed by relatively sparsely populated developing countries with vast areas (e.g., Brazil, Argentina, Paraguay), a wealth of diverse and more complex systems have persisted in many places of the tropics (see section "Distribution of Agroforestry Systems").

The following sections characterize the most important and distinctive agroforestry practices. Due to the limitations of the present document, the list is not exhaustive and the accounts are as short and succinct as possible. For more details, the reader is referred to Nair (1993) and MacDicken and Vergara (1990) and to the journal "Agroforestry Systems." Following the arguments of Leakey (1996) to view agroforestry practices as different stages along the continuum of succession, the listing starts with practices that correspond to "early-stage" (i.e., systems with

Table 1 Major agroforestry practices and their main characteristics (Modified from Nair 1993)

Agroforestry practice	Description/ arrangement of components	Major components (T = tree; C = crop; A = animal)	Agroecological adaptability
Agrisilvicultural systems combining trees with crops (including shrubs and vines)			
1. Improved fallow	Woody species are purposely planted and left to grow during the "fallow phase"	T: fast-growing preferably leguminous C: common agricultural crops	In shifting cultivation areas
2. Taungya	Temporary association of agricultural crops with young tree plantations (usually until tree canopy closes)	T: spp. for plantation forestry C: common agricultural crops, preferably some shade tolerance	No restrictions
3. Alley cropping (hedgerow intercropping)	Agricultural spp. are grown in the alleys between hedges of woody spp; microzonal or strip arrangement	T: fast-growing, leguminous, vigorous regrowth/ coppicing C: common agricultural crops	Subhumid to humid areas with high human population pressure and fragile (productive but easily degradable) soils
4. Multipurpose trees on crop lands	Trees maintained with or without a systematic pattern on bunds, terraces, or plot/field boundaries	T: multipurpose and fruit trees C: common agricultural crops	All ecozones, esp. in subsistence farming; often with animals
5. Plantation crop combinations	(i) Integrated multistory (mixed, dense) mixtures of plantation crops (ii) Mixtures of plantation crops in alternate or other regular arrangement (iii) Shade trees over plantation crops (iv) Intercropping with agricultural crops	T: timber, fruit, and multipurpose service trees; plantation crops like coffee, cacao, coconut, rubber, black pepper, etc. C: usually shade-tolerant spp., more preponderant in (iv) and (i)	Humid lowlands or humid/subhumid highlands; often smallholder subsistence system
6. Homegardens	Intimate, multistory combination of many tree and crop species around homesteads	T: often dominated by fruit trees, woody vines C: shade-tolerant vegetables and medicinal plants	All zones, particularly in areas of high population density
	Trees on bunds, terraces, and raisers,	T: multipurpose and/or fruit trees,	Sloping lands, reclamation of

(*continued*)

Table 1 (continued)

Agroforestry practice	Description/ arrangement of components	Major components (T = tree; C = crop; A = animal)	Agroecological adaptability
7. Trees for soil conservation and reclamation	sometimes with grass strips: trees on degraded or marginal lands and wastelands	often leguminous and pioneer species	degraded, acid, alkali soils, and sand-dune stabilization
		C: deep-rooted perennial crops and grasses	
8. Windbreaks and shelterbelts, living fences or hedges between fields	Trees and shrubs around farmland and plots	T: combination of tall, erect, and short dense species; wind tolerant	Wind-prone areas
		C: common agricultural crops	
9. Fuelwood production	Interplanting firewood species on or around agricultural lands	T: firewood species	All ecozones
		C: common agricultural crops	
10. Multilayer tree gardens and Forest farming	Multispecies, multilayer dense plant associations with no organized planting arrangement	T: woody components of varying form and growth habits	Areas with fertile soils, labor availability, and high human pressure
		C: sometimes shade-tolerant spp.	
11. Forest farming	Production of shade-adapted crops under tree overstory	T: typically species of commercial interest	Various
		C: shade-tolerant spp. such as ginseng or mushrooms	
Silvopastoral systems (trees + pasture and animals)			
12. Trees on rangeland or pastures	Trees scattered or in systematic arrangement on rangeland and pastures	T: multipurpose, preferably legume or high fodder value; occasionally high-value timber	Extensive grazing areas
		C: improved pasture species	
		A: grazing and browsing animals	
13. Fodder/protein banks	Production of protein-rich tree fodder on farm and rangelands for cut-and-carry fodder production	T: leguminous fodder trees/shrubs	No limitations; particularly on steep lands
		C: improved fodder species and/or legumes	
		A: stabulated	

(*continued*)

Table 1 (continued)

Agroforestry practice	Description/ arrangement of components	Major components (T = tree; C = crop; A = animal)	Agroecological adaptability
14. Plantation crops with pastures and animals	Example: cattle under coconuts in Asia or the Caribbean	T: plantation crops C: preferably improved fodder spp. A: grazing animals	Areas with relatively low population pressure
Agrosilvopastoral (and other) systems (trees + crops + pasture and animals)			
15. Homegardens with animal production	Intimate, multistory combination of many tree and crop species, plus animals around homesteads	T: often dominated by fruit trees, woody vines C: shade-tolerant vegetables and medicinal plants A: minor species, specialty markets	All zones, particularly in areas of high population density
16. Multipurpose woody hedgerows and riparian buffers	Woody hedges for browsing and provision of mulch, green manure, soil conservation, etc.	T: fast-growing and coppicing fodder shrubs and trees C: agricultural crops A: grazing and browsing animals	Humid to subhumid areas with hilly and sloping terrain
17. Apiculture with trees on farmlands	Melliferous trees and bees on farmlands	T: melliferous tree species of complementary phenology C: bee-pollinated crops, e.g., cucurbits A: bees	Various regions, particularly semiarid to subhumid rangelands remote from conventional agriculture
18. Aqua-agroforestry	Trees lining fishponds (leaves and fruits serve as fish fodder). Example: chinampa system in Mexico	T: trees and shrubs producing leaves and fruits for fish A: fish, shrimps, etc.	Various
19. Multipurpose woodlots	Mix of species for various uses (fuelwood, fodder, soil protection, etc.)	T: multipurpose, leguminous, timber, fruit, etc. C: shade-tolerant crops A: various	Various

young and relatively small or sparse woody components) and evolves toward practices of “late-stage” agroforestry succession with dominant and permanent woody components. For information on appropriate species, please see section “Plant Selection for Agroforestry” on plant selection for agroforestry.

Improved Fallows

The traditional use of the word "fallow" refers to a temporal sequence of crop or tree species on a given piece of land. In shifting cultivation, after a period of agricultural use of several crop cycles until soil fertility has declined or weeds, pests, and diseases have built up to a point of unacceptably low yields, the land is left "fallow" for an extended period of time. During this time, usually several years, the successional vegetation of noncultivated crops and trees rebuilds the ecological webs and the stocks of organic matter and nutrients in the soil, reconstructing, at least partly, the former soil fertility which allows for another few cycles of crop production.

The term "improved" fallow refers to a system in which the fallow vegetation includes crop or tree species that have been selected and planted, or favored, by man in order to speed up the desired soil fertility recuperation (Buresh and Cooper 1999), a requirement due to the ever-increasing human population pressure on the limited land resources. Often, the "improvement" may also include management interventions such as the inoculation with microbial symbionts such as N-fixers or mycorrhizae in order to favor the plant establishment and growth (Stamets 2005). Depending on the degree of this human-lead biological intensification, the ultimate result is the transformation of a shifting cultivation system to one of permanent cultivation.

Besides the ecological benefits mentioned, the selection criteria of the most appropriate plant species for improved fallows may also consider economic benefits derived from using products generated during the fallow period. These include tree products such as poles or firewood, medicinal plants, and even beans and other edible or useful products from annual plants established for soil improvement. Examples of improved fallow system include the enrichment planting of rattan by the Luangan Dayak people of Borneo, *Casuarina* species in Papua New Guinea, gum arabic in the Sahel (von Maydell 1986), or multipurpose fallow woodlots in the Philippines. From different parts of the world, examples of tree and crop species, many of which are N-fixers, include *Acioa barteri*, *Anthonotha macrophylla*, *Alchornea cordifolia*, *Gliricidia sepium*, *Leucaena leucocephala*, as well as annual or perennial climbers or scramblers in the genera of *Mucuna*, *Pachyrrhizus*, and others (Fig. 4). Together with taungya systems and alley cropping, improved fallows correspond to early successional stages in which the plant components are relatively young and have restricted dimensions of root and shoot systems. Details on these systems from Latin America were given by Kass and Somarriba (1999) and worldwide reviews were published by Buresh and Cooper (1999) and by Thurston (1997).

Alley Cropping

Alley cropping, often also known as "hedgerow intercropping," refers to the practice of growing crops between hedgerows of planted shrubs or trees, preferably

Fig. 4 *Left*: improved fallow in Talamanca, Costa Rica, with the leguminous yam bean (*Pachyrhizus erosus*) for soil enrichment with N and occasional volunteer plants of sesame and manioc. *Right*: intercropping system of manioc with perennial pigeon pea (*Cajanus cajan*) for soil improvement and bean production (Photo credits: R. Muschler; photos taken at "Finca Loroco," Bribri, Costa Rica).

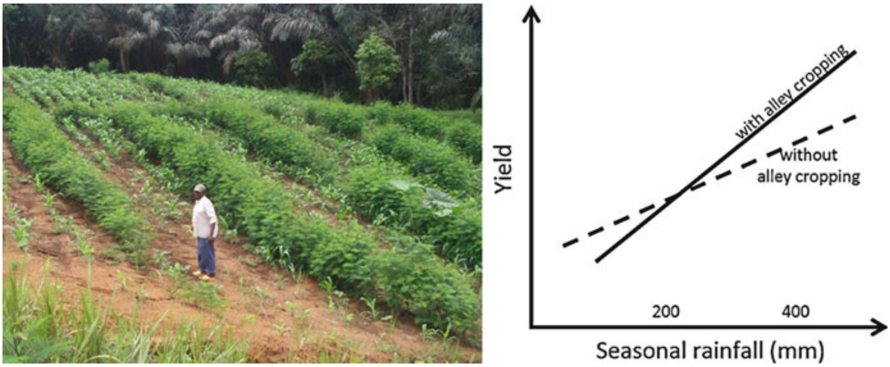

Fig. 5 *Left*: typical alley cropping system with hedges of leguminous trees or shrubs that are pruned to provide biomass to the crops grown in the alleys. This example from Cameroon shows maize growing between hedges of *Leucaena leucocephala*. *Right*: alley cropping is more successful in subhumid and humid environments. In arid and subarid environments with less than 200–300 mm rain, water competition by the trees reduces crop yields (Photo credit: pixgood.com; Graph redrawn from Nair 1993)

leguminous species to provide biologically fixed N to the cropping alleys (Kang et al. 1989; Kang and Wilson 1987; Fig. 5). According to Nair (2012), alley cropping may be practiced on up to 100 Mio ha globally. To reduce shading and root competition for the associated crops, while at the same time providing nutrients and soil protection to the alleys, the hedges are periodically pruned and the biomass is spread onto the alleys. Typically, the pruning period ranges from 2 to 6 months, depending on the intensity of pruning and the speed of growth of the hedges. Partial pruning allows for more frequent harvesting than pollarding, i.e., the pruning of all branches at the same time. In order to synchronize the availability of the nutrients as they are being released during decomposition with the demand of the developing crop, it is essential to choose the right time of pruning, considering the speed of growth of the hedges and of the nutrient demands of the crops (Crews and Peoples 2005). For example, for growing maize, the pruned biomass should not release most of its nutrients until the time of maximum demand of the maize plants after 2–8 weeks of growth (Witt et al. 2009; Cadisch and Giller 1997).

Alley cropping is one of the most widely researched agroforestry practices, largely due to (i) the linear arrangement of woody and annual components, (ii) the same age and size of the individual crop plants or trees, and (iii) the relatively small number of species involved. Having only two (one crop + one tree) species for the simplest system (like in Fig. 5), up to a handful of species in others, the "tree-crop interface," i.e., the region where crops and trees interact, is relatively easy to define and study. In this setting, research on above- and below-ground interactions becomes much more tractable than in systems with complex and irregular distribution patterns of a multitude of different-sized and different-aged plants, as is the case with species-rich systems such as homegardens.

Where does alley cropping work best? In many parts of humid and subhumid Africa, where water limitations are not extremely strong, trials have shown a positive effect of the tree component on soil fertility and nutrient supply for the crops. For example, in an 8-year alley cropping trial on sandy soils in southern Nigeria, maize yield could be raised from 0.66 t/ha in control treatments to 2 t when *Leucaena* prunings were applied and even to over 3 t/ha, when an additional 80 kg N/ha was applied as supplement (Kang et al. 1989). Similar results were obtained from many other humid or subhumid areas in the tropics. For example, Kang and Duguma (1985) demonstrated that maize yields in 4 m wide alleys of *Leucaena* were the same as when 40 kg/ha of N were applied to the crop. In Malawi, after 11 years of intercropping *Gliricidia sepium* with maize, Makumba et al. (2006) concluded that the 4–5 Mg DM ha^{-1} of *Gliricidia* prunings, when applied to the crop, increased maize yield threefold (3.9 Mg ha^{-1}) over sole maize cropping (1.1 Mg ha^{-1}). A fertilizer complement of 46 kg N ha^{-1} increased maize yield by another 29 %. These results show that a significant portion of crop nutrient demand can be met by adding pruning residues of the mostly leguminous hedges (Kang et al. 1990). Often, a combination of biomass from the hedges and a fertilizer supplement produces the best results. Of course, the effects vary greatly with the site conditions, particularly soil fertility and water availability (Witt et al. 2009), as well as with the plant species used and the pruning regime applied. Besides the species attributes, these factors determine largely the quality of mulch in terms of its rate of decomposition and its nutrient content (Cadisch and Giller 1997; Budelman 1988, 1989).

However, while these results are encouraging, the effects of alley cropping are not universally positive (Nair 1993; Szott et al. 1991; Kass 1987). For example, on acid soils in Yurimaguas, Peru, the yields of all crops in alleys, except for cowpea, were extremely low, often below that of the control plots. The main reasons for this were attributed to root competition and shading from the hedges, but also to reduced seedling emergence under the mulch applied to the alleys and, possibly, also to the extremely low fertility of the soils which may have impeded the nutrient recycling expected of the woody hedges (Szott et al. 1991). Another well-studied aspect in alley cropping is competition for water between the crops and the trees. It turns out that the degree of water competition is key for determining the success of alley cropping systems (Fig. 5, right). As a result, under conditions of water limitations in semiarid environments in India, NW Nigeria, and Kenya, the hedgerow species actually reduced the crop yields due to competition for water (Corlett et al. 1989; Mittal and Singh 1989; Nair 1993). In some cases, even the biomass yields from the hedgerows were lower under alley cropping than from non-alley-cropped hedgerows. So, under severe moisture limitations, the competition for water between the trees and the crops can become too severe to allow alley cropping to work, at least on the score of production.

The unfavorable performance of alley cropping under nutrient- or moisture-limited conditions demonstrates that this agroforestry practice, like others, requires certain minimal conditions that allow the tree-crop interactions to unfold their positive potential. On extremely acid soils in the Peruvian Amazon, some fertilizer may have to be supplied to allow cropping to work, and there is a great need to identify the most appropriate tree species for such conditions. Some examples are *Inga edulis*, *I. felulei*, *Erythrina* spp., *Cassia reticulata*, or *Gliricidia sepium* (Szott et al. 1991).

In order to evaluate the potential of alley cropping under particular site conditions, it is important to not only consider the agronomic performance but also other benefits such as long-term contributions to soil fertility, biological interactions with pests and diseases, as well as limitations such as the costs of establishment and labor requirements for maintaining the systems (Kang et al. 1989). When animals are integrated into alley cropping, the system has been called alley farming (Kang et al. 1990), and the pruned biomass can be used as animal fodder. In these cases, the economic value of the hedgerow products is likely to augment, and the recycling of animal residues as soil amendments can improve the biophysical interactions in the systems. A short practical guide on alley cropping has been provided by Elevitch and Wilkinson (1999).

Linear Tree Plantings: Windbreaks, Shelterbelts, and Living Fences

Around the world, linear tree plantings are important components in the landscape. Usually they are established to confine animals to patches of pastures, to separate plots, or to protect cropland from strong winds and resultant erosion. The latter was the case for the government-promoted establishment of windbreaks in the USA after the massive dust storms and soil displacement during the Dust Bowl. Windbreaks and shelterbelts, two expressions often used interchangeably, are widely used, protecting around 300 Mio ha of farmland (Nair 2012). In many tropical silvopastoral and agricultural systems, living fences are used to separate pasture areas and to protect agricultural plots from animals. These agroforestry practices share the two-dimensional arrangement of trees or shrubs planted in single or

Fig. 6 *Left*: windbreaks in crop fields in Oklahoma. *Right*: living fence of *Gliricidia sepium* to separate pastures in the north of the Dominican Republic (Photo credits: Oklahoma Forestry Service and R. Muschler)

narrow multiple row arrangements on farmland. Depending on their function and the environment, they differ in the width, the spacing between trees, and the species composition of the tree rows. With increasing fragmentation of tropical landscapes, windbreaks, living fences, and isolated trees become more and more important as "biological corridors" for the displacement and survival of many animal species (Harvey et al. 2004).

Windbreaks/shelterbelts. The central function of windbreaks is to protect crops, animals, soils, water bodies, and infrastructure from strong winds and their negative effects (Mendez et al. 2000; Reifsnyder and Darnhofer 1989; Fig. 6). For example, in many semiarid savannas of Africa, hedgerows of *Euphorbia tirucalli* protect crop fields and settlements, and multispecies shelterbelts with drought-resistant species protect cropland from drying winds and, hence, desertification. Around the world, particularly in wind-exposed highlands, but also in coffee fields in the southern plains of Brazil, windbreaks of different-sized shrubs and trees protect vegetables, coffee, and other crops. In addition to the beneficial effects from reducing wind speed, these rows of trees and shrubs also generate important benefits for the protection and enrichment of soils and provide habitat for the local fauna and flora (Harvey et al. 2004).

For maximum effectiveness of a windbreak, the different-sized plants should form a two-dimensional mosaic, which, ideally, should have a permeability of 20–50 % through the windbreak to avoid the formation of potentially negative turbulence on the leeward side of the windbreak (Stigter et al. 1989). The higher values should be in the bottom third. As a rule of thumb, the protective effect of a windbreak is commonly estimated to extend to a leeward distance of eight to ten times the height of the windbreak (Mendez et al. 2000; Geilfus 1994). Details on the biophysical effects of windbreaks and shelterbelts, and recommendations for their design, were given by Cleugh et al. (2002), Stigter et al. (1989), Brandle et al. (1988), and Dronen (1988). On the ecological side, it is interesting to note that windbreaks, even when they consist of only a few species of trees, can be important for the (re-)establishment of forest trees. The visiting birds and other animals can bring in substantial amounts of seeds, which can find favorable conditions for germination in the understory of the windbreak (Harvey et al. 2004). For example, in a study at Monteverde, Costa Rica, the windbreaks (consisting of *Montanoa guatemalensis*, *Cupressus lusitanica*, *Casuarina equisetifolia*, and *Croton niveus*) received 2 times more species and 40 times more seeds than adjacent pastures (Harvey et al. 2004). When windbreaks were connected with adjacent forest, or less than 20–50 m from forests, the numbers of tree seedlings and species increased even further than for windbreaks at greater distances.

In many places, the species used for windbreaks are also selected to provide additional products such as firewood, fodder (e.g., *Prosopis*), fruits (e.g., cashews), nectar, honey, and others. Occasionally, where grazing animals may be a problem, some unpalatable species such as neem (*Azadirachta indica*) can be included on the outer sides to protect the windbreak from animal damage. However, care must be taken that the species on the outside of the windbreak are compatible with the adjacent crops. This can be a problem, for example, for *Azadirachta indica* or species of *Eucalyptus* and *Juglans* that are known to reduce growth of nearby crops due to competition or allelopathy. The effects of windbreaks on crop yields vary greatly, from significant increases in the productivity of the protected crops to reductions due to competition by the trees, shading, and “loss” of agricultural land occupied by the shelterbelts. However, if one considers the integral benefits of these structures, including their long-term benefits for soil fertility, water protection, and habitat for biodiversity (including seed dispersers, pollinators, and agents of biological control), then the sum of all effects is likely to be positive in most cases. Furthermore, management interventions in the form of pruning and selective harvesting, as well as the inclusion of species that are more compatible with the crops, will help to tip the scale toward an overall positive balance.

Living fences. In many agricultural and pastoral landscapes, individual plots of land are separated from each other by living fences, which, typically, consist of closely spaced trees in a single row that serve as supports for horizontal sticks, vines, or barbed wire (Fig. 6). In some cases, the trees are planted so closely together or are so tightly interplanted with spiny unpalatable plants that there is no need for wires. Budowski (1987) provided an overview of the practice of using living fences in the Neotropics. Ideally, the species used for living fences are trees which can be readily pruned or pollarded, usually two or three times a year, and which can be established easily from stakes. Furthermore, in order to not strain the wires, it is desirable that the trees do not have a particularly strong secondary growth of the stems. By using stakes of 2–2.5 m length that will be planted 20–30 cm deep, the emerging shoots at the top of the poles will be out of reach of most grazing animals, and the trees will be able to establish themselves in 2–3 months. In the Neotropics, some of the most widely used tree species include *Erythrina berteroana*, *Gliricidia sepium*, *Diphysa robinioides*, and *Bursera simaruba*. All of them can be easily reproduced and planted from stakes.

An interesting side effect is the possibility of using living fences for the reintroduction of tree seedlings into pastures. Love et al. (2009) showed that the survival of timber tree seedlings (*Cedrela odorata*, *Samanea saman*, *Tabebuia rosea*, *Pachira quinata*) was much higher when these trees were planted within living fences rather than in the open pasture. Further information is available through the online resources of the "World Agroforestry Centre."

Silvopastoral Systems

According to FAOSTAT, the global area under pasture and fodder crops was about 3.5 billion ha in 2000, representing 26 % of the total land surface and about 70 % of the global agricultural land. This area supports some 360 million cattle and over 600 million sheep and goats. Globally, grazing animals are the principal source of livelihood for some 100 million people in arid areas, and probably a similar number in other zones, supplying about 10 % of beef and about 30 % of sheep and goat meat. Unfortunately, in many places, extensive cattle production has caused widespread environmental degradation due to the loss of soil plant cover from tree cutting, overgrazing, and soil compaction, causing massive erosion. In addition, the residues of the animals may contaminate waters, and ruminants contribute around 30 % of all agricultural emissions of greenhouse gases (equivalent to about 5 % of all GHG emissions), particularly in the form of CH_4 (Houghton et al. 2001). Consequently, there is a great need for developing more sustainable and climate-friendly animal husbandry systems.

One of the most promising options is the development of intense silvopastoral systems, which combine trees with pastures and livestock (Ibrahim et al. 2010; Pezo and Ibrahim 2001). In addition to the pasture grasses, silvopastoral systems include dispersed trees for fodder and shelter, as well as closely spaced trees for living fences, windbreaks, and fodder banks or alleys (Fig. 7). When possible, highly nutritious, often N-fixing, species are preferred (Pezo and Ibrahim 2001). If well chosen and appropriately managed, these additional tree components enhance nutrient cycling; benefit the pastures; provide complementary tree products in the form of fodder, timber, firewood, and other tree products; and improve animal productivity (Yamamoto et al. 2007). Of particular interest is the use of high-quality fodder shrubs, mostly legumes, planted at high densities (more than 10,000 plants ha^{-1}) in so-called protein banks, and the introduction of trees, palms, and improved pastures. Controlled rotational grazing, feed supplements, and a permanent water supply for the animals allow for higher stocking densities and increased production of milk and meat. Supplementing low-quality fodder with foliage of leguminous trees or shrubs, such as *Erythrina poeppigiana* or *Gliricidia sepium*, improves ruminant digestion and can increase milk yield relative to standard urea supplements (Camero et al. 2001), while reducing CH4 emissions by up to 75 % (Reid et al. 2004).

Due to their higher structural and biological complexity than simple pasture systems, silvopastoral practices also benefit biodiversity. In fact, systems with a

Fig. 7 *Top*: trees in silvopastoral systems provide shade to pastures and animals and are often used as living fences, which also provide high-quality fodder, e.g., from *Erythrina berteroana* in Costa Rica (*bottom left*) or from *Gliricidia sepium* in the Dominican Republic (*bottom center*). Although *Trichanthera gigantea* (*bottom right*) is not a legume, its highly nutritious leaves and fast growth make it a highly valued species for fodder banks in humid climates (Photo credits: R. Muschler)

high number of trees in pastures and multistrata living fences can match the animal species richness of early secondary forest, and networks of living fences in pastures are key for landscape connectivity (Francesconi et al. 2011; Harvey et al. 2006). Furthermore, these systems can also fix significant amounts of carbon (Ibrahim et al. 2007; see also section "Multifunctionality of Agroforestry: Climate-Smart Production, Protection and Ecosystem Services"), while augmenting water infiltration and improving water quality compared to traditional pastures (Ríos et al. 2007). Given their local adaptation and ecological values for wildlife, it is often preferable to use native trees and shrubs for rehabilitating overgrazed and degraded lands (Murgueitio et al. 2011). In order to motivate farmers to plant or retain a broad range of tree species in pasturelands in Panama, Garen et al. (2010) pointed to the importance of matching appropriate tree species to the individual site conditions and the farmers' production goals.

The main limitations for a more widespread adoption of these systems are difficulties to establish trees or improved pasture species in or around pasture areas, insufficient access to water, as well as lack of capital and high labor costs for establishing and managing the systems to maintain appropriate light levels and fencing (Dagang and Nair 2003). However, as demonstrated in Nicaragua, Costa Rica, and Colombia, when farmers received "payments for environmental services" for including more trees in their systems (from 82 to 92 USD ha^{-1}), many of them were able to transform their systems into improved silvopastoral systems with economic and environmental benefits (Ibrahim et al. 2010; see Box 3). Similarly, in dry African savannas, even modest payments of carbon credits could contribute to retaining the carbon in undisturbed savannas (Reid et al. 2004). Considering the societal benefits generated by improved silvopastoral systems (soil retention, water quality, biodiversity, etc.), a more widespread application of such compensation schemes should help promote the climate-smart transformation of this sector.

Another promising approach is the development and application of environment-friendly certification programs such as the "standard for sustainable beef production" developed by the "Sustainable Agriculture Network" (www.san.ag) in 2010. This standard promotes practices with ecological, social, and economic benefits. As points of departure on silvopastoral systems, practitioners may want to consult the following training materials: for Latin America, Pezo and Ibrahim (2001) produced a comprehensive training material on silvopastoral systems, and the work of Benavides (1994) on trees and shrubs as animal fodder continues to be a reference. For Africa, Wambugo et al. (2006) assembled a practical extension manual on fodder shrubs for dairy farmers. Further materials are available through ICRAF and partners.

Taungya

Taungya systems, derived from the Burmese words taung (hill) and ya (cultivation), refer to the practice of intercropping young forest stands with agricultural crops as long as the trees permit adequate crop growth (Jordan et al. 1992). Once the trees have grown enough to establish crown closure and larger root systems, usually after 3–5 years depending on the tree species, planting arrangement, and growth conditions, the conditions for the agricultural crops become marginal. The integration of the crops allows deriving early income at a time when the trees are still too young to yield products, and the crop management, particularly weeding and fertilization, will also benefit the trees. This system, originally developed in British colonial India in the 1850s, is now widely used in many parts of the tropics to establish forest plantations. Some of the most widely used timber species include *Eucalyptus* spp., *Gmelina arborea*, *Pinus* spp., *Shorea robusta*, *Tectona grandis*, *Terminalia*, and others (Schlönvoigt 1998; Nair 1993).

In some regions, this system is used to promote the establishment of forest plantations by providing the benefits of temporary land use to the farmers who care for the annual crops. One successful example is the "forest village" scheme in Thailand, which combines the land use benefits during the early phases of crop planting with a permanent allocation of agricultural plots to former shifting cultivators (Boonkird et al. 1984). In the Caribbean lowlands of Costa Rica, the taungya system has allowed to establish plantations of *Cordia alliodora*, *Eucalyptus deglupta*, *Acacia mangium*, and other timber species with Arazá (*Eugenia stipitata*), a perennial fruit shrub introduced from the Amazon, which starts to produce already after 2–3 years (Schlönvoigt 1998). However, when introducing new crops (as was the case with Arazá in Talamanca), care should be taken that the introduction of the crop into the planting system responds to a market demand and is accompanied by parallel activities to process and promote the new product. Based on a systematic spacing experiment in Costa Rica, Schlönvoigt and Beer (2001) concluded that maize was compatible with *Cordia alliodora* and *Eucalyptus deglupta* during the first year of growth, while cassava (*Manihot esculenta*) significantly reduced the growth of these trees. Therefore, care must be taken to choose compatible tree-crop combinations and appropriate spacing in order to not compromise the trees' growth. In systems with wide-enough spacing between the trees, or when the tree stand gets thinned with time, it may be possible to maintain crops for longer or even permanently, at which point the taungya system may transform into a forest farming or shaded plantation system. Further details about taungya systems can be found in Schlönvoigt (1998) and Nair (1993), as well as in "Agroforestry Systems."

Plantation-Crop Combinations

In the tropics, perennial plantation crops occupy a substantial portion of the agricultural lands. The most important plantation crops include oil palm, rubber, coconut, coffee, cacao, sugarcane, tea, fruit trees (particularly citrus, avocado, bananas, mangos, cashews), pineapple, and black pepper. Depending on the crops' light requirements, their size and architecture, and the local growing conditions, they may be grown as the overstory of the systems or as part of the understory. In many regions, most of these crops have been grown extensively as monocultures in full sun exposure. However, due to the increasing pressure from pests and diseases in long-standing large monocultures (very pronounced in banana plantations, but increasingly important also in coffee, cacao, and pineapple) and environmental degradation, there is now a growing need to diversify monocultural landscapes by adding trees and shrubs in hedges, windbreaks, living fences, riparian buffer zones, or as living supports for climbing crops like black pepper or vanilla. This landscape diversification adds "islands" for organisms of biological control and generates other ecological benefits such as the protection of soils, waters, and fauna (Vazquez 2014).

Several of these crops, particularly rubber, coffee, cacao, tea, and black pepper, are often grown under some level of shade (Fig. 8), depending on the site conditions and the level of inputs. In general, the more limiting the conditions are for a specific crop, the more it will benefit from shade as such and also from the other benefits of shade trees, such as biologically fixed N, or organic matter provided to feed the soil (Muschler 2001a; see section "How and Where Does Agroforestry Work?" for a discussion of the sun-shade issue). The tree architecture, phenology, and vigor must be considered for adequate spacing, and thinning, pruning, or pollarding can be used to adjust the shading pattern and the biomass production of the trees to the needs of the associated crops. For example, for sun-loving black pepper plants, the lighter shade under *Gliricidia sepium* trees used as living supports is usually

Fig. 8 Plantation crop combinations with coffee and vanilla. *Top left*: the dominant tree species in this coffee plantation in Costa Rica is the red-flowering legume *Erythrina poeppigiana* used to provide shade and biomass. When pollarded, the trees form small dense crowns over the coffee as seen in the foreground and in the coffee fields behind the tall trees. *Top right*: a mix of many species form three shade strata for coffee in Caranavi, Bolivia. The species richness and the structural diversity of this coffee plantation make it eligible as "bird friendly" (see text for further details). *Bottom left*: coffee under *Inga* shade, with bananas and root crops in the foreground. *Bottom right*: biodynamic vanilla in Costa Rica on living stakes of *Gliricidia sepium* (Photo credits: R. Muschler)

preferable over the heavier shade of *Erythrina* spp., unless the latter species is pruned or pollarded more often (Muschler et al. 1993). In any case, the microclimatic benefits need to be balanced against those from the production of biomass for soil improvement and other benefits and, of course, against the management costs. Similarly, the spacing and management of shade trees for coffee, cacao, tea, and other crops need to be custom-tailored to the needs of the crops as a function of tree attributes and environmental parameters (Muschler 2001a; Muschler et al. 2006).

In various regions, studies have shown that some particularly shade-tolerant plantation crops, such as coffee and cacao, can sustain very high levels of biodiversity. In fact, the structurally and botanically most complex systems under agroecological management (e.g., Fig. 8, right) can sustain a major portion of the biodiversity of tropical rainforests (Perfecto et al. 1996; Schroth et al. 2004; Vaast and Somarriba 2014). Interestingly, for some types of organisms, the species diversity in such agroforestry systems can even exceed that of the forest.

For example, Hoehn et al. (2010) reported from Indonesia that the highest species richness of bees was actually found in cacao agroforestry systems, exceeding the values of closed primary forest and also those of open agricultural land.

Clearly, these examples illustrate the great potential to "use" species-rich plantation crop systems for combining production with protection. Considering that Central America alone is home to more than 2,000 tree species, it becomes clear that there is a vast potential to incorporate many more species, ideally favoring those of highest ecological importance ("keystone species") as we learn more about their roles for productivity and the conservation of the associated flora and fauna (Yépez et al. 2003; Muschler et al. 2006). Similar to the case of sustainable production of livestock, systems of environmental, social, and economic certification can help drive the transition of plantation crop systems toward higher biodiversity and sustainability. Good examples are the standards established by the "Sustainable Agriculture Network" for the production of crops like coffee or cocoa (www.san.ag) and other standards that are even more rigorous, such as for organic production or, still more complex, the criteria for "bird-friendly coffee" production established by the Smithsonian Migratory Bird Center (http://nationalzoo.si.edu/SCBI/MigratoryBirds/Coffee/default.cfm; see section "Agroforestry for Biodiversity Conservation and Ecosystem Services"; Fig. 25).

Homegardens, Multistrata Systems, and Tree Gardens

In the continuum of plant successional stages, homegardens, multistrata systems, or tree gardens, expressions sometimes used synonymously, correspond to the final stages sharing similar architectural characteristics. The intense mix of a wide range of edible, medicinal, and utilitarian plants, including annuals and perennials of all dimensions, all the way up to possibly decades-old emergent overstory trees, establishes a complex multistrata system (Fig. 9). In many regions, the expression "homegarden" is primarily associated with relatively small units around the farmers' homes that provide a wide range of products. In contrast, multistrata systems, sometimes also called multistrata tree gardens, are not necessarily linked to a homestead. Often, they include one or a few components such as coffee, cacao, coconut, or some spice, which may provide a dominant share of the family income. However, as stated by Nair (2001), there is no clear-cut distinction between multistrata systems and homegardens. The large structural, functional, and taxonomic diversity of homegardens, as their central defining feature, has been characterized in the classic paper by Fernandez and Nair (1986), followed by a wealth of other descriptive studies. In a study of 80 Mayan homegardens in Mexico, DeClerck and Negreros-Castillo (2000) have reported more than 150 species of plants and their specific roles as analogs of plants in different successional stages.

In the species-rich homegarden shown in Fig. 9, an example from the humid tropical lowlands of SE Costa Rica ("Finca Loroco," Bribri, Talamanca), the most prominent plants include emergent timber trees (*Cordia alliodora*, *Cedrela odorata*), fruit trees (mango, *Spondias* spp., *Chrysophyllum caimito*, *Citrus* spp.),

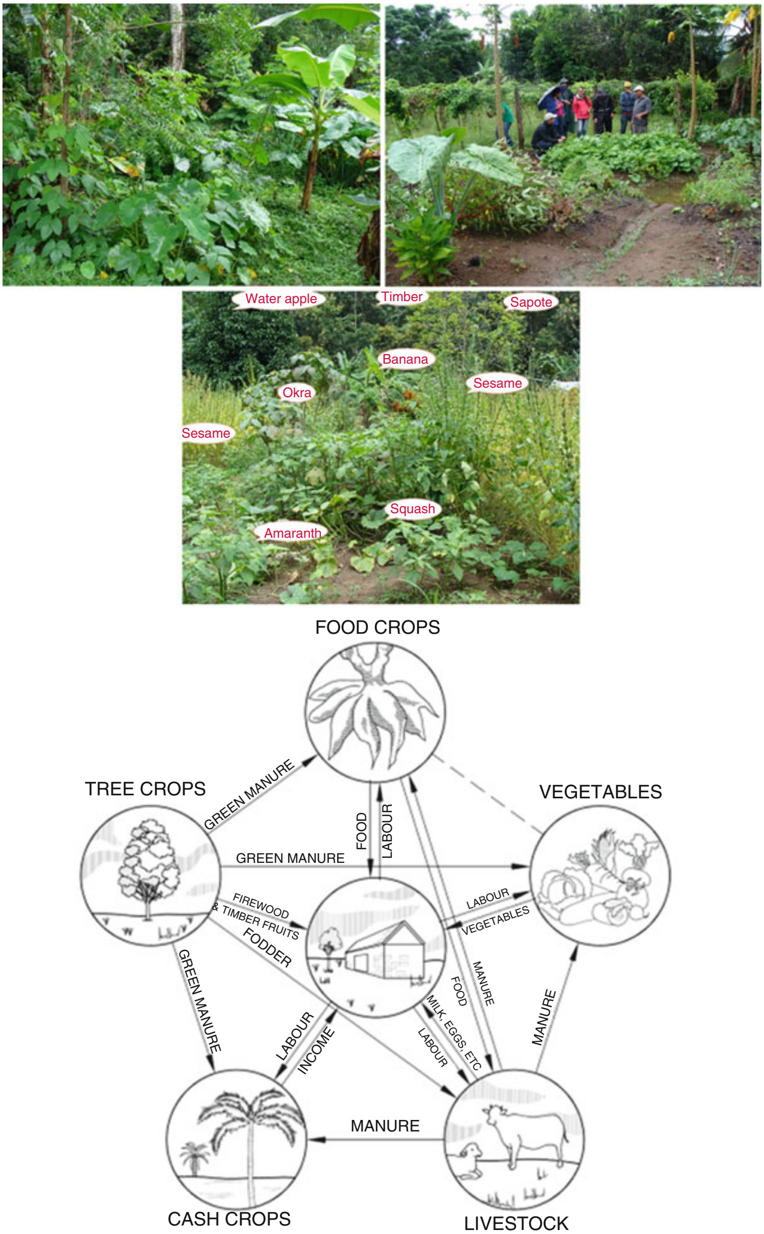

Fig. 9 *Top*: a typical homegarden assembly of annual and perennial species. In this example from the lowlands of Costa Rica, more than 50 species are mixed, including annual and perennial plants of different sizes and animals. For details please refer to the text. *Center*: the presence of many species generates an ecologically more stable system and prevents the buildup of pests or diseases. *Bottom*: interactions among the different components of a homegarden from Kerala in India (Photo credits: R. Muschler at "Finca Loroco"; drawing from Nair and Sreedharan 1986).

bananas/plantains, tubers (*Colocasia esculenta*, *Ipomoea batatas*, *Pachyrhizus erosus*, *Manihot esculenta*), annual vegetables (squash, amaranth, sesame, okra), spices (aromatic herbs, *Fernaldia pandurata*, turmeric), and medicinal plants. Furthermore, various species are used for soil improvement (e.g., *Canavalia*, *Mucuna*, *Pachyrhizus erosus*), live fences (*Erythrina berteroana*, *Diphysa robinioides*, *Gliricidia sepium*), and the production of fodder (*Erythrina poeppigiana*, *Trichanthera gigantea*) for the goats, pigs, chicken, and fish that are also being raised. In addition, the system contains hedges along plot borders with melliferous and small-fruit-bearing species to support the undomesticated yet beneficial diversity of insects (bees, wasps, and many others), mammals, birds, and microorganisms, which provide the essential services of pollination (Nicholls and Altieri 2013), biological control, soil suppressivity, and, one of the most important yet often ignored services, the prevention of pest and disease problems to start with (Vazquez 2014; Daily 1997).

The high diversity of species, and the structural and functional richness of the system, creates a wealth of ecological interactions, which make these systems resemble forest ecosystems (DeClerck and Negreros-Castillo 2000). It is this richness that generates higher levels of resistance and resilience to extreme climatic events and to price volatility of individual crops. As elaborated by Nair (2001), there is a great need for developing further tools to better understand the proven long-term ecological and socioeconomic stability of these systems, which have perdured more environmental and economic shocks than systems with fewer species. The classic global compilation of homegarden studies by Landauer and Brazil (1990) was complemented by a collection for Central America by Lok (1998a) and the global review by Kumar and Nair (2006).

Practices for Soil Conservation and Watershed Rehabilitation

For soil conservation in hilly terrains and for watershed rehabilitation, agroforestry practices such as the establishment of vegetative barriers of woody perennials along contour lines or across erosion gullies can stabilize the soil (Fig. 10). For higher effectiveness, these rows can be interplanted with, or bordered by, parallel rows of perennial grasses such as vetiver or lemongrass and dense-rooted groundcovers like *Arachis pintoi*. In contrast with physical measures to retain soil, such as stone or concrete walls or terraces, living barriers tend to be more effective due to their permanent root system. In addition, once they are well established, they can provide sticks, stakes, fodder, and ecological services such as habitat for wildlife.

For the protection of riverbanks and lakeshores, it is necessary to retain or establish riverine forests or vegetative buffers along watercourses (Fig. 10). Often these linear vegetative strips are the remnants of former forest or brush lands that have persisted along water courses or that were put back in order to stabilize the river banks from being eroded and undercut by floods (Fig. 10, bottom). Furthermore, in high-input agricultural landscapes, riverine forests are essential to protect the water from runoff of fertilizers and agrochemicals. Finally, these elongated structures are

Fig. 10 *Top left*: gully formation during massive soil erosion can be slowed, or even reverted, by establishing fast-growing perennial plants with dense root systems. This example comes from the Lake Bogoria watershed in Kenya. *Top right*: rehabilitation of gully with the establishment and protection of fast-growing legumes in Haiti. *Bottom left*: a riverine protection forest along a river in Iowa. *Bottom center and right*: tree roots protect riverbank in Haiti while unprotected portions are being undercut and eroded by floods (Photo credits: Amundsen et al. (2015) (*top left*); USDA, public domain (*bottom left*); R. Muschler (others))

important ecological corridors for wildlife and constitute important reservoirs for beneficial soil organisms (Harvey et al. 2006; Stamets 2005). The great ecological importance of these perennial vegetative strips is also reflected in certification guidelines like the ones of the "Sustainable Agriculture Network" (www.san.ag).

Another important avenue of using agroforestry is through the establishment of artificial lakes in drylands, which serve as "oasis" that become the starting points for "regreening" the landscape. For example, during the past 20 years, more than 120 artificial lakes were established with great success in the dry highlands of Haiti (Gantheret 2010; Nicolas 2010). There, the artificial lakes retain rainwater as high up as possible in the watershed in order to maximize its potential use in gravity-fed irrigation systems downhill from the lakes (Mollison 1996; Fig. 11). As the lakes get established, flash floods diminish and the moisture permits to plant multipurpose trees in the agroforestry buffers around the lakes. As the trees grow, goats can be kept in enclosures and fed with a cut-and-carry system of annual and perennial fodder. With time, ecosystem services are reestablished and the retained water feeds a growing system of irrigated agriculture. Furthermore, fish and other animals can be produced in and around the lakes, providing additional income and high-quality food.

The success of these efforts to rehabilitate degraded watersheds with community support, even more so under the extreme conditions of Haiti, illustrates the power inherent in applying agroforestry and permacultural knowledge and tools. In the

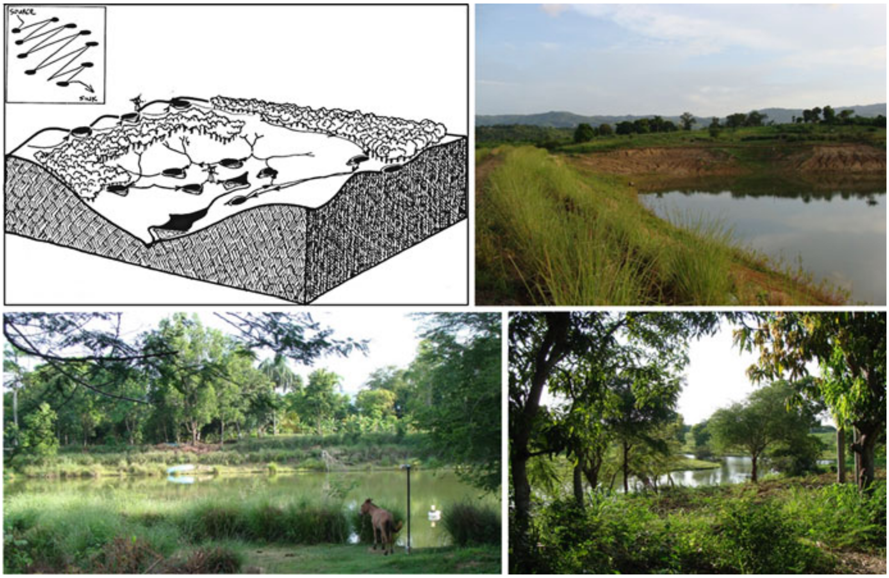

Fig. 11 *Top left*: the establishment of artificial lakes in the upper watershed allows retaining water in the highlands and diverting it for many uses along its downhill course (Source: Mollison 1996). *Others*: examples of artificial lakes established in a largely deforested semiarid landscape in the entral Highlands of Haiti. The shorelines of newly established lakes can be protected with strips of Vetiver or other grasses. In the course of some years, the lakes permit to "regreen" the environment (Photo credits: R. Muschler)

medium term, it is desirable to continue enriching the system with further ingredients until a patchwork of permaculture is established that maximizes production and protection functions at the same time (Mollison 1996). Undoubtedly, this experience merits being studied and replicated in many other regions with appropriate geological and social conditions. For further details on agroforestry for soil protection, see section "Benefits of Trees for Soil Fertility and Protection."

Other Agroforestry Practices

Besides the most common agroforestry practices discussed so far, others are restricted to local importance, often for specialty products, such as honey, fish, waterfowl, and others. These systems can include fish farming in natural or artificial ponds established for retaining water. Ideally, these ponds should be protected by a border of multipurpose trees and shrubs. In the example in Fig. 12, the protective ring of plants around the pond protects the banks and provides food for birds and fish. The water hyacinths (*Eichhornia crassipes*), a highly invasive species, are fed to pigs and chicken, and leftovers are composted. Another attractive agroforestry practice is bee farming, preferably in regions with limited exposure to pesticides.

Fig. 12 Aquaculture and bee keeping as part of agroforestry systems in Costa Rica and Cuba. *Top Left and Right*: the pond serves as water reservoir for the dry season and is used to produce *Tilapia* fish. Notice the densely vegetated border with fruiting shrubs and trees to protect the banks, shade the pond, and feed the fish. The highly nutritious fodder species *Trichanthera gigantea* (in the foreground of the left picture) is used for feeding goats, pigs, and the fish in the pond. When the water hyacinths overgrow the pond, they are removed and fed to pigs and chicken, and the residues are composted. *Bottom*: honey production can provide an important source of income. In this example from Cuba, the trees in the system are selected to provide forage for the bees (Photo credits: R. Muschler at "Finca Loroco," Costa Rica, and "Finca La Marta," Cuba)

When the system is designed in such a way that the trees, shrubs, and annual crops provide nectar and pollen during most of the year, the production of honey can become a major source of income, as is the case in the "Finca La Marta" in Cuba (Fig. 12). Numerous sources on bee keeping are online through ICRAF and other centers. The Spanish-speaking reader may want to consult the recommendations on melliferous plants for bee keeping in the tropics by May and Rodriguez (2012) or by Espina and Ordetx (1983), as well as the compendium on tropical bee keeping by Medina-Solís (1990).

Distribution of Agroforestry Systems

Except for deserts, trees are an integral part of most agricultural landscapes. Using the criterion of a minimum of 10 % tree cover on agricultural lands, Zomer et al. (2014) estimated that some form of agroforestry is being practiced on more than 43 % of all agricultural land globally. This area covers over 1 billion ha and is home to 30 % of the rural populations, i.e., more than 900 million people. According to Nair (2012), some 60 % of this land may be under some form of tree intercropping, including improved fallows and tree intercropping in African parklands (Fig. 13).

Using the same criterion, agroforestry is particularly prevalent in Central America where 95 % of agricultural land has >10 % tree cover, in Southeast Asia with 77 %, and in South America with 53 %. For other regions, the figures are Europe 49 %, East Asia 45 %, North America 40 %, sub-Saharan Africa 27 %, Southern Asia 19 %, and, finally, N and W Africa 10 %. Two key findings of the comparison between 2000 and 2010 were that (1) tree cover continued to increase slightly on agricultural lands in most regions around the world (except for Northern and Central Asia), and (2) tree cover tends to increase with humidity (Zomer et al. 2014). These figures and tendencies demonstrate the tremendous ecological and social relevance of agroforestry.

Similar to the tendency of increasing species diversity toward the tropics, also the diversity of farming systems is particularly high in the tropics. While scattered trees in the landscape can be found in most tropical landscapes, the most complex and biodiverse systems, such as homegardens, are found primarily in humid or

Fig. 13 Trees outside of forests: in many regions, the most important tree resource is not found in forests, but as scattered trees in the landscape. Wide spacing allows intercropping of many plants including maize with various timber and fruit trees in Haiti (*left*; photo by R. Muschler) or with *Faidherbia albida* and *Borassus akeassii* in parkland of Burkina Faso (*right*; photo by Marco Schmidt)

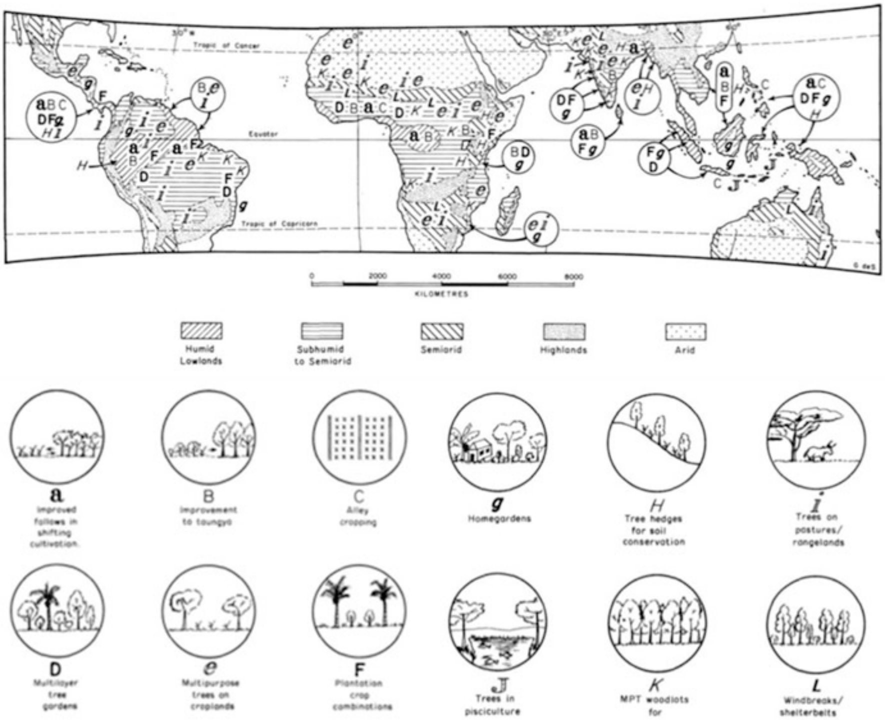

Fig. 14 Distribution of agroforestry systems in the different agroecological zones of the tropics (Source: Nair 1993)

subhumid regions, often with high population densities. Examples are homegardens in Java (Marten and Abdoellah 1988), India, El Salvador, Haiti, Nicaragua (Méndez et al. 2001), and many other countries in Africa and Latin America (Landauer and Brazil 1990). Figure 14 gives a geographic overview of the distribution of the major agroforestry practices, and Fig. 15 indicates the prevalence of different practices according to humidity and elevation.

The availability of moisture, in general correlated with higher population density, is possibly the most important factor for the distribution of agroforestry systems. Humid and subhumid zones show many systems of improved tree fallows, taungya systems, alley cropping, plantation crop combinations (cacao, rubber, bananas), and homegardens. In contrast, semiarid and arid lands tend to be dominated by multipurpose and fuelwood lots, scattered trees on pasture and rangelands, and shelterbelts and windbreaks. At intermediate moisture levels, we find fodder banks and an overlap of the mentioned systems. In the highlands, the predominant agroforestry practices are directed at the production of fuelwood, plantation crops (particularly coffee and tea), and animal fodder, with a more prominent role for shelterbelts and windbreaks to protect soils and crops.

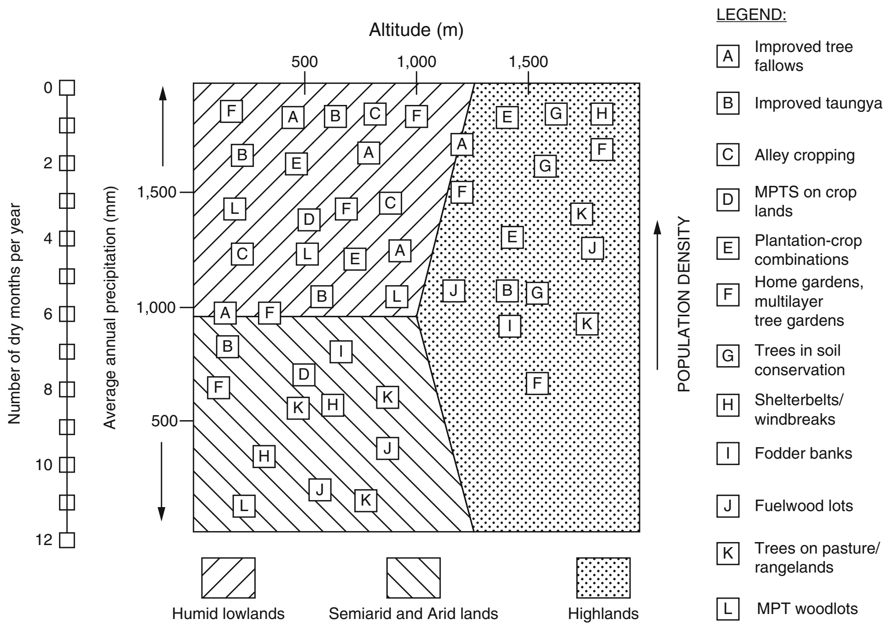

Fig. 15 Schematic distribution of agroforestry systems according to a matrix of rainfall and elevation (Source: Nair 1993)

Roles and Potential of Agroforestry for Sustainable Land and Landscape Management

This section reviews the role of trees for sustainability and sketches the environmental conditions for the successful incorporation of trees into climate-smart landscapes.

Requirements for Sustainable Land Use

For systems to be attractive and ecologically sustainable in the long run, land use systems should (Benyus 2002; Daily 1997; Ewel 1986, 1999):

1. **Be adapted to the natural environment and mimic natural successional communities** in order to make efficient use of sunlight and recycle natural resources without degrading them (e.g., soils, water) or losing them (nutrients, functional biodiversity)
2. **Foster biological activity** at all levels (from soil microbiology, e.g., mycorrhizae and N-fixers, all the way to the macroflora and macrofauna) in order to maximize (i) nutrient capture mechanisms through symbiotic associates,

(ii) ecosystem suppressiveness to pests and diseases, (iii) pollination, and (iv) resistance and resilience to extreme climatic events

3. **Minimize the liberation of greenhouse gases and the dependency on external inputs** (particularly agrochemicals) to reduce the C footprint and negative externalities
4. **Correspond to an early successional stage to be productive enough** to be economically interesting
5. **Be diverse enough to resist** ecological and economic stress to individual products (e.g., coffee affected by leaf rust, bananas by Sigatoka, cacao by *Monilia* etc.)
6. **Be socially acceptable** to be adopted and maintained

Ideally, these systems should be simple enough to be horticulturally manageable, yet diverse enough, and have sufficient active biomass (deep root system, high leaf area index, flower and fruit production, etc.), to sustain the abovementioned essential ecosystem services. Without these services, the systems cannot function in the long run as demonstrated by many societies that have disintegrated after their agroecosystems collapsed (Diamond 2011). To a large extent, these services are provided by the high above- and belowground biomass of mid- to late-successional ecosystems with perennial components. Unfortunately, the ecosystems' investment for maintaining this high biomass limits their harvestable output compared to annual crops (Ewel 1999). Consequently, the challenge for the ecosystem designer is to strike the right balance between high productivity of early successional stages and the protection services of mid- or late-successional stages (Mollison 1996). It is the capacity of agroforestry to combine production with protection that establishes it as a pivotal tool for the long-term sustainability of productive systems (Smith 2010). As mentioned in Fig. 2, striking the right balance involves not only finding the right components and their best arrangement but also finding the most appropriate dimension and location for each type of land use within the landscape mosaic. For this, we need to recognize the effects of trees on their environment. The following sections summarize the main effects of trees.

Benefits of Trees for Microclimate Improvement

The most obvious microclimatic benefit of trees is to provide shade to associated crops, animals, and, of central importance yet often ignored, the soil. Shade, and protection of the soil by mulch or living plants, is beneficial for most soil organisms (Martius et al. 2004) and can be essential for the symbionts in the topsoil (Bardgett and van der Putten 2014; Stamets 2005). The other effects of trees include reducing wind speed and the variability of air humidity and protecting plants in the understory from direct rain (Geilfus 1994; Fig. 16). Depending on the particular climatic setting, these modifications can have positive or negative effects. In general, where crops or animals are exposed to growth-limiting factors, such as scorching sun, chilly winds in the highlands, or desiccating winds in drylands, the beneficial

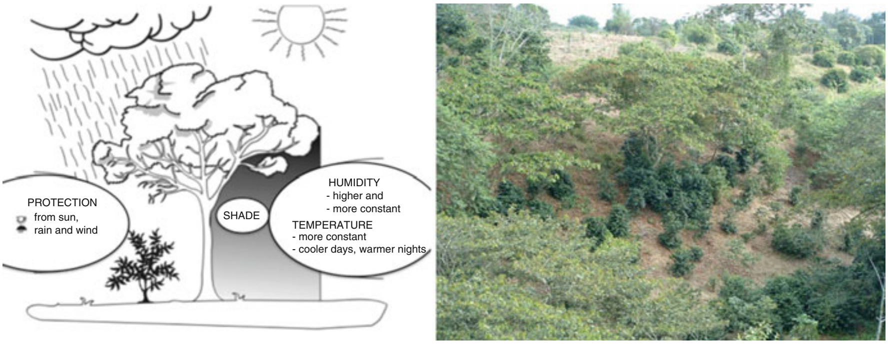

Fig. 16 *Left*: principal microclimatic benefits provided by trees (Source: Geilfus 1994). *Right*: notice the vigor of the coffee plants under the shade of this *Inga* tree in Northern Mexico. In contrast, unprotected coffee bushes have died back where neither shade nor agrochemicals alleviate the stress of full sun exposure. It must be noted that the microclimatic benefits are confounded with belowground effects of the trees (Photo credit: R. Muschler)

effects of trees become obvious when the plants protected by trees perform better than plants away from the trees (Fig. 16) or when animals seek out the trees. Concepts and applications were compiled by Reifsnyder and Darnhofer (1989) for a wide range of agroforestry systems, complemented by the recent sourcebook on agrometeorology by Stigter (2010), an excerpt of which was given by Stigter et al. (2011). For coffee systems, shade effects are amply documented, including the works by Barradas and Fanjul (1986) and by Muschler (1998), who reported detailed PAR measurements under different levels of shade. Caramori et al. (1996) reported on the use of *Mimosa scabrella* for frost protection of coffee plantations in Brazil. Martius et al. (2004) described positive effects of canopy closure on the soil fauna.

Benefits of Trees for Soil Fertility and Protection

Among the many roles of trees for ecosystem sustainability, probably the most important one is the capacity of trees to conserve soil and, sometimes, even improve it under appropriate conditions (Mutua et al. 2014; Magdoff and Van Es 2009; Young 1989). The main mechanisms are the physical anchoring of soil by the presence of tree roots (see Fig. 10), the formation of a mulch layer to cover the soil (Fig. 17), and the inputs of soil organic matter (SOM) from the decomposition of leaves, branches, roots, and wood. The main functions of SOM include the following:

1. Increasing nutrient cycling and retention by increasing the soils' capacity to retain nutrients in plant-available forms (Sanchez 1995)
2. Feeding the soil organisms responsible for a healthy rhizosphere (Bardgett et al. 2014; Nardi 2007) and disease suppressivity (Lowenfels and Lewis 2010; Stamets 2005)

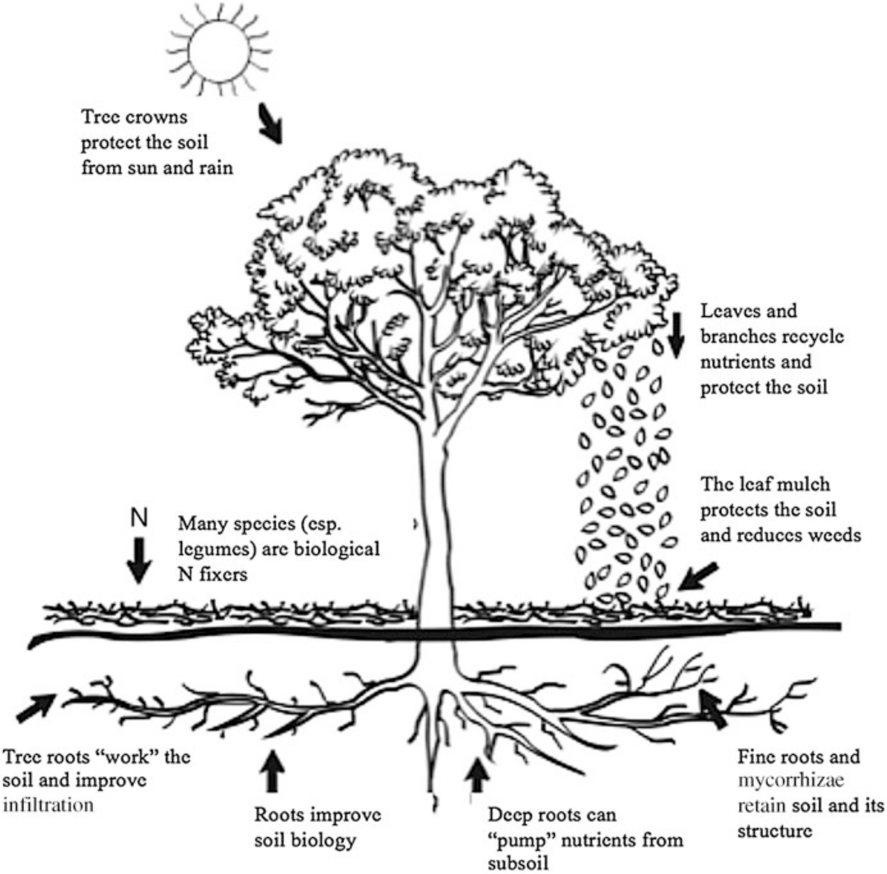

Fig. 17 Schematic representation of the benefits of woody shrubs and trees for nutrient cycling and the conservation of soil fertility (Source: Geilfus 1994)

3. Improving aggregation and soil structure which, in turn, augment water infiltration and water holding capacity
4. Reduced evaporation and soil crusting
5. Better root development (Huxley 1999)

The central effects of including trees and woody shrubs in agroforestry systems are illustrated in Figs. 17 and 18.

Since SOM is "the warehouse of most of the N, P, and S potentially available to plants, is the main energy source for microorganisms, and is a key determinant of soil structure" (Ewel 1986), long-term sustainability of production hinges on continuous inputs of biomass to protect and nourish the soil and its fauna and flora. Perennial trees and shrubs with extensive root systems and high biomass productivity are ideally suited for this. As much as it is necessary to maintain SOM inputs, it is also important to minimize soil disturbance, and consequent

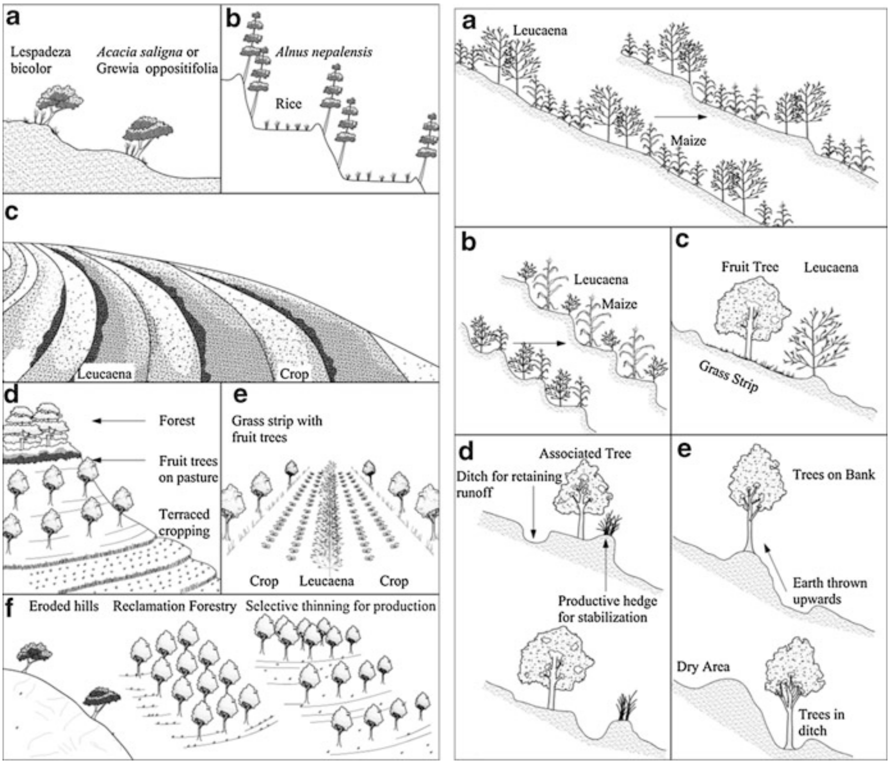

Fig. 18 Some of the most widely used tree-crop arrangements on slopes for the conservation of soils in different land use systems. For details, the reader is referred to Young 1989 (Illustrations redrawn from Young 1989)

decomposition of SOM, by using practices such as "conservation agriculture" with minimum or no tillage (Mutua et al. 2014; Derpsch et al. 2010).

The soil fauna provides a range of substances that facilitate the formation of organo-mineral complexes that are essential for the stability of soil aggregates. Fungal hyphae and their products contribute further to aggregate stability (Cardoso and Kuyper 2006: Jiménez and Thomas 2001). The burrowing and mixing actions of soil fauna, a widely recognized service of earthworms in humid climates (Lavelle et al. 1999) and of ants and termites in dry environments (Evans et al. 2011), increase the number and dimensions of macropores and, therefore, the infiltration capacity of soils, a determinant for the retention and slow release of water in watersheds (Jiménez and Thomas 2001). In many tropical agroecosystems, earthworms can increase agricultural productivity by 40 % and even more, an effect that is particularly pronounced for grain crops (Brown et al. 1999). For dryland grain production in Australia, Evans et al. (2011) reported a 36 % increase due to the presence of ants and termites. However, to sustain earthworms and other beneficial organisms, the inputs of crop and tree residues from permanent agroforestry systems are indispensible since they represent the principal source of energy for the heterotrophic soil organisms. In coffee systems, shade and organic crop management increased earthworm abundance substantially (Sánchez de León et al. 2006).

Another beneficial effect of some perennials is linked to the unique capacity of certain perennial mycorrhizal species like *Cajanus cajan* (Shibata and Yano 2003) and *Tithonia diversifolia* (Jama et al. 2000; Phiri et al. 2003) to solubilize P from insoluble pools that are usually not available to other plant roots. Using the capacity of plants like these, and their microbial associates, allows to "mine" nutrients and incorporates them into the mobile P cycle of the system (Cardoso and Kuyper 2006). Given the increasing scarcity of P supplies (IASS 2015), this is a topic that merits further research.

Over the past decades, a massive body of quantitative information has been amassed on nutrient stocks and flows in agroforestry systems. The summary of the first decade of research by Fassbender et al. (1991) and Fassbender (1993) was complemented by a series of studies on the transformation and flow of individual elements, particularly N and P, using nutrient balance studies and methods with tracers (Schroth and Sinclair 2003; Cadisch and Giller 1997; Sanchez 1995; Haggar et al. 1993, 1991). Hartemink (2005) presented a review on nutrient stocks and cycling in cocoa systems. For detailed information on methods to assess aspects like the effects of trees on nutrient cycling, SOM, soil properties, carbon sequestration, and related topics, the reader is referred to Schroth and Sinclair (2003). Young (1989) provided a detailed review on the use of agroforestry for soil conservation. The effectiveness of trees for soil conservation and, given appropriate conditions and enough time, even recuperation is illustrated by the capacity of residual tree "islands" to retain soil and water and from reforesting degraded landscapes by community-supported tree planting and protection trees in Haiti (Fig. 19).

How and Where Does Agroforestry Work?

Trees are perennials, which means that they will usually be longer present in the system than animals, crops, and man. Consequently, their effects will be felt for decades or longer. Due to their larger size (in most cases), their foliage and branches can permanently, and predictably (often modified by pruning), moderate the microclimate for the crops underneath by reducing wind speed and extremes of temperature and moisture which otherwise might be growth limiting. At the same time, and in the absence of rooting barriers (not always the case) or chemical or water limitations, their roots can potentially exploit a larger soil volume than those of the relatively short-lived and smaller crop plants. This can, then, translate into an uptake of nutrients which otherwise would not be accessible to the crops and the incorporation of these nutrients into the crop environment once the tree sheds leaves, branches, and roots. This is the most basic premise for the benefits of plant associations in agroforestry (Ong and Huxley 1996). Put in other words, agroforestry is beneficial whenever trees can protect crops, of particular importance in stressful environments, or help crops to access more nutrients and water than they would be able to access or use if they were alone.

Fig. 19 Signs of hope: trees to protect and recuperate soils. In the south of Haiti, the determined community of "La Vallue" has started a slow but steady recovery of their natural resources by judicious use and protection of trees on hilltops and exposed ledges. Of particular importance are multipurpose trees that provide biologically fixed nitrogen for soil improvement and fodder for the stabulated animals as well as fruits for human consumption. Note how the presence of trees allows protecting the soil in the three agroforestry "islands" (*top left*) and on the ridge of the steep slopes (*bottom*). Without the protection of the trees, soil degradation leads quickly to complete loss of fertile topsoil. This results not only in the loss of productivity of the land but also of its capacity to store rainwater for slow release during the dry season (Photos: R. Muschler)

An illustrative example comes from a study of nutrient cycling in coffee ecosystems in Costa Rica (Table 2; Muschler 1998), which showed that the inputs of N, P, K, Ca, and Mg in the form of pruning residues of *Erythrina poeppigiana* shade trees were higher (for many nutrients by a multiple) than the nutrient extraction in the form of harvested coffee beans, even at a high productivity or 7.5 t of coffee beans per ha. The differences were particularly high when the trees were subject to "selective pruning" (i.e., selective removal of some large branches to create an "open shade" pattern) compared to complete pruning of all juvenile branches ("pollarding"), because the trees were able to provide more biomass. With "selective pruning," about half of the large branches are retained, which allows the trees to produce biomass year-round. In contrast, "pollarding" sets back the biomass production drastically due to the loss of all branches until they resprout 3–6 weeks after pruning. As a result, the C supply to the N-fixing bacteria is interrupted causing N-fixation to decline drastically until 3 months after the pollarding (Nygren

Table 2 Nutrient balance for agroforestry systems with coffee under the leguminous *Erythrina poeppigiana* shade trees subjected to different pruning regimes. The inputs stem from fertilization and the nutrient inputs of pruning residues[a] from *Erythrina poeppigiana* shade trees. The nutrient export was calculated for extracting 7.5 Mg of fresh ripe coffee berries per ha (Muschler 1998)

	OM[a]	N	P	K	Ca	Mg
Input/output via	kg ha^{-1} $year^{-1}$					
Inputs						
1. Pollarding[b]	1,241	58	3.6	18	18	4.0
2. Open shade (selective pruning)[b]	2,277	106	6.6	33	33	7.3
3. Commercial fertilization[c]	–	219	31.5	94.5	100	37.8
Outputs						
4. Harvested coffee (7.5 Mg fresh weight ≅ 30 sacks green coffee of 46 kg each)	1,380	−27	−1.5	−27	−3.6	−1.5
Balance for pollarding (1 + 3 − 4)	–	250	33.6	85.5	114.4	40.3
Balance for open shade (2 + 3 − 4)	–	298	36.6	100	119.4	43.6

[a]Organic matter inputs from tree pruning (dry weight of leaves and green non-lignified shoots); does not include litter fall, branches, stems, roots, or coffee residues
[b]Calculated for 156 trees per hectare (8 × 8 m spacing)
[c]Standard recommendation per hectare and year: 2 × 315 kg of complete fertilizer (18-5-15-6-2; N-P-K-Mg-B) + 315 kg NH_4NO_3 + 250 kg $CaCO_3$

and Ramirez 1995). However, even when the shade trees were pollarded twice per year, the most drastic treatment possible, the nutrients in the pruned biomass still exceeded the extraction, except for K. When the inputs from the commercial fertilization were included in the nutrient budget, the overall balance for N indicated an excess of 250 kg of N per ha and year. Besides economic implications, this excessive fertilization also has strong ecological implications due to N leaching into water systems and N losses to the atmosphere. As this example shows, the integration and management of the tree component can, under appropriate conditions, supply a substantial portion of needed nutrients for the long-term sustainability of the production systems (Muschler 2001a, 2004; Beer et al. 1998). At the same time, the nutrient contributions from the trees contribute to mitigate climate change by reducing the needs for synthetic fertilizers (see section "Multifunctionality of Agroforestry: Climate-Smart Production, Protection and Ecosystem Services").

Another central benefit of agroforestry is its capacity to harvest and use more sunlight than simpler agricultural systems. A more complex system with more plants, distributed in different strata and with a higher leaf area index, can channel more sunlight into photosynthetic products compared to simpler systems. This explains the generally higher land equivalent ratio of agroforestry compared to annual cropping systems. The challenge is to match the most compatible crops and trees and manage them in such a way that the complementary phenology and optimum display of leaves throughout the year and the diurnal course of the sun will maximize light interception (Ong et al. 1996). When animals are added, the biggest benefit is obtained when they can make use of plant material which otherwise would not be used and transform them into useful products such as meat, milk, and organic fertilizer. Examples are the use of savanna grasses or the foliage of fodder shrubs and trees in dryland silvopastoral systems.

When the trees in a given agroforestry system are able to capture more additional resources with only minimal effects on the resource capture of the crops, the interactions are positive and complementary (Fig. 20; Ong and Leakey 1999). This is the case, for example, when trees are able to access nutrients or water below the rooting depth of the crops or to make better use of off-season rainfall, which could not be used by crops. In contrast, when the capture of a given resource by trees causes a disproportionately large reduction of the same resource for the crop, the interaction is competitive. This occurs, for example, under water stress when the water use by trees may cause a drastic reduction of crop yield (Fig. 20), as shown for maize growing at less than 250 mm of rain in Kenya (Ong and Leakey 1999). With higher humidity (above 650 mm), this competition did not occur. It is this same relationship of competition as a function of resource availability that allows alley cropping to work only as long as there is enough water and a minimum of nutrients for both trees and crops (see section on "Alley Cropping").

Since agroforestry systems can transform more sunlight into photosynthates than simpler agricultural systems, there will be more living biomass and, therefore, also more dead biomass. In turn, this contribution of transformed sunlight (much like the fossil fuel, a reminder of million-year-old transformed sunlight, that modern society depends on so desperately) feeds the soil fauna and its heterotrophic microflora.

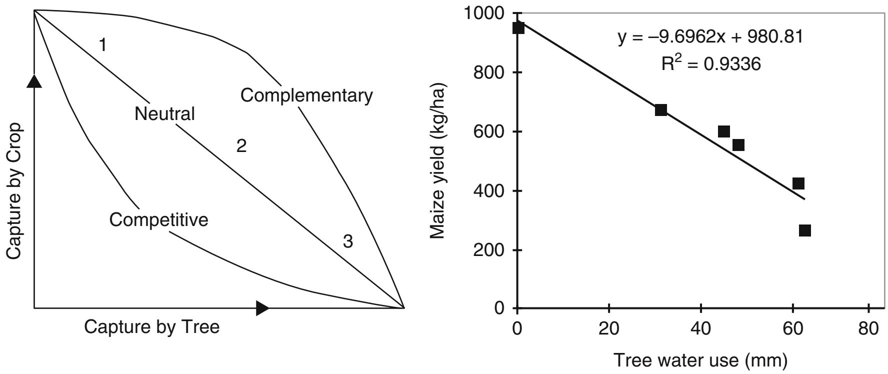

Fig. 20 *Left*: depending on the attributes of the species used and the environment in which they grow, the interactions between trees and crops can be complementary, neutral, or competitive, depending on the overall sum of resource capture by the trees and crops. *Right*: under moisture-limited conditions, tree water use determines the productivity of maize (Source: Ong and Leakey 1999)

As described in section "Benefits of Trees for Soil Fertility and Protection," "feeding the soil" and its biota is essential for moving closer toward the goal of ecological intensification and true sustainability (Lowenfels and Lewis 2010; Stamets 2005). After all, SOM and the associated soil organisms are key to protect soil fertility (Bardgett and van der Putten 2014; Young 1989), to access more nutrients and water, and to prevent the buildup of pests and diseases (Altieri and Nicholls 2003). Thus, the trees contribute both to the improvement of the crop environment[2] and to the maintenance of soil productivity as the fundamental prerequisite for productive and ecologically sustainable agroecosystems (Gliessman 2015).

The overall benefits of the system depend on the components and their interactions which, in turn, depend on the species mix, the planting arrangements, the management and pruning, as well as on the biophysical and socioeconomic environments which define growth rates and the availability of natural resources, labor, and inputs (Muschler 1993). Just as the availability of water determines whether an alley cropping arrangement can be beneficial or not (see section on "Alley Cropping"), so are temperature/elevation and soil fertility two key factors that determine the overall benefits of shade for *Coffea arabica* (Fig. 21).

Figure 21 illustrates generalized shade responses of long-term coffee production across the elevational range for coffee. These graphs reflect the quantitative data of many studies (for details see Muschler 2004). Irrespective of soil condition, the highest production of unshaded coffee typically occurs at intermediate altitudes since they provide the ideal climate for coffee. In Central America, this is often the case between altitudes of about 900 and 1,300 masl. At lower elevations, unshaded

[2]In the ideal agroforestry system, also the reverse is true: crops will improve the environment for the trees, e.g., through contributions of biologically fixed atmospheric N from N-fixing crops which can benefit the trees.

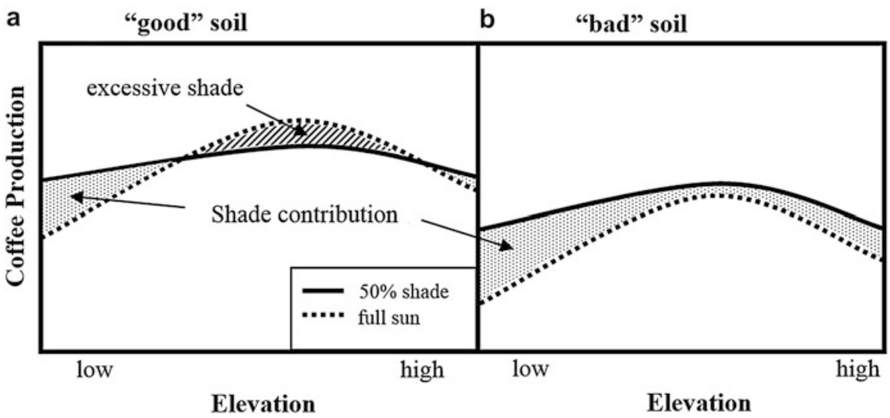

Fig. 21 Idealized coffee production in full sun (*dotted lines*) and under trees giving 50 % shade (*thick lines*) as a function of elevation for soils without (**a**) and with (**b**) limitations of rooting depth, nutrients, or moisture. Notice that the benefit from shade ("shade contribution") is largest at elevations below or above the optimum elevation for coffee. For further explanation see text

coffee production decreases in response to increasing heat stress, while at higher elevations it decreases due to low temperatures and possibly wind damage. Under such suboptimal conditions, trees can reduce the microclimatic stress to the coffee plants through shading at low elevations and through reducing winds at high elevations. Consequently, trees tend to increase coffee production over that of unshaded plots. This benefit is marked as the dappled area in Fig. 21 referred to as "shade contribution." In contrast, within the optimum elevational range, because the microclimate is already ideal for coffee, trees cannot exert such a beneficial effect via microclimate improvement. Under these conditions, shading may even reduce coffee production. This is marked as the hatched area labeled as "excessive shade" in the "good soil" scenario.

On "bad" soils, the productivity of both coffee systems is relatively lower as a result of the nutrient or moisture limitations. However, the productivity of unshaded coffee drops off more under such conditions due to the absence of the beneficial effects of trees on nutrient cycling and water retention. Consequently, the "shade contribution" becomes larger and probably extends across the whole elevational gradient. Considering these different environments, the seeming contradiction between studies that report benefits of shade and others reporting shade-induced yield reductions disappear: both positions can be right, but each one for a different environment. The benefits of trees and shade under suboptimal conditions for coffee have been amply characterized by Muschler (1998), who found that intermediate levels of shade (40–60 % shade) were the best option because they permitted combining high productivity with improved coffee quality (Muschler 2001b), while generating environmental benefits through weed control, increased nutrient cycling, and better plant health. The work on coffee quality of Salazar et al. (2000) and recent work of Pinard et al. (2014) in East Africa has confirmed these conclusions. Furthermore, it is interesting to note that tree benefits can even be detected for some environments under optimal conditions (Siles et al. 2010). Having reviewed these positive effects of trees, the question arises why trees are not used in all land use systems. What are the constraints that limit or prohibit their association with crops under certain conditions?

Constraints to the Success of Agroforestry

The main limitations for agroforestry are due to historic, socioeconomic, or biophysical factors. The historical limitation is that industrial agricultural development of the last 50 years or so has focused on yield maximization of high-input monocrops, often hybrids selected for high productivity in full sun. This is usually achieved through the complete separation of trees and crops. When the objective is to maximize the yield of one single product, there is little room for other plants, let alone high-diversity systems. This tendency remains strong even today as illustrated by the strong push for monocultures of rubber in Asia (van Nordwijk et al. 2012), of cocoa in Ghana (Ruf 2011), and of coffee in Latin America (Jha et al. 2014). The reasons for limited interest to plant trees include labor costs for planting and tending the trees, reduced productivity of the main crop, insecure land holding rights, mobility of farmers, limited rights over the use of the planted trees, little information about compatible trees, and lack of financial recompensation for generating ecological benefits from a diversified production. In different mixes, these limitations are commonplace in the tropics. The main socioeconomic constraints to agroforestry success are higher labor demand for, e.g., pruning and biomass recycling (this argument is often mentioned against alley cropping) and delayed returns from the trees, which may need more than a decade to grow to commercial dimensions.

The main biophysical limitations for tree-crop associations fall into three groups. First, the production of sun-demanding crops may be strongly reduced by excessive shade of the trees. Adequate selection and management of the trees to reduce shading and of the crop species and varieties to tolerate more shade can reduce or even eliminate this problem. Second, in nutrient- or water-limited situations, trees can affect crops negatively via competition for water and/or nutrients. An example of this is the failure of alley cropping in arid environments where water competition by the tree reduces crop production strongly (see the section on "Alley Cropping"). Furthermore, some tree species, for example, certain species of *Juglans* and *Eucalyptus*, have been shown to suppress associated plants with chemicals liberated into the soil. This effect of allelopathy is particularly pronounced in dry climates where the allelochemicals are not leached from the soil before they can act. In both cases, competition and allelopathy, it is, again, the environment that determines the degree to which the tree may negatively affect associated crops. But also the expression and magnitude of positive effects depend on the environment. And this is the third biophysical limitation. In optimum environments, with minimal or no environmental stress for the crops, the beneficial effect of trees by alleviating a stressful condition may simply not be important. Examples may be the nutrient-rich and deep volcanic (some coffee areas of the Central Highlands of Costa Rica) or alluvial soils in moist climates where crops are not stressed for nutrients or water. Under such conditions, the benefits from the trees, ignoring their universal long-term contribution to maintain soil fertility, may not be strong enough to balance their negative effects. However, such sites are the exception. Sites with some soil or climatic constraints are much more common, and it is on such sites where the positive contributions of trees can be exploited for the benefit of the associated crop.

With recent concerns about environmental degradation from high-input monocultures and the volatility of commodity prices, the production objectives are starting to become wider to include income diversification, hence increased stability, plus increased ecological resistance and resilience of the systems to pests, diseases, and climatic extremes. Increasingly, low-input technologies are being investigated where biological inputs and services substitute chemical inputs. This work assumes special relevance in tropical countries with limited financial resources. In order to generate the most effective systems, the selection of the most appropriate plants is key.

Plant Selection for Agroforestry

The experiences with agroforestry over the past four decades have shown great promise for associating trees, crops, and animals for mutual benefit and for generating essential ecosystem services for the people who depend on these systems. The use of ecologically appropriate and economically attractive trees and crops is possibly the main tool in the fight against the "monoculturization" of many systems, including rubber (van Nordwijk et al. 2012), cacao, or coffee (Jha et al. 2014; Klein et al. 2008). Finding the right trees and compatible productive crops, and promoting their use in appropriate environments, should be a central goal of future efforts.

In order to allow for the systematic screening of tree species compatible with particular crops, various authors generated lists of selection criteria of tree attributes. The criteria for identifying compatible shade trees for coffee, cacao, and tea given in the classic papers by Willey (1975) and Beer (1987) were taken up, and complemented, for the training manuals written by Geilfus (1994) and Muschler (2001a). With a focus on optimizing belowground interactions, Schroth (1995) generated a list of tree root characteristics for selecting appropriate species. As mentioned in the section on agroforestry for soil improvement, the selection of plants based on root attributes should also consider the particular capacity of mycorrhizal plants like *Cajanus cajan* and *Tithonia diversifolia* to extract P from insoluble pools in the soil. These criteria and species lists were further expanded by ICRAF and other organizations. Today, they are largely incorporated into the databases with a wealth of plant descriptors and the selection tools provided by ICRAF (see Box 1).

For the selection of overstory plants, the most desirable attributes, besides their products, include their capacity to quickly provide shade, shelter, and environmental benefits to the associated trees, shrubs, and crops. Ideally, these services should be synchronized with the needs of the associated plants (for N synchrony, see Crews and Peoples 2005) along with their phenological cycle, and of increasing importance under the scenarios of climate change, the overstory trees should be able to provide these services even under extreme climatic events. Therefore, the most desirable attributes for overstory plants include the capacity to sprout and grow easily, even on poor or shallow soils, the development of a strong and deep root system for good anchoring of the plant, and the resistance to drought and wind (Muschler 2001a; Geilfus 1994; Nair 1993; Beer 1987; von Maydell 1986).

Unfortunately, as the experiences over the past decades with the widespread introduction of the leguminous shade tree *Erythrina poeppigiana* in Costa Rica and other regions have shown, these requirements cannot always be met simultaneously. This species, native to Colombia, has been widely promoted and planted in most of the coffee regions of Costa Rica since the 1950s due to its ability to sprout easily from branch cuttings, to grow very fast so as to provide substantial shade within 6 months, and to produce much biomass. However, when trees that have been established from cuttings grow to more than 10 m in height, they may be easily toppled by strong winds; their root systems are not as strong as those from trees planted from seed. Another limitation of this species is its aggressive reproduction, which, together with its fast growth, makes it a species that is potentially invasive. Today, in many coffee farms in Costa Rica, this species has become so dominant that there is little space for other shade species and their products and services. With the interest in diversifying systems also for sustaining ecological services, care must be taken that the selection of trees and crops avoids the promotion of invasive species which can take over large areas as was the case with *Leucaena leucocephala*, neem, *Casuarina*, and many other species (Richardson et al. 2004).

Lists of appropriate crop and tree species, and their attributes, have been assembled for different regions. Notable examples are the classic "Crop Species Manual" by Nair (1980), lists of multipurpose and other trees by Nair (1993), as well as the compilation of von Maydell (1986) on trees of the Sahel. Authoritative publications on the selection, improvement, and management of trees are *Árboles de Centroamerica* (Cordero and Boshier 2003), *Specialty Crops for Pacific Islands* (Elevitch 2011), *Brazilian Fruits & Cultivated Exotics* covering 827 types of fruits by Lorenzi et al. (2006), and the classics on *Tropical Forests and their Crops* by Smith et al. (1992) and *Fruits of Warm Climates* by Morton (1987). The following sections cover central aspects of selection of trees, crops, animals, and microorganisms for creating productive and ecologically stable agroforestry systems.

Tree Domestication in Agroforestry

With respect to the domestication of trees for agroforestry, Leakey (1999) provided a review on the potential for novel food products from agroforestry trees. Recently, Leakey et al. (2012) summarized the development of this important field since its kickoff at the 1992 conference in Edinburgh, UK, on "Tropical trees: The Potential for Domestication and the Rebuilding of Forest Resources." It was at this conference that the attention focused on the need to work on these overlooked and underutilized "Cinderella" species holding a considerable potential for developing specialty products for niche markets and for improving the nutrition and income of their cultivators. The first decade of tree domestication for agroforestry in the 1990s was dedicated primarily to assess the potential of more than 50 different tree species, mostly from Africa. The species include *Irvingia gabonensis* and *Dacryodes edulis* from Cameroon and Nigeria, two of the most widely studied indigenous fruit trees from Africa. With time, farmers added other tree species to the list of promising species for providing timber, fodder, medicines, and fuelwood.

The research topics included techniques for the production of improved germplasm, the characterization of morphological and genetic variation, the promotion and marketing of such species, and farmers' rights. Successful vegetative propagation (marcotting) of trees allows to obtain fruits as early as 2 or 3 years after planting. This aspect is essential for farmers who need to receive a fast return on their investment in future tree crops. A key lesson learned is the importance of differentiating among the quality, size, and taste of fruits from individual trees. Only when this is done from the start, and maintained during the promotion of a new crop, can the market provide financial incentives for the speedy evolution of new high-quality fruits.

Looking at the topics covered by 424 scientific publications on tree domestication between 1992 and 2012 (Leakey et al. 2012), the vast majority of papers refer to the domestication concept and strategy (61 papers), propagation and germplasm (69), species potential (69), genetic and morphological characterization (89), followed by much less emphasis on nutritional benefits (23), agroforestry enrichment (22), commercial issues (22), and only a few handful of papers on all other topics. In particular it calls attention that only 14 papers addressed ecology, with a meek 5 papers on adoption and impact (all from Africa) and 6 on participatory implementation on farms (5 from Africa). Assuming that such an analysis (despite its limitations due to thematic overlaps) reveals a real trend, it shows that more work needs to be done on the upper portion of the value chains and also on strengthening the work in Asia and Latin America.

Although, compared to Africa, more work may already have been done in Asia by the PROSEA network which collected detailed information on medicinal crops, fruits, and vegetables (see online resources) and Latin America (Chizmar-Fernández et al. 2009; Padulosi et al. 2002; BOSTID 1989; Morton 1987), the realm of underutilized tree species from all continents exceeds the number of currently (widely) used species by one and possibly up to two orders of magnitude. Globally, estimates indicate that more than 50,000 species of plants are edible, including many trees. From the Brazilian Amazon, possibly the largest remaining pool of NUS, some of the salient accounts of underutilized species include more than 800 species and varieties (Lorenzi et al. 2006; Smith et al. 1992, 2007). From Africa, Nyambo et al. (2005) have summarized information about fruits and nuts for Tanzania, and Msyua et al. (2009) have reported the contents of *Fe*, *Zn*, and β-carotene for noncultivated indigenous vegetables.

For Latin America, one of the most useful resources for the agroforester, available for free download at www.arbolesdecentroamerica.info, is an authoritative compendium on the ecology, growth, and uses of more than 180 tree species, including many native species of Central America (Cordero and Boshier 2003).

With increasing uploading of essential passport information of tree and crop species to databases on the Internet, mostly through organizations of the CGIAR and UN systems, universities, and NGOs, the amount of information on tree species for the tropics is now overwhelming, although some aspects are largely missing (see section "Lessons Learnt from Tree, Crop, and Animal Domestication: Widening the Search"). Key information on more than 600 tree species for agroforestry and on over 22 000 tree and crop species can be accessed through the "Agroforestree" Database and the "Agroforestry Species Switchboard" of ICRAF (Box 1).

Box 1. Online Resources on Tree and Crop Species of the "World Agroforestry Centre" (ICRAF)

On the page http://intranet.icraf.org/treesnmarkets/sd3/decision_support_tools.php, ICRAF provides access to a series of support tools for selecting and managing tree species for agroforestry and forestry. The two most widely used systems are the "Agroforestree Database" and the "Agroforestry Species Switchboard." Other tools on tree domestication, nursery practices, species selection for different environments, genomics, and other relevant topics are found under this same link.

1. **The Agroforestree Database**
   This database (Orwa et al. 2009) is a species reference and selection guide for currently 600 tree species that are deliberately grown and managed in agroforestry systems to provide multiple outputs. The database provides key information on native and exotic trees globally and allows users also

(*continued*)

to search by country, whether a species is native or exotic, or by products and/or services provided. The characterization of each species includes a botanic description plus details on climate, distribution range, ecology, propagation, management, and uses.

URL: http://www.worldagroforestry.org/resources/databases/agroforestree

2. **The Agroforestry Species Switchboard**

The Agroforestry Species Switchboard (Kindt et al. 2013) currently includes more than 22,000 plant species in 13 web-based databases. When possible, hyperlinks are provided to facilitate access of information to the linked databases.

URL: http://www.worldagroforestry.org/products/switchboard/index.php

Selection of Crop Species for Agroforestry

Besides its desired products and functions, whether a particular plant species is appropriate or not for agroforestry depends on the attributes of this species that make it fit into the specific agronomic niche in an agroforestry arrangement. For example, for understory plants, this includes the capacity to tolerate a certain level of shade and tolerance of the associated plants. As summarized by Cannell (1983), the response of a crop plant to shading depends on the type of plant and whether its final product will be a fruit, a leaf, or a storage organ (Fig. 22, left). Similarly, the response of crop plants to soil fertility will vary between different types of crops depending on the size of their root systems and symbiotic partners. While nonleguminous vegetables and fruit trees tend to suffer heavily on less fertile soils, N-fixing legumes and many tree species are able to cope better with lower soil fertility (Fig. 22, right), being helped by N-fixing symbionts, mycorrhizae, and larger root systems. This generalized behavior has obvious implications for the choice of appropriate crops under particular conditions of shading and soil fertility. Of course, it must be stressed that, as always, generalizations must be treated with caution and that there are exceptions.

The response of crop plants to shade has been studied in great detail for some tropical crops, particularly coffee and cacao (*Theobroma cacao*) that have been produced very successfully as an understory crop under the shade of multiple tree strata (Vaast and Somarriba 2014; Somarriba and Beer 2011). Another example is coffee, which can, depending on species and variety, cope with a wide range of light conditions ranging from full sun exposure in the lowlands for Robusta or Liberica coffee (*Coffea canephora* or *C. liberica*) all the way to an intermediate shade level of 40–60 % or even more under suboptimal conditions for *C. arabica* (Muschler 2004). While the agronomic research since the 1970s has generated a lot of research on the shade-sun requirements or preferences of these two crops as a function of environmental and management factors, this detail of information is, unfortunately, still only partially available for many other crops. For the agroforestry practitioner, the classic summary of environmental requirements of many crops (Nair 1980) is still a good starting point, complemented by additional information from online resources.

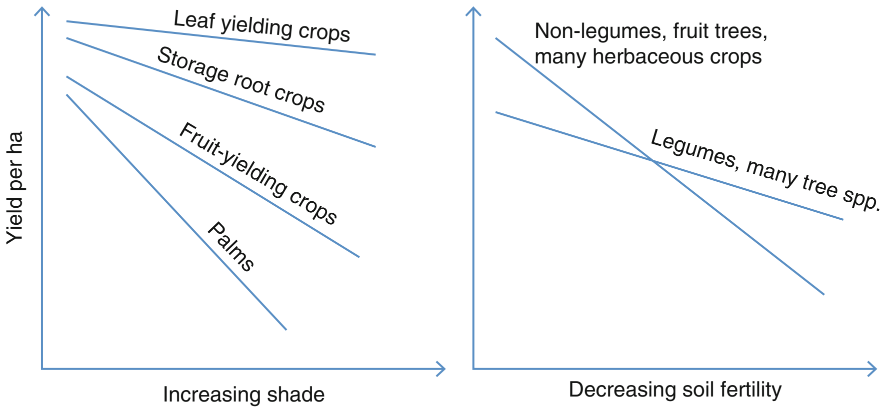

Fig. 22 Generalized response of different types of crops to increasing levels of shade and decreasing soil fertility (Modified from Cannell 1983)

For the selection of underutilized crops, a good starting point is the recent review by Ebert (2014). The range of promising crops and trees includes more than 100 edible species from Central America (Chizmar-Fernández et al. 2009) and a multiple from many other tropical regions. While some of them provide relatively small contributions to the overall productivity because only their flowers, select leaves, or a small portion of their stems are commonly used, some of them offer an interesting potential as complementary crops, particularly when they substitute plants of less use. With regard to the conservation and better use of agrobiodiversity, it should be a high priority to collect locally adapted crop species and their seeds or other reproductive tissues and to document the tacit information about their uses. One interesting example comes from El Salvador, where more than 20 species have been documented recently as promising components in climate-smart agroforestry systems designed for improving food security (Sánchez-Salmerón et al. 2015; Box 2).

Box 2. Identification of Underutilized Promising Species for Agroforestry Systems in El Salvador (Sánchez-Salmerón et al. 2015)

The leaves of many plants can provide high levels of vitamins A and C, as well as proteins and micronutrients such as Fe and Zn, which are often deficient in the diets of many poor communities in the tropics (FAO 2011). Based on interviews with farmers of different ages, Sánchez-Salmerón et al. (2015) obtained a list of 23 promising species that combine favorable agronomic attributes (Geilfus 2002) with adaptation to stress of extreme climate change events and high micronutrient content. Of these 23 species, 18 are high in Fe, 11 high in Zn, and 8 have medium or high levels of vitamin A. In addition, 12 of these species are reported as drought resistant, 11 resist

(*continued*)

strong winds, 4 resist inundations, and 8 withstand high temperatures. Finally, two of the top species (*Moringa oleifera* and *Cnidoscolus chayamansa*) provide nutritious leaves for human nutrition throughout the year; both are woody agroforestry species. The list includes the species presented in Table 3.

Similar information from Africa, Asia, and elsewhere should be increasingly considered for the search for new food crops that allow adding nutrition and agronomic resilience to the food systems of the future. Good starting points are the publications on *Lost Crops of the Incas* and *Lost Crops of Africa* by BOSTID (1989, 1996a, b) as well as the encyclopedic information of the *Plant Resources of South-East Asia* Network (PROSEA), as well as Smith et al. (1992). Although many promising crop materials are already available in the extensive germplasm collections of organizations like CATIE (Ebert et al. 2007) in Costa Rica and "The World Vegetable Center" (AVRDC) in Taiwan, they are yet to be studied in more detail in order to realize their agronomic and nutritional potential. Although still greatly underfunded and in its infancy, an increasing amount of information is coming online on underutilized crops, also called "orphan crops" or "foods of the future" (Jaenicke and Höschle-Zeledon 2006), promoted by international nongovernmental initiatives such as "Slow Food" (www.slowfood.org) or "Grain" (www.grain.com), which support small farmers and social movements in their struggles for community-controlled and biodiversity-based food systems.

Undoubtedly, in the years to come, the search for new crops or trees for agroforestry systems will also have to address the potential and limitations of genetically transformed crops. The range includes not only first- or second-generation GMOs but also plants modified for nutritional benefits or for higher photosynthetic capacities such as a C4-type rice that is currently in development. The recent reviews of Antoniou et al. (2012) and by Funes-Monzote and Freyre (2009) are good starting points to analyze the potential implications for human and ecosystem health.

For the selection and best arrangement of crops and trees, it would be good to build on the experiences of "companion planting," i.e., the matching of particularly compatible species such as carrots and tomatoes (Riotte 1998; see also the section in Wikipedia). While companion planting is a time-proven practice in horticulture and gardening, the systematic application of this practice is yet pending for agroforestry. The positive examples of species matches such as certain legume and timber species with coffee and cacao (Somarriba et al. 2014; Somarriba and Beer 2011), or the tree – pasture – animal matches in silvopastoral systems, illustrate that much information exists, but the building of a structured systematic tool for identifying the best matches is still pending. The development of a matrix of crop-crop, crop-tree, and tree-tree compatibility may be a useful step. Finally, considering the large intraspecific variability of crop responses and quality (e.g., hundreds of varieties of squash, tomatoes, etc.), also this level of variability should be considered to match the most appropriate varieties to the specific system and the

Table 3 Promising underutilized plant species for agricultural and agroforestry systems in El Salvador (Sánchez-Salmerón et al. 2015)

Plant name			Adaptation to CC				Micronutrient level[a]			Harvest season in El Salvador											
			Tolerant to:																		
Scientific name (bold letters indicate woody spp.)	Common name (in El Salvador)	Plant part used	Drought	Strong winds	Inundation	High temperature	Fe	Zn	VitA	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Artocarpus altilis	Árbol de pan	*Seed*			x		h	h	l			x	x								x
Bromelia alsodes	Piñuela	*Young shoots*	x	x		x	m	l	nd												
Brosimum alicastrum	Ojushte[b]	*Seed*	x	x		x	h	h	m				x	x			x				
Calathea macrosepala	Macuz	*Flower, root*			x		h	h	nd								x			x	
Cnidoscolus chayamansa	Chaya	*Leaf*	x				h	h	a	x	x	x	x	x	x	x	x	x	x	x	x
Crescentia alata	Morro	*Seed*	x	x		x	h	a	nd		x	x	x								
Crotalaria longirostrata	Chipilín	*Leaf*		x			h	nd	m						x	x	x	x	x	x	
Gliricidia sepium	Madre cacao	*Flower*	x				m	nd	nd		X										
Ipomoea batatas	Camote	*Root*		x			l	l	a	x	x										
Matelea sp.	Chuchulaya	*Leaf*		x			h	l	nd						x	x	x	x	x	x	
Moringa oleifera	Moringa	*Leaf*	x				h	m	m	x	x	x	x	x	x	x	x	x	x	x	x
Portulaca oleracea	Verdolaga	*Leaf*		x		x	h	nd	m												

(*continued*)

Table 3 (continued)

Plant name			Adaptation to CC				Micronutrient level[a]			Harvest season in El Salvador											
			Tolerant to:																		
Scientific name (bold letters indicate woody spp.)	Common name (in El Salvador)	Plant part used	Drought	Strong winds	Inundation	High temperature	Fe	Zn	VitA	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Sesamum indicum	Ajonjolí[b]	*Seed*	x				h	h	l											x	
Solanum americanum	Mora	*Leaf*		x	x		h	m	m						x	x	x	x	x	x	
Sorghum sp.	Maicillo[b]	*Seed*	x			x	h	H	nd	x										x	x
Spondias purpurea	Jocote	*Fruit, leaves*	x			x	h	nd	m			x	x		x	x	x	x	x	x	
Phaseolus lunatus	Frijol chilipucas[b]	*Seed*	x	x		x	h	h	nd	x										x	x
Vigna umbellata	Frijol arroz[b]	*Seed*	x	x			h	h		x										x	x
Xanthosoma sagittifolium	Malanga	*Root*			x		h	h	b	x	x	x	x	x	x	x	x	x	x	x	x
Yucca elephantipes	Izote	*Flower, shoot*	x	x		x	h	l	nd			x	x								
Zea mays	Maíz amarillo[b]	*Seed*	x				h	h	b							x			x		
Zea mays	Maíz negro[b]	*Seed*	x				h	h	nd							x			x		
Zea mays	Maíz tizate[b]	*Seed*	x				h	h	nd							x			x		

[a] *h* high, *m* medium, *l* low, *nd* not determined
[b] Plant products can be stored for more than a year

season. This is already a practice in urban gardening in Cuba by using different varieties for different seasons (INIFAT 2011).

Selection of Animal Species

While most of the mainstream agricultural and agroforestry work with animals has concentrated largely on systems with cattle (Pezo and Ibrahim 2001), goats (Benavides and Arias 1995), and chicken, there is also great potential in exploring other animal species for the design of locally adapted agroforestry systems. For example, in some places, sheep are being used for the production of meat and milk or for providing the service of weeding as, for example, in coffee fields in Central America (Leupolz 2000). In other cases, pigs can be integrated to produce meat and biogas for cooking. Furthermore, there is a wide field to be explored with the production of "exotic" species and microbreeds for special animal production systems. A global review published by BOSTID (1991) revealed a significant potential for microbreeds of cattle, goats, sheep and pigs, but also more than 30 species of poultry, rodents, lizards, and others. In many places, rabbits, guinea pigs, and other small animals can be raised profitably with tree fodder from agroforestry systems, but so far, relatively little attention is being paid to these options. In Central America, a remarkable example is the native green iguana, which can easily be raised for meat production on a leafy diet from agroforestry systems (BOSTID 1991). Undoubtedly, with increasing pressure on natural resources and the evolution of specialty markets, there is a significant potential to be explored.

Another field that is yet to be developed is the production of edible insects. Compared to the production of beef, pork, chicken, or milk, the production of an equivalent amount of animal protein from raising insects such as mealworms requires only a fraction of the food and water and liberates much less greenhouse gases, up to 100 times less (van Huis et al. 2013). Considering the lower feed requirements of cold-blooded insects and the higher edible proportion of insect biomass (up to 80 %), the feed efficiency for crickets, for example, is twice as high as that of chicken, at least four times higher than that for pigs, and even 12 times higher than for cattle. Clearly, this makes edible insects an interesting alternative to the conventional production of meat, either for direct human consumption or for indirect use as feedstock for animals (van Huis et al. 2013). However, much work needs to be done to boost awareness about the contributions of insects for sustaining, complementing, or even enhancing agroforestry systems and for contributing valuable and nutritious food and feed.

The synergistic effects of having a higher insect diversity were shown by Brittain et al. (2013) for the improved pollination of almond trees when honeybees are accompanied by stingless bees. Overall, there is a great need to make better use of the potential benefits that can be generated by diversifying the insect communities in agroforestry systems. Again, also this dimension underlines the pivotal importance of diversifying the production systems with more plant species, not only for providing a broader palette of products but also to foster the survival and services of an effective and synergistic associated and auxiliary biodiversity (Vazquez 2014; Nicholls and Altieri 2013).

Selection and Use of Microbial Symbionts and Other Beneficial Soil Organisms

As mentioned in the section on agroforestry benefits for soil fertility, increasing attention should be given to the active selection and more widespread use of free-living and symbiotic microbes and soil fauna, particularly earthworms. Of the more than 6000 species of earthworms, only about 10 have been studied in some detail (Lavelle et al. 1999). There is a great need to advance our knowledge about their ecology and management in order to maximize their benefits for the overall productivity of the agroforestry systems of the future. The impressive developments in composting and vermiculture, i.e., the use of earthworms to transform organic materials into high-quality fertilizer, demonstrate the vast potential (Benzing 2001; Aranda et al. 1999; Beck 1997). One illustrative example was reported by Castellón et al. (2000), who demonstrated that adding 25 % of composted or vermicomposted coffee pulp to the substrate of organically grown coffee seedlings stimulated growth and plant health just as much as the conventional fertilizer and fungicide treatment. Therefore, the conventional treatment with synthetic chemical inputs can be substituted with no harm by biological treatments. This is but one example for mitigating climate change, as discussed in section "Multifunctionality of Agroforestry: Climate-Smart Production, Protection and Ecosystem Services."

At least 90 % of all plant species have evolved in association with beneficial soil microorganisms such as bacteria, actinomycetes, and fungi as symbiotic partners (Lowenfels and Lewis 2010). Some of them, particularly rhizobial bacteria, convert atmospheric N to N forms that can be used by plants, and others, particularly fungi, form symbiotic relationships with plant roots to access soil nutrients which would often not be available to just bare roots (Hauggaard-Nielsen and Jensen 2005; Margulis 1998). Just as important as the N-fixers are for providing nitrogen to plant associations (Jalonen et al. 2009; notice that natural forest ecosystems tend to have an adequate supply of nitrogen as evidenced by the color of their canopy), so are mycorrhizal fungi for improving physical, chemical, and biological soil quality (Bardgett and van der Putten 2014; Jordan 1985). The association of plant roots with mycorrhizal fungi increases the active surface of the now greatly extended root system of the plant-fungus complex by several orders of magnitude, multiplying the capacity of the associated plant to access poorly available nutrients, particularly P and some micronutrients like Zn (Lowenfels and Lewis 2010; Stamets 2005; Sieverding 1991). Furthermore, the mycorrhizae can reduce Al and Mn toxicity, benefit N-fixing rhizobia and other beneficial soil organisms, and help protect against pathogens (Cardoso and Kuyper 2006). Finally, recent research has demonstrated how "common mycorrhizal networks" can benefit plants, even of different species and photosynthetic pathways, when they are connected by joint mycorrhizal networks. Walder et al. (2012) demonstrated an increase of 11 % for plants of sorghum and flax when they were connected by mycorrhizae. For flax, productivity even increased by 46 % when the plants were linked to hyphal networks. These examples illustrate the great potential to be explored by optimizing the matching plants and microbial partners.

Doubtlessly, for the much needed "biological intensification" of agroforestry and other systems (FAO 2013), it will become of increasing importance to identify and make wider use of free-living and symbiotic N-fixers and their most effective mycorrhizal partners which can help to greatly boost both the water and nutrient use efficiency of the inoculated crops. To reduce costs of inoculation and to avoid time lags until the symbionts are well established, increasing attention should also be given to foster agroforestry interventions, reduced soil disturbance, minimum tillage, and appropriate crop rotations so as to assure the survival and activity of these beneficial microorganisms in the soils (Mutua et al. 2014; Magdoff and van Es 2009; Cardoso and Kuyper 2006).

Furthermore, given the essential functions of these symbiotic, and other free-living, microorganisms for soil health and its suppressiveness, i.e., the biological capacity of a given soil to use its beneficial microorganisms and the soil fauna to hold in check potential pathogens and nematodes, it becomes clear that much more attention should be given to study the effects of fertilizers and pesticides on the soil microbiota (Stamets 2005; Sieverding 1991). While synthetic inputs often affect the soil flora and fauna negatively (Kimbrell 2002), the opposite is true for organic compounds from tree and crop residues produced on site or from biological inputs in the form of animal manures, composts, and waste materials. This constitutes the base for the obligate positive feedback loop of "feeding the soil to feed the crops," which is not only the key message of concerned soil scientists (Montgomery 2012; Magdoff and Van Es 2009) but is also at the heart of permaculture (Mollison 1996), biointensive agriculture (Jeavons 2014), and biologically intensified urban agriculture in Cuba and elsewhere (Altieri 2002, 1999). Clearly, being able to produce (sustainably) more than 10 kg/m^2/year of fresh organic vegetables on poor lateritic soils under stressful climatic conditions in Cuba (INIFAT 2011) gives convincing evidence of the central importance of incorporating organic matter into the soils and adding, as well as caring, for the beneficial soil microbes (Martinez-Viera and Dibut-Álvarez 2012; Lowenfels and Lewis 2010) for increased nutrient access and disease suppressiveness (Thuerig et al. 2009; Weller et al. 2002).

For agroforestry practitioners, the Internet resource www.mycorrhizae.com provides easily readable materials on the "whys" and "how to" aspects of using mycorrhizal inoculants (Amaranthus et al. 2012). The textbook *Mycelium Running* by Paul Stamets (2005) is a comprehensive reference. For Spanish-speaking practitioners, Martinez-Viera and Dibut-Alvarez (2012) published a detailed review on bacterial biofertilizers, based on the extensive advances in this field in Cuban organic urban agriculture. For the future, the conscientious selection and more widespread use of microbial symbionts will have to play a much more important role for the agroecological optimization of agroforestry systems.

Lessons Learnt from Tree, Crop, and Animal Domestication: Widening the Search

The selection of trees, crops, and animals for climate-smart agroforestry systems of the future should start from a wider scope of potential candidate species (FAO 2015; Kahane et al. 2013; Padulosi et al. 2002), including a wide range of un- or semidomesticated fruit trees and underutilized, sometimes forgotten, crops from the Amazon (Lorenzi et al. 2006; Villachica 1996), Africa (Abukutsa-Onyango 2014), and Asia (Ebert 2014; Keatinge et al. 2010) which may offer substantial nutritional benefits (Leterme et al. 1996). The breeding and selection efforts should give special attention to striking a balance between productivity and quality traits on the one hand and the plants' capacity to resist pests and diseases as much as possible (Robinson 2007).

The selection of crops to withstand stressful conditions, such as increasingly frequent and severe droughts that are likely to occur under the scenarios of climate change, must respond to a wider range of attributes beyond the standard agronomic characteristics and should also make wider use of the experiences on other continents. For example, the extensive experiences on breeding of drought-resistant varieties of sorghum and millets from Africa (Reynolds et al. 2010) are likely to become of increasing importance also for the Caribbean and for increasingly drier areas on the Pacific side of Central America and elsewhere. Another example comes from the breeding and promotion efforts on making better use of highly nutritious plants like the African nightshade, spider plant, jute mallow, vegetable cowpea, slenderleaf, African kale, and vine spinach (Abukutsa-Onyango 2014). The experiences with the promotion of NUS should be shared more widely without being subject to continental limits.

In the Neotropics, ancestral or new uses of traditional crops such as *Portulaca oleracea*, *Cnidoscolus chayamansa*, *Brosimum alicastrum* (called "Maya Nut," a tall, nutritious, and productive tree for subhumid environments), or species of *Amaranthus* ("food of the gods" for indigenous Neotropical populations, but vilified by Spanish colonizers) for the production and human consumption of highly nutritious edible leaves in the form of a tropical spinach should become more important as we diversify our diets with fruits and vegetables (Keatinge et al. 2010; Box 2 and Fig. 23). As Leterme et al. (1996) have shown for Colombian lowland species, the mineral content of leaves of edible woody plants can be much higher than that of fruits and tubers, especially in Ca (280–1,242 mg Ca/100 g edible portion) and Fe (0.7–8.4 mg Fe/100 g edible portion), two elements often deficient in human diets. As the outstandingly high concentrations of Ca, Fe, and other elements in the leaves of *Trichanthera gigantea* (Fig. 23) show (up to more than 40 times higher than corn, bread fruit, and fruits; this species is already being promoted for improved animal nutrition), there is great potential for improving also human nutrition by adding more leaves to the diets. Interestingly, the high concentration of Ca, Fe, and Zn in the tubers of *Pachyrhizus erosus* (on average, five to ten times higher than most "traditional" crops; Leterme et al. 1996; Fig. 23) illustrates that there is also great potential among tropical tubers. *Pachyrhizus* sp. is an example of a very promising multipurpose plant to diversify production systems with an edible, drought-resistant N-fixing scrambling crop for soil protection or recuperation. At a global level, more support should be

Fig. 23 Some examples of the wide range of promising underutilized crop species which can help to diversify diets and the production systems, adding micronutrients, vitamin A, and "climate smartness." *Top*, from *left* to *right*: *Trichanthera gigantea*, *Sesamum indicum*, amaranth for leaf consumption. *Bottom*: yam bean (*Pachyrhizus erosus*) is a N-fixing legume for soil improvement and produces an edible tuber. The nutritious plate is loaded with vitamins and minerals from squash, tree spinach (*Cnidoscolus chayamansa*), peach palm fruits (*Bactris gasipaes*, *bottom left*), beans, and a mix of tomatoes with white pieces of fresh yam bean. The drink is made from roasted sesame seeds (Photo credits: R. Muschler at "Finca Loroco," Costa Rica)

given to identify and promote neglected and underutilized crops (NUS = "orphan crops"), for human consumption and the (demand-driven) diversification of land use systems (Jaenicke and Höschle-Zeledon 2006).

Information to be Added to Crop and Tree Databases

While there is a lot of information in the abovementioned databases, there is yet little information on the nutritional composition of many of these plants[3] (Leterme

[3]A good starting point is the USDA National Nutrient Database at www.nal.usda.gov/fnic/foodcomp/search/index.html

et al. 1996) and on their average productivity that could be expected given appropriate conditions for growth. This information is essential for estimating the total nutritional contributions that could be derived from individual plants (total nutritional output per plant = number or quantity of fruits or other edible plant part * weight/fruit * edible portion * nutritional concentration). In turn, such estimates are essential for calculating the number of plants needed to meet certain nutritional targets, particularly with respect to micronutrients and enzymes important to combat “hidden hunger.”

Furthermore, there is often very limited, if any, information on (i) acceptable or ideal soil conditions (often the categories used are so broad to be of little practical value); (ii) the association with beneficial microorganisms such as N-fixers and mycorrhizae (species/strains, inoculation, etc.); (iii) the speed of growth that can be expected; (iv) the best management (pruning intensities, planting, etc.); (v) the importance for pollinators and other organisms; and (vi) indications about harvesting, post-harvest handling/transformation, and storage. Two other key aspects almost completely lacking despite their great importance are (vii) the ecological/agronomic compatibility with other crops and trees (in the sense of “companion planting”) and (viii) the capacity to resist extreme climatic events such as inundations, extreme droughts, and strong winds. Undoubtedly, this information, arranged in an expanded matrix approach, possibly like the one proposed by Sanchez-Salmerón et al. (2015) will become more and more important for deciding on the best species mixes for the climate-smart agroforestry systems of the future.

Multifunctionality of Agroforestry: Climate-Smart Production, Protection, and Ecosystem Services

One of the central attractives of agroforestry is its multifunctionality, which allows combining the provision of different products with effective environmental protection and resulting ecosystem services; the latter are a prerequisite for climate-smart production systems that are able to adapt to, and mitigate, climate change. Wherever the trees’ beneficial effects, including income from the sale of timber, fuelwood, and fruits, outweigh possible competitive effects, the agroforestry association will be a better land use option than a monocrop. This is likely true for large areas of the tropics where trees can alleviate climatic or edaphic constraints and supply the increasing demand for tree-derived products. Furthermore, the increasingly urgent quest for environmental sustainability and conservation of biodiversity (bees and migratory birds are two of the most widely discussed groups), the rising demand for timber, and the recent interest in C sequestration and a reduction of greenhouse gas emissions from agriculture and livestock also drive the growing interest in planting more trees in agroforestry (Nair and Garrity 2012).

Still, decided efforts are needed on multiple fronts to raise the common awareness about the benefits of agroforestry systems for long-term sustainability.

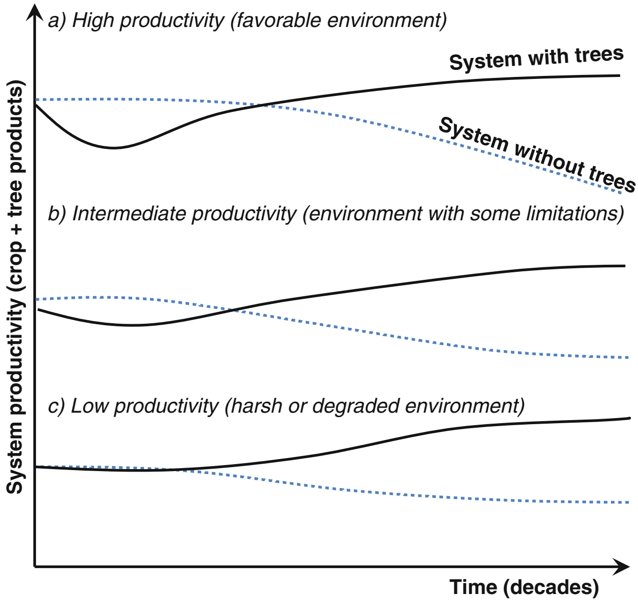

Fig. 24 Conceptual graph to illustrate the tendencies of system productivity (i.e., crop plus tree products) of land use systems with trees (*solid lines*) compared to systems without trees (*dotted lines*). Scenarios *a–c* indicate that the tendencies vary according to the initial productivity as a function of environmental factors, particularly soil fertility and climatic patterns. Although trees may cause temporary reductions as the immature trees compete with the crops without providing products themselves, well-managed agroforestry systems tend to generate benefits in the long run. These are due to their production of multiple outputs and their contributions to conserve or even improve soil fertility, water retention capacity, and beneficial biodiversity. The long-term ecosystem benefits of agroforestry systems are now widely recognized as essential for designing climate-smart land use systems

One starting point for this is to recognize that short-term losses during the first years of establishing agroforestry systems, if they occur, are usually over-compensated by long-term benefits (Fig. 24). The four key messages from Fig. 24 are as follows: (i) agroforestry systems tend to maintain their productivity including ecosystem services over time, while treeless systems tend to decline in the long run due to the loss of soil, water, or biodiversity; (ii) there is a time lag of some years after establishing agroforestry systems during which the total productivity may be lower compared to a treeless system, because the juvenile trees start to compete with the crops without providing products yet. However, this short-term disadvantage is usually compensated by the long-term effects; (iii) the productivity decline in treeless systems is likely higher in environments that have initially high productivities, because there are more natural resources to be lost over time, and (iv) in harsh or limiting environments, the benefits from including trees can lead to a long-term net increase of system productivity due to slow improvements of soil fertility and the recuperation of other natural resources. The following sections present some salient examples of how agroforestry contributes to the conservation of biodiversity and ecosystem services on the one hand and to climate-smart production systems on the other.

Agroforestry for Biodiversity Conservation and Ecosystem Services

Agroforestry systems have more plant, animal, and microbial species than typical agricultural systems. In addition, the distribution of these species often is nonuniform, forming patches of different plant associations in the landscape. In addition, the higher species richness and patchiness of the planted components in agroforestry systems favor the presence of more associated biodiversity in the form of insects, birds, and other heterotrophic organisms. Consequently, these attributes permit that agroforestry contributes significantly to the conservation of cultivated and wild biodiversity. The authoritative multiauthor review of the contributions of agroforestry to biodiversity conservation in tropical landscapes (Schroth et al. 2004) provides a wealth of information on the linkages between conservation biology, landscape ecology, and agroforestry. It reviewed the contributions of different agroforestry practices to the conservation of wild biodiversity by establishing, or serving as, biological corridors, buffer zones, or surrogate forests. As natural ecosystems continue to be transformed and, hence, loose much of their original biodiversity, agroecosystems are becoming more and more important for the conservation of biodiversity. Agroforestry systems and agroecological practices are at the heart of this.

Compared to biologically impoverish sun-grown systems, shaded coffee, cacao, or tea plantations are among the most biodiverse agroforestry systems (Philpott et al. 2008; Perfecto et al. 1996). Other examples of high-biodiversity systems include rubber agroforests in Asia, homegardens in India, Chagga homegardens in Africa, and many other complex systems elsewhere (Nair 1989, 1993). These agroforestry systems are examples of ecologically rich, and therefore more stable, systems (Rapidel et al. 2011; McCann 2000). The web of interactions among their many components reduce the probabilities of devastating pest and disease outbreaks (Staver et al. 2001; Ewel 1986) and enable these systems to sustain themselves over time, while generating income and work through the varied outputs such as coffee, cacao, timber, fruits, and fuelwood (Beer et al. 1998). When such systems are replaced by simpler ones, it is often due to economic incentives or distortions that respond to short-term objectives or ignore the real costs of negative externalities such as soil erosion or water contamination. Unfortunately, this is the case for the current substitution of many biodiverse rubber agroforests in Indonesia by rubber monocultures (van Nordwijk et al. 2012) or for the ongoing abandonment or transformation of many shade-coffee systems in Central and South America by more productive high-input unshaded systems in countries with lower production costs in Asia and Brazil (Jha et al. 2014; Philpott et al. 2008). Of course, in these cases, “more productive” refers to rubber or coffee as the only products, while the tree products and services from the shaded systems are lost. These shifts, trading long-term benefits and multiple products for short-term gains and just one product, pose great threats due to the loss of the associated biodiversity and environmental services essential for the long-term sustainability. In Latin America, the loss of biodiversity from coffee fields is of particular concern, because most coffee production areas coincide with biodiversity "hotspots" (Hardner and Rice 2002).

As a response to Daily's (1997) classic call of attention regarding the modern erosion of "Nature's Services" and the "Millennium Ecosystem Assessment" in 2005, which provided further evidence of a global decline of ecosystem services, there has been an increasing interest in understanding the factors responsible for this decline. Undoubtedly, as mentioned in section "Agroforestry: Evolution, Definition, Practices and Systems," the green-revolution practices oriented toward monocultures played (and continue to play) a major role (Kimbrell 2002) besides increasing human population pressure. During the past decade, research has revealed many ways for agroforestry to contribute to biodiversity conservation (Schroth et al. 2004) and for providing and paying for ecosystem services (see Rapidel et al. (2011) for a wealth of case studies from Latin America).

The major ecosystem services of agroforestry can be arranged in six dimensions (Table 4): (1) biodiversity conservation (above- and belowground; from microorganisms to mammals and trees), (2) tree/crop/animal facilitation (positive effects among the components), (3) soil conservation and enrichment (biological and chemical), (4) conservation of air and water quality and quantity, (5) carbon sequestration and climate change mitigation (including through the deposition of slow-release C in the soil as SOM and biochar), and (6) aesthetic and cultural richness. These services have high relevance for the long-term sustainability of ecosystems, as well as for the adaptation to and mitigation of climate change. Just like the conservation of functional biodiversity is key to reducing the environmental footprint of chemical plant protection agents by substituting these by (ideally, self-reproducing) biological means, so is soil enrichment key to reducing the needs for synthetic fertilizers (cf. section "Selection and Use of Microbial Symbionts and Other Beneficial Soil Organisms"). It is interesting to note that while all functions have local relevance, some also have regional relevance within the local landscape context such as the services for the prevention and management of pests and diseases or pollination (Fig. 2), and a few have even global relevance, as is the case for migratory birds which depend on habitat and food along their annual migratory routes (NABCI Canada 2012).

Although our understanding has greatly increased regarding the interactions between agroforestry systems and biodiversity conservation (Schroth and Harvey 2007; Schroth et al. 2004; Stolton et al. 2000; Rice and Greenberg 2000), much remains to be discovered. Of particular importance is the question of how to optimize symbiotic and synergistic species associations to increase water and nutrient use efficiencies as well as the pest and disease suppressivity of the system (Vazquez 2014), while maximizing the products and services of the system (Vaast and Somarriba 2014). Only when we learn more about the functions of the different organisms, including birds (Sekercioglu 2012) and their potential as predators of arthropods (e.g., van Bael et al. 2008); different organisms that pollinate crops (Klein et al. 2008); others like ants, wasps, and spiders that are key for pest and disease suppressiveness (Daghela et al. 2013); and decomposers such as dung

Table 4 Spatial scale of ecosystem services of agroforestry (Expanded from Jose 2009)

Ecosystem service		**Spatial scale**		
Dimension (mechanism)	*Function/effect*	*Local (farm)*	*Regional (landscape)*	*Global*
Biodiversity conservation	Locally adapted crops, trees, animals and microorganisms			
	Prevention and biological control of pests and diseases			
	Pollination/seed dispersal			
	Migratory species (birds, mammals…)			
Facilitation among components	Microclimatic benefits (e.g. effects of nurse/shade trees)			
	Symbiotic interactions (N fixation, mycorrhizae)			
	Deep-soil nutrient capture and cycling			
Soil conservation & enrichment	Improved soil cover			
	Enrichment with organic matter			
	Soil suppressiveness (diseases, nematodes, etc.)			
	Soil stabilization/erosion control			
Air and water	Clear air and water (filters dust and pollutants)			
	Fosters water retention in watersheds			
	Flood mitigation			
C sequestration & CC mitigation	C storage in growing biomass and long-term deposition (e.g. as biochar in soils)			
	Biological synergies reduce needs for synthetic inputs (fertilizers, pesticides)			
	Improved nutrition of ruminants reduces CH_4 emissions			
Aesthetics & cultural values	Scenic beauty			
	Food diversity & nutrition benefits			
	Local identity/traditions			

beetles which affect soil fertility greatly (Nichols et al. 2008), will we be able to better value, and foster, their services by paying attention to each organisms' needs for survival. Clearly, additional research is needed on the links between biodiversity, ecosystem functions, and ecological services in order to optimize the system design (Kremen 2005).

Recognizing the great importance of multistrata agroforestry systems with coffee and other crops for migratory birds, including many whose numbers are rapidly dwindling (some by more than 60 %, NABCI Canada 2012), the "Smithsonian Migratory Bird Center" has established certification criteria[4] for the production of "bird-friendly coffee" (Fig. 25). These criteria include using at least 11, preferably native, tree species per ha, arranged in 3 strata, and growing the coffee under organic management. Using such a certification approach can contribute greatly to promote the maintenance of species-rich multistrata systems. Unfortunately, the price differential that a producer can receive for bird-friendly coffee is not sufficient for most producers to compensate for the lower productivity of coffee in such a system under organic management (Lyngbaek et al. 2001). Much needs to be done to create more consumer awareness, more fairness in the value chain (increasing the benefits to the producers), and to promote this and other certification approaches effectively (Soto and Le Coq 2011). A very useful overview of different certification criteria, including biodiversity, social, and economic standards, is available at http://www.coffeehabitat.com/certification-guide/.

[4]http://nationalzoo.si.edu/SCBI/MigratoryBirds/Coffee/default.cfm

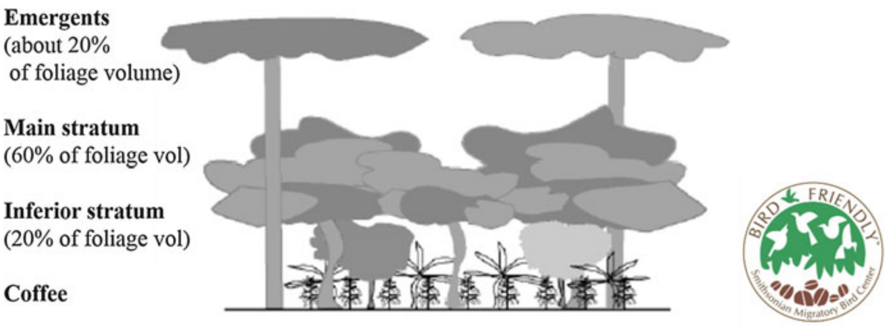

Fig. 25 The three main strata required for the certification of "bird-friendly coffee" according to the criteria established by the "Smithsonian Migratory Bird Center"

In order to help map ecosystem services, Kareiva et al. (2011) recently assembled a methodological toolbox. Undoubtedly, the application of such tools, including modeling and valuation approaches, holds great promise for the design of climate-smart landscapes including agroforestry systems at the interface of production and conservation of ecosystem services.

Contributions of Agroforestry to Climate-Smart and Multifunctional Agriculture

The potential of agroforestry for climate-smart agriculture, sometimes also called multifunctional agriculture, has been amply recognized by the research and development community. One central aspect is that a higher diversity of species tends to favor stability (McCann 2000), and another one is derived from the long-term benefits of trees on soil fertility, carbon stocks, and the reduction of the needs for chemical inputs (see section on "Soil Fertility"). In its sourcebook of climate-smart agriculture, FAO (2013) recognizes that agroforestry can contribute both to climate change mitigation and adaptation through different ways. For mitigation, the main mechanisms are (i) C sequestration and retention in biomass and the soil, (ii) the substitution of synthetic inputs by biological mechanisms (this is of particular importance for N fertilizers which may release significant amounts of N_2O), and (iii) the reduction of enteric CH_4 emissions from ruminants by receiving improved feed and fodder. For adaptation, agroforestry can increase the resistance and resilience of the system to climate variability because the trees buffer against extreme climatic events, protect soils and watercourses, and diversify the production (Matocha et al. 2012; Muschler 2001a): shade trees reduce heat stress on animals and crops; fruit, timber, and fuelwood species provide additional products which buffer against price fluctuations of individual products; and fodder trees supply high-quality forage to reduce grazing pressure, land degradation, and methane emissions (Thornton and Herrero 2010; Reid et al. 2004).

Table 5 Absolute and relative carbon content in agroforestry systems compared to other ecosystems

System	C in biomass (t C/ha)	C in soil (t C/ha)	Total C in ecosystem (t C/ha)	(%)	Sources
Primary forest (>30 years)	138	194	332 ± 37	100	Cifuentes-Jara (2008)
Secondary forest (25–30 years)	73	184	257 ± 14	77	Cifuentes-Jara (2008)
Coffee agroforestry system	38 14.3–43.5	127	164 ± 30	50	Callo-Concha et al. (2002) Van Rikxoort et al. (2014)
Cacao Agroforestry system	66	51	117 ± 47	36	Somarriba et al. (2013)
Extensive silvopastoral system	51	63	114 ± 18	35	Hassan (2011) and Ibrahim et al. (2007)
Improved pasture	28	81	109 ± 12	33	Hassan (2011) and Ibrahim et al. (2007)
Degraded pasture	2	56	58	17	Hassan (2011) and Ibrahim et al. (2007)

The importance of agroforestry systems for climate-smart production systems is linked to their ability to maintain relatively high levels of carbon in living biomass and soils (Table 4), as well as high levels of biodiversity; this places these systems between agricultural and forest systems (Fig. 26). The data in Table 5 locate representative agroforestry systems in the range of one third to one half or more of the total C stock in climax forest systems. Obviously, systems with very few trees such as open parklands, severely degraded sites (see the examples of Haiti or some African experiences), or extremely dry systems will have lower values. More data on mitigation of different agroforestry systems can be consulted in Nair 2012.

Figure 26 demonstrates how the transition from forest systems to less complex agroforestry systems, to agricultural systems, to pastures and, finally, to degraded lands leads to drastic reductions of biodiversity and carbon stocks, following roughly the numbers of Table 4. Just like the arrows labeled “mismanagement” indicate a reduction of C and biodiversity stocks when the resources of soil and biodiversity are not adequately protected, the reverse process allows recuperating these stocks, at least partially. However, an essential difference is the speed of these processes: while the degradation can happen in just a few years or even less time given extreme climatic events, the recuperation tends to require many years to decades of decided management and effective protection, as demonstrated by the successful examples of recuperating upland systems in Haiti through the construction of artificial lakes and

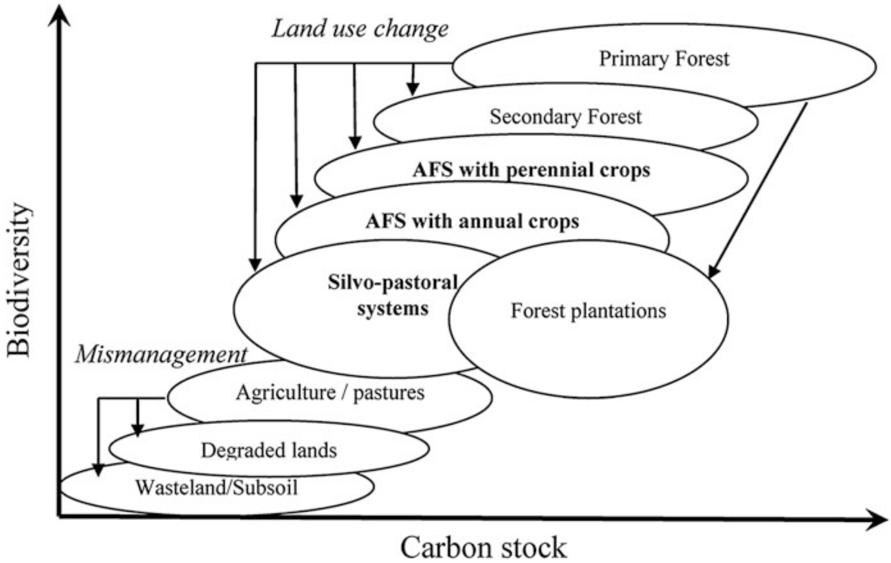

Fig. 26 The principal land use systems can be arranged by their carbon stocks and biodiversity levels. This conceptual graph situates the land use systems relative to each other to visualize the changes in carbon and biodiversity as one system gets transformed to another. The width and height of the ovals indicate varying ranges for different land use systems. For the sake of simplicity, the graph does not account for special systems with exceptional values. Notice that the three principal groups of agroforestry systems, highlighted in bold letters, are found at intermediate to high levels of both parameters indicating the potential of agroforestry systems for combining climate-smart production with biodiversity conservation. In order to be truly sustainable, land use systems should aim for the top right quadrant and preserve and/or increase carbon levels and biodiversity as far as possible

the establishment of agroforestry systems. Today, these systems provide, again, both products and the protection of environmental resources and services.

As long as degraded ecosystems retain a sufficiently high[5] stock of natural resources (soil, water, and biodiversity) to allow recuperating the functions of the ecosystems, the losses of biodiversity and C due to land use changes and mismanagement are, at least partially, reversible. Plants and animals can be reestablished, or may even migrate back in as the habitat conditions improve, particularly when native species are being used and connectivity is given (Montagnini and Finney 2011), and C will accrue as plants grow.

[5]The definition of what is "sufficiently high" depends on the ecological factors which determine or limit the capacity of "reconstruction." Clearly, once all topsoil has been eroded, plant growth in the subsoil is greatly inhibited and the recuperation may be limited to the much slower processes of "primary succession" rather than "secondary succession," requiring decades or even more time.

According to Montagnini and Nair (2004), smallholder agroforestry systems in the tropics can sequester around 1.5–3.5 t of C ha^{-1} $year^{-1}$, leading to average aboveground C stocks of about 10 t ha^{-1} in semiarid regions, 20 t ha^{-1} in subhumid, and 50 t ha^{-1} in humid regions. Considering both above- and belowground C, the C sequestration potential for agroforestry ranges from about 0.3 Mg ha^{-1} $year^{-1}$ for Sahelian fodder banks to more than 15 Mg ha^{-1} $year^{-1}$ in species-rich systems in the humid tropics such as Puerto Rico (Nair et al. 2009). In general, the C sequestration potential increases with rainfall, soil fertility, and temperature.

Carbon stocks in soils tend to be one to two orders of magnitude larger than those of aboveground biomass (Table 6). The C sequestration potential (CSP) is an estimate of the quantity of C that can be added to recently planted systems until they reach their *C* saturation indicated by the highest values of *C* stocks. Considering that the systems that cover the largest areas are intercropping systems (650 M ha), followed by silvopastoral systems (450 M ha), and protective systems (300 M ha), it becomes evident that improvements in these systems represent the largest potential for C sequestration. However, even multistrata systems, although represented on less than 10 % of global agroforestry coverage (about 100 M ha), can also contribute substantially since the total amount that can be stored in these systems is higher than in any other agroforestry system. Adding, furthermore, the potential reductions of N_2O emissions by substituting some of the synthetic *N* fertilization in high-input systems through biologically fixed N, the mitigation impact of agroforestry becomes even higher. These aspects are at the heart of "nationally appropriate mitigation actions" like the Costa Rican pilot "NAMA coffee" project starting in 2015. This project, funded under the "International Climate Initiative" by Germany and the UK, is one of the first, globally, to explore the full potential of agroforestry for climate change mitigation in the coffee sector.

Assuming a median C sequestration potential in biomass and soil of 94 Mg ha^{-1}, and that 585–1,215 M ha of tropical lands are, or could be, under agroforestry, Dixon (1995) estimated the global C sequestration potential over 50 years as 1.1–2.2 Pg, a figure that was adjusted to 1.9 Pg C for 1,023 M ha by Nair et al. (2009). Obviously, improving the vast amount of degraded croplands and pasturelands with AF practices holds an enormous additional potential to sequester carbon. Recently, Kumar and Nair (2011) provided a global assessment of the carbon sequestration potential of agroforestry systems. Besides a comprehensive reporting of data, this volume also raises the issue about the large variability of data, and data reliability, and makes a call for a more rigorous reporting and standardization of research methodologies used for assessing *C* stocks and sequestration potential. According to Kuyah and Rosenstock (2015), appropriate allometric relationships based on the simple measurement of the DBH of trees may still represent the best and cheapest way to obtain reliable and accurate data on *C* stocks in agroforestry systems. For most purposes, the negligible improvement of predictive power (1.3 %) by including additional variables such as tree height and crown diameter may not justify the additional time investment for measuring the additional variables.

Table 6 Global estimates of area, carbon stocks, and carbon sequestration potential (*CSP*) for the major types of agroforestry systems (Modified from Nair 2012). CSP corresponds to the estimated difference in carbon stocks between a recently established and a mature system in each category

Group of AFS	Region (including potential)	Area (Mio ha, incl. potential)	Estimated C stock (Mg ha^{-1})		Estimated CSP on new plantings (Mg ha^{-1})	
			Aboveground	Belowground	Aboveground	Belowground
Intercropping systems (incl. alley cropping)	Humid and subhumid tropics	650	Up to 15	Up to 150	2–5	25–75
	Temperate regions (North America, Europe)	50	Up to 10	Up to 200	2–6	50–150
Multistrata systems (shaded perennials, homegardens)	Humid and subhumid tropics, mostly lowlands, but up to 2,000 m elevation	100	2–18	Up to 300	2–10	100–200
Protective systems (windbreaks, shelterbelts, riparian buffers)	Arid and semiarid, primarily sub-Saharan (Africa, China, and N and S America)	300[a]	2–10	Up to 100	1–8	20–60
Silvopastoral systems	Grazing systems, predominantly in semiarid to subhumid lands in (Africa, India, and the Americas)	450	2–15	Up to 250	3–10	80–120
Woodlots (firewood, fodder, land reclamation, etc.)	Firewood and fodder-tree systems mostly in tropics; land reclamation plantings in special problem areas	50	1–12	Up to 140	1–5	40–70

[a]Planted in linear rows; the area refers to the area protected by the protective plantings

Many agroforestry and agroecological interventions permit combining adaptation with mitigation objectives. Examples include the planting of trees and woody shrubs, the protection of soils and protected areas, and the fostering of beneficial interactions among the components of the systems (Table 7). Integrating these practices into land use mosaics increases the capacity of landscapes to resist extreme climatic events.

Design and Modeling of Agroforestry Systems

This section provides recommendations and tools for the design and modeling of agroforestry systems oriented toward long-term sustainable production and the provision of environmental services. In their thematic spread, the recommendations in this section expand the work of Jose and Gordon (2008) who compiled a series of review articles and case studies on above- and belowground resource allocation and on modeling approaches for the design of agroforestry systems. One of the foremost objectives for agroforestry design is to maximize production in a sustainable manner, i.e., "ecological intensification."

Designing for Agroecological Intensification

As shown in previous sections, the services of trees (e.g., shade, deep nutrient extraction, or microbially mediated nutrient access) can often be used to alleviate or overcome microclimatic or edaphic limitations. At the same time, trees diversify farm income, feed animals, and increase the resistance and resilience to extreme climatic events, and the higher levels of biodiversity in species-rich agroforestry systems help prevent or control pest and disease outbreaks (Vázquez-Moreno 2014; Newton et al. 2011; Staver et al. 2001). Hence, trees can be essential for the "ecological intensification" and for the long-term sustainability of systems with coffee (Muschler 2001a, b, 1998), cacao, and other crops. As Somarriba et al. (2013) have shown, cacao systems can be designed to combine high yields of cacao with that of the associated trees (Somarriba and Beer 1987), which, in turn, are essential for the provision of ecosystem services, including carbon sequestration (Vaast and Somarriba 2014). The key tools for such "ecological intensification" are the use of selected cacao materials that combine high productivity with quality and resistance to pests and diseases (Phillips-Mora et al. 2013); optimum plant spacing for cacao and associated crops and trees (Somarriba and Beer 2011); the selection of appropriate tree species based on their architecture, phenology, and functional traits (Tscharntke et al. 2011); and an intensive phytosanitary and agronomic management. To maximize C stocks while minimizing excessive shading to cacao, Somarriba et al. (2013) suggested to use tree species with (1) tall, cylindrical, and thick stems (a "sequoia" type of tree); (2) small canopies and small, light foliage; (3) deep and thick roots; (4) rapid growth; (5) high-density timber; and

Table 7 Benefits of land use practices for climate change adaptation and mitigation. These practices can be part of, or should be associated with, agroforestry interventions (Modified and expanded from Matocha et al. 2012)

Practice	Adaptation benefits	Mitigation benefits	Key references
Tree planting in crop and pasture systems or on unproductive land (agroforestry systems such as shade trees, alley cropping, living fences, windbreaks; reforestation)	Microclimatic benefits by reducing the impact of extreme weather events on crops, pastures, and animals Soil protection and fertility improvement by perennial root systems Product diversification reduces vulnerability	Increased carbon storage in biomass and soils Nitrogen from biological N-fixation can reduce fertilizer requirements (reducing liberation of GHG)	Akinnifesi et al. (2010), Douglas (2009), Hergualc'h et al. (2012), Kumar and Nair (2011), Montagnini and Nair (2004), Muschler (1998, 2001a), Nair (2012), Schroth et al. (2004), and Somarriba et al. (2013)
Practices to maintain or increase long-term soil fertility, including conservation agriculture, biointensive production, etc. (e.g., cover crops, intercropping with perennial grasses/ shrubs, mulching, use of compost and manures, minimum/no tillage)	Moderate soil temperatures Improve water retention and soil protection Increase soil biological activity for increasing nutrient and water use efficiency (mycorrhizae, N-fixers, beneficial microorganisms for suppressiveness) Reduced dependency on external inputs	Increased carbon storage in biomass and soils Nitrogen from biological N-fixation can reduce fertilizer requirements (reducing liberation of GHG)	Amundson et al (2015), Bardgett and van der Putten (2014), Lal (2015), Trumper et al. (2009), and Young (1989)
Restoration and conservation of "protection areas" such as buffer zones, forest corridors, riparian forests, mangroves, and wetlands	Improved soil retention and protection against flooding and landslides Ecological services from pollination and from prevention and biological control of pests and diseases Conservation of terrestrial and aquatic biodiversity Regulation of water flows	Increased carbon storage in biomass and soils	FAO (2013), Heller and Zavaleta (2008), Pyke and Andelman (2007), and Scherr and Sthapit (2009)
Protection and fostering of symbiotic or beneficial associations between plants, animals, and microorganisms	Improved access and use of nutrients and water Ecological services from prevention and biological control of pests and diseases	Reduced dependency on external inputs (reduced liberation of GHG)	Bardgett and van der Putten (2014), Gliessman (2015), and Vazquez (2014)

(6) an inverted phenology to reduce shading and phytosanitary problems during the rainy season.

When these recommendations are complemented by adequate shade and phytosanitary management, as well as by the other agroecological practices mentioned in previous sections, the cacao agroforestry system can meet the challenges of "ecological intensification" (Fig. 27). This way, the loss of ecological services from eliminating trees in high-input systems (the "simplification" arrow on the path to highest productivity but also highest vulnerability in full-sun systems) can be reverted to create an ecologically enriched system, which combines high production with the provision of environmental services. Notice that in this case of "intensified cacao agroforests," the species composition of the trees and the genetic composition of the cacao clones will be drastically different from that of low-productivity unimproved rustic cacao systems. While structurally and functionally similar, the improved systems are much more productive and, hence, economically viable than the rustic systems.

Factors for the Tree/Shade Decision

The decision whether to use trees, which ones, and how many in a given field depends also on the environmental factors, particularly the microclimatic and soil conditions, the production goals, the conservation objectives, and the availability of labor, inputs, and financing. For coffee and cacao, and possibly most crops, these factors can be arranged by objectives, environmental factors, and inputs (Fig. 28). Whenever the objectives of production and protection include aspects of climate-smart production, the conservation of soils, water, and biodiversity, as well as the production for specialty markets such as organic or bird-friendly coffee, the system will typically require the presence of trees. The same is, of course, the case when the outputs of the trees play a major role and when their services are needed to alleviate environmental limitations such as low soil fertility, lack of water (as long as this is not extreme – see discussion on "Alley Cropping"), high temperatures (for Arabica coffee), or wind. In contrast, unshaded systems oriented toward maximizing the production of a single product tend to be favored under ideal biophysical conditions and when sufficient inputs are available to supply the higher needs of sun-exposed plants (Muschler 2004). For coffee systems, Muschler (1998, 2004) provided a detailed account of the effects of tree and shade management on coffee productivity, quality, and environmental factors.

Designing Agroforestry Systems for Ecological Sustainability

To maximize the productive potential and long-term ecological resilience of agroforestry systems, the following recommendations should be considered:

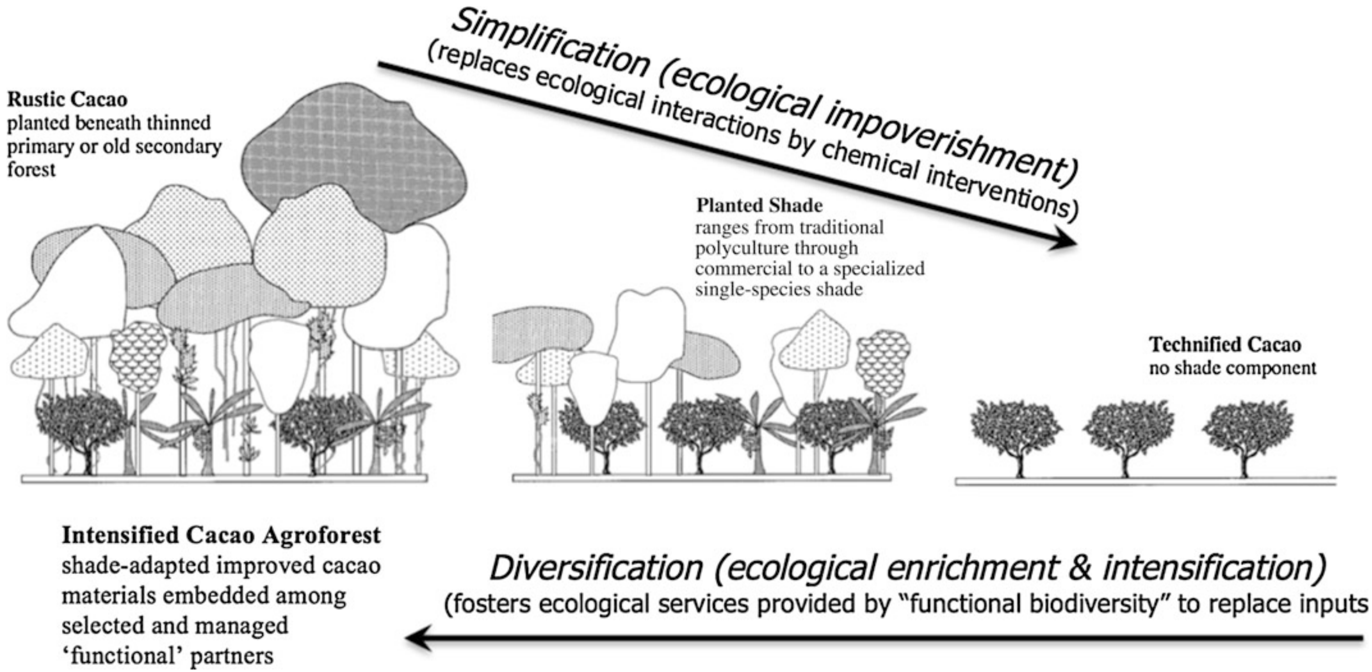

Fig. 27 Transition between cacao systems of different complexity. While the simplification of the system eliminates competing plants, it also eliminates beneficial functional biodiversity. Therefore, species-poor systems suffer a loss of ecosystem services, become more susceptible to pests and diseases, and depend strongly on external inputs. The reverse path, i.e., the diversification of cacao systems with carefully selected improved cacao materials combined with compatible crops and trees, and accompanied by active agronomic and phytosanitary management, creates systems that are more resistant and resilient to pests and diseases as well as to climatic and price fluctuations. The agroecological intensification will lead to a productive intensified cacao agroforest that is botanically different, yet functionally similar, to the rustic low-productivity system. Its goal is to combine higher productivity of high-quality cacao with a maximum of environmental services (Drawings from Rice and Greenberg 2000)

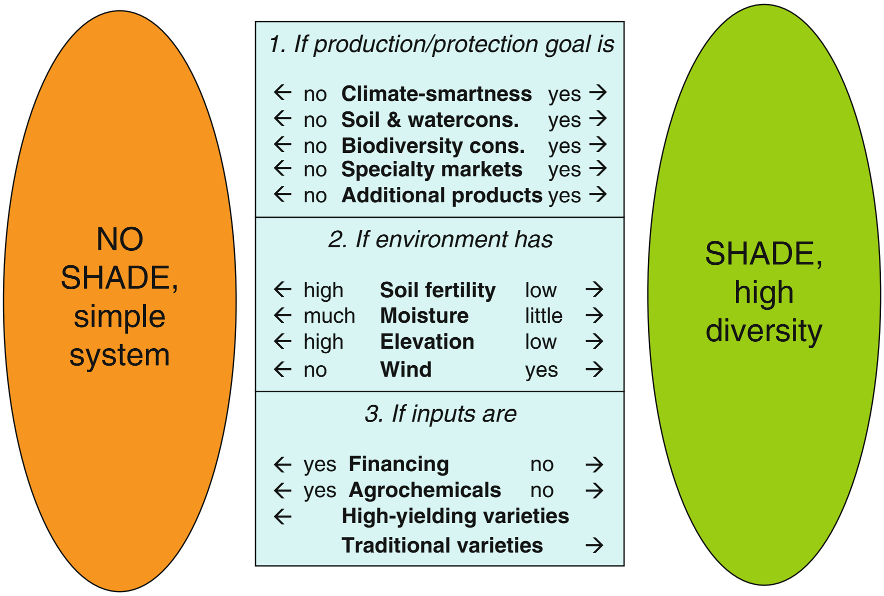

Fig. 28 The three principal groups of factors which determine the decision about growing coffee, cacao, or other plantations crops under shade or not. The combination of the site-specific factors with the production goals and the tree attributes determines the number and diversity of trees to be planted and the appropriate management (Modified from Muschler 2004). For details see text

1. Use plants of different ages, sizes, and attributes to generate the **highest possible structural and functional diversity** in the system.
2. **Associate compatible crop and tree species** (e.g., coffee and *Erythrina* spp. or *Inga* spp.) and apply the experiences of "companion planting"[6] (e.g., Cunningham 2000; Riotte 1998).
3. Aim for a certain **genetic diversity** within each crop or tree species and avoid monocultures of clones or hybrids as much as possible[7]; the recommendation to plant "polyclones" in improved cacao plantations (Phillips-Mora et al. 2013) is probably of universal validity.

[6]In agroecological crop production, the association of compatible crops, such as tomatoes intercropped with carrots, can prevent and suppress diseases and may increase production; see also "companion planting" and "list of companion plants" at Wikipedia.

[7]The negative experiences with the monoclonal large-scale plantations of banana varieties illustrate the high susceptibility of such plantations to specialized diseases such as *Mycosphaerella* or to nematodes. When highly productive clones of cacao are planted, it may be best to establish "polyclones," i.e., mixes of different clones, in the plantations to reduce the risks associated with disease and pest susceptibility (Phillips-Mora et al. 2013).

4. Incorporate aromatic **repellent and trap crops** where possible (Vázquez-Moreno 2014).
5. **Rotate crops** of different types such as grain crops with tubers, leafy crops, and N-fixing crops.
6. Aim for **permanent soil cover/protection** and shading (live and/or dead plant cover).
7. **Favor prevention and biological control** over chemical options.
8. **Minimize the use of agrochemicals**, particularly herbicides and fungicides that impoverish the soil biota (rhizobia, mycorrhiza).
9. Integrate patches of land use under agricultural, agroforestry, animal husbandry, or forestry uses into **climate-smart landscapes** (Perfecto and Vandermeer 2010).

To optimize the system performance and long-term ecological sustainability, mechanisms for efficient nutrient cycling and agroecological pest management need to be built into the systems. With regard to nutrient management, a massive body of information is available on nutrient budgets, which were emphasized particularly in early agroforestry research until the 1990s (e.g., Sanchez 1995; Fassbender 1993; Nair 1993; Fassbender et al. 1991; Beer 1988). Since then, more attention has been given to understand the processes and factors that determine the stocks and speed of transformation of nutrients in plants (Akinnifesi et al. 2010; Jalonen et al. 2009; Mafongoya et al. 2000; Cadisch and Giller 1997) and their roles for soils and animals (Mafongoya and Hove 2008). Work has been done on nutrient budgets, fractions, and decomposition patterns as a function of (a) climatic and edaphic factors, (b) tree spacing and management (pruning intensity, e.g., Muschler 2004), (c) the type and attributes of trees (often N-fixers versus non-fixers, e.g., Budelman 1988), (d) degradability of tree litter depending on their composition and the presence of polyphenols and tannins (e.g., Mafongoya et al. 2000) ranging from easily degradable materials (e.g., *Erythrina* spp., *Gliricidia sepium*, or *Leucaena* spp.) to more persistent litter (e.g., *Inga* spp., *Cordia alliodora*, or *Eucalyptus*), and (e) the composition of simple versus complex litter or compost mixes, some with animal manure or other microbial additions such as efficient microorganisms (EM).

One illustration of the potential importance of the last point is the recent work by Barantal et al. (2014) on the speed of decomposition as a function of decomposing fauna, litter composition, and nutrient stoichiometry. The leaf litter of six tropical tree species decomposed faster when leaves of different species were mixed rather than when individual species decomposed alone; nutrient addition experiments demonstrated that the relatively slower decomposition of leaves of any single species was due to C, N, or P limitations for the decomposing organisms. The authors demonstrated that stoichiometric dissimilarity of litter mixtures (i.e., the divergence in C/N/P ratios among species) can speed up decomposition by fostering the activity of the decomposers. This study shows a mechanism for modifying decomposition patterns.

Undoubtedly, the information from these studies is key for maximizing the supply of organic matter and nutrients from trees and for synchronizing their availability with the needs of the crops. While much knowledge has been generated specifically from agroforestry systems (e.g., Akinnifesi et al. 2010; Beer 2000; Beer et al. 1998), often including animal components (Mafongoya and Hove 2008; Benavides 1994; Kang et al. 1990), much of it also comes from the fields of agronomy or forestry. The rapidly increasing research also in these fields offers the opportunity to make wider use of the relevant information from all three areas for optimizing agroforestry systems.

Another central aspect for long-term sustainability is the creation of climate-smart and pest-suppressive landscapes, based on an improved understanding on how different land use types interact at the landscape level and how to better link production with the provision of environmental services. For agroforestry systems with coffee, the reviews of Staver et al. (2001) and Avelino et al. (2012) provide central recommendations for preventing or reducing pests and diseases. The two principal avenues are (a) the establishment of site-specific optimum shade conditions and (b) the creation of biodiverse landscapes with patches of different land use. Both approaches will reduce the spread of the pest complex and maximize the effects of beneficial microflora and fauna acting against it. Obviously, the appropriate selection of tree species, the best density and spatial arrangement, as well as the optimum shade management regime are critical decisions. These recommendations apply also, in principle, to other crops. In general, higher structural and botanic diversity tends to generate higher pest and disease suppressiveness (Vázques-Moreno 2014; Altieri et al. 2005), hence reducing the need for pesticides, while simultaneously increasing the resistance and resilience the extreme climatic events.

Besides these factors essential to reduce pest and disease incidence, there is also increasing evidence that the resistance of plants to pests is significantly affected by their nutrition. Since the use of high doses of inorganic N tends to lower pest and disease resistance of plants, more emphasis should be placed on keeping soil fertility high enough to provide N primarily from organic sources (Altieri and Nicholls 2003). This is also in the interest of climate-smart production aiming at mitigating greenhouse gas emissions. However, more studies are needed to understand the interactions between pest populations and plants treated with synthetic versus organic fertilizers. Another research priority should be to learn more about how to maximize the synergies when different species collaborate to provide ecological services such as pollination (Brittain et al. 2013), pest prevention or control (Vázques-Moreno 2014), or sustaining soil fertility and health (Amundsen et al. 2015; Bardgett and van Putten 2014; Akinnifesi et al. 2010), including the transformation of organic wastes by surprisingly important dung beetles that turn out to provide a range of important ecological functions (Nichols et al. 2008). Besides these agroecological factors, also aspects of human nutrition should be considered for the design of sustainable agroforestry systems so as to address the challenges of food and nutrition security.

Designing Agroforestry Systems for Nutrition

As the global diet is getting increasingly more homogeneous (Khoury et al. 2014) and unhealthy, with an oversupply of cheap carbohydrates and fats, we should increase the amount of vegetables and fruits in our diets to reduce nutritional deficiencies (Ebert 2014; Frison et al. 2011; Keatinge et al. 2010). Such changes require marked adjustments to our systems of production, promotion, and distribution of food. Healthier diets with more green, red, and orange vegetables on our plates should go hand in hand with the diversification of our production systems with such crops. Species-rich agroforestry systems are a good starting point. The fastest way would be by including highly nutritious annual crops to quickly improve the nutritional output of our production systems (e.g., Marten and Abdoellah 1988). Obviously, changes in fruit and nut production from trees need more time. Work is needed on both fronts to make optimum use of all available resources. In many places, this means also reviving nutritious traditions (Fallon 1999) such as the consumption of edible "weeds" and other plants that have been lost over the past decades. Fortunately, today, there is a wealth of online information on edible "weeds" and leaves of crops such as manioc, tree spinach or "Chaya" (*Cnidoscolus chayamansa*), *Moringa oleifera*, sweet leaf or "katuk" (*Sauropus androgynus*), *Amaranthus* spp., lamb's quarters (*Chenopodium album*), purslane (*Portulaca oleracea*), chickweed (*Stellaria media*), and many others (Ebert 2014). Ideally, the selection of such crops should be based on desirable agronomic attributes and high nutritional value. For a humid tropical environment, a simple example of a species mix for a complete diet was given by Thornton (2009). Clearly, more efforts will have to be dedicated to custom-tailor the species mix to the nutritional needs and the agroecological environment of each specific region, with an increased attention to the potential of NUS (Sánchez-Salmeron et al. 2015). The USDA "National Nutrient Database" (USDA 2015) can be used as a key reference for the nutrient contents of more than 8,000 types of food.

Considering the multiple essential functions of trees besides nutrient provision, such as soil and water protection, biodiversity conservation, microclimate moderation, etc., it becomes clear that the judicious design of agroforestry systems must be based on a holistic balance of the multiple functions of its perennial and annual components. Of particular importance are the capacities of the components to provide useful products and large quantities of biomass for maintaining or improving soil fertility (one of the central elements of "biointensive" production; Jeavons 2014) and for improving the ecological balance in the system (Vázquez-Moreno 2014). The following training materials give practical advice for the design of such systems.

Training Materials for Promoting and Designing Agroforestry Systems

One of the indications of the evolution of agroforestry is the publication of practical training materials for practitioners, extension services, and promoters of agroforestry for development. Some of the most notable materials were assembled over the past two decades in the context of impact-oriented agroforestry projects. From Latin America, they include the basic reference by Geilfus (1994) on the multiple roles of trees and the series of training materials on agroforestry developed at CATIE (in Spanish) on "functions and applications of agroforestry systems" (Jiménez et al. 2001), "trees in line plantings" (Mendez et al. 2000), "silvopastoral systems" (Pezo and Ibrahim 2001), "traditional tropical homegardens" (Lok 1998b), "trees in coffee systems" (Muschler 2001a), and "taungya systems" (Schlönvoigt 1998). Other examples are the "Manual Keba Sula" (PAF-Ngöbe-Buglé 2003) developed for work with indigenous groups in Panama on sustainable management of natural resources; the manuals on organic coffee production by Figueroa et al. (1998), Castañeda and Castañeda (2000), and Christiansen (2004); as well as the detailed review by Benzing (2001) on the mechanisms for sustaining organic production systems in the tropics. These illustrated and didactic manuals continue to be key references for Spanish-speaking practitioners. An extensive body of similar materials is available also from other parts of the world. However, unfortunately, their circulation is often limited when projects end and their reproduction stops. Some are available as (bulky) pdf files, but individual topics and figures cannot be searched easily. To facilitate access to these materials, it would be desirable to create a universally accessible electronic training platform where the individual figures and topics of these manuals are searchable by keywords and in multiple languages, possibly adopting the approach of Wikipedia. To facilitate the access to agronomic information for agroforestry, we should make more use of information available through initiatives or organizations like OISAT (2015), "Crops for the Future," Bioversity International, and "Practical Action" (2015) and incorporate experiences from related fields such as biointensive agriculture (Jeavons 2014), permaculture (Mollison 1996; Permaculture Design n.d.), and urban agriculture (INIFAT 2011). Since agroforestry systems require a relatively long time to deliver all of their products and services, modeling of these systems has become an important tool for their design.

Modeling Agroforestry Systems

The increasing climatic variability and resultant stresses for agroecosystems heightens the need to predict likely changes at different regional and temporal scales. Such predictions are essential for designing appropriate measures of adaptation and mitigation of climate change. Ideally, the models should allow to generate predictions at different regional and temporal scales, ranging from changes and recommendations at a national or regional level all the way down to the level of individual growers. However, due to their great vertical, horizontal, and temporal variability, agroforestry systems represent a formidable challenge for modeling. This is further complicated by the complexity and management of the generally nonlinear and often unknown interactions among the many species, which may be more than 50 in homegardens. Nevertheless, there is a growing field of emerging approaches to generate useful and accurate predictions. For an overview of the most widely used approaches and models, the reader may wish to consult the online tools provided by the "World Agroforestry Centre," the compilation of modeling approaches by Rapidel et al. (2009), and the section on modeling in Jose and Gordon (2008). Some of the models under development include the following fields and approaches:

(A) **Biophysical models to simulate the flow of light**, **water**, **nutrients**, **carbon**, **and other substances**:
   - "WaNuLCAS," a model to simulate the flows of water, nutrients, light, and carbon in agroforestry systems. This model, based on tree-crop architecture, physiology, and soil science, can be used for exploring positive and negative interactions for different combinations of trees, crops, soil, climate, and plant management (http://www.worldagroforestry.org/sea/Products/AFModels/wanulcas/index.htm).
   - The "CASTANEA" model (Le Maire et al. in Rapidel et al. 2009) to simulate the carbon and water balances in homogeneous forests and, potentially, agroforests.
   - "Shade Motion 2.0" (Quesada and Somarriba in Rapidel et al. 2009) simulates tree shade patterns and generates a graphical representation of the shade patterns in a plot over the course of a day as a function of the characteristics and dimensions of the individual trees.
   - The "Agricultural Production and Externalities Simulator" (APES, www.apesimulator.org) to model the biophysical performance of agricultural and agroforestry production systems (Casellas in Rapidel et al. 2009). The outputs include plant growth and phenology, water and N soil dynamics, water, N and light competition, root profiles, the fate of pesticides, and a management module.
   - A biophysical conceptual model for coffee agroforestry systems making use of the "Agroecological Tool Kit" (Rebolledo et al. in Rapidel et al. 2009).
   - Plot-scale modeling of agroforestry systems with coffee (van Oijen et al. in Rapidel et al. 2009) to predict productivity, N leaching, N losses to the atmosphere, as well as the loss of organic C and N in surface runoff. This model separates the agroforestry system into sun-exposed and shaded regions.

(B) **Ecological models to simulate the behavior of biodiversity**, **pests, and diseases**:
   - The "Agricultural Production Systems Simulator" (APSIM; Huth and Carberry in Rapidel et al. 2009), a model developed in Australia that evolved from simulating biophysical processes in farming systems into a decision-making tool for land managers. It has been used for modeling crop production and economic performance of agroforestry systems such as crops with windbreaks. Web-based tools allow incorporating climatic information and biodiversity benefits.
   - "OLYMPE" (INRA, France; Deheuvels and Penot in Rapidel et al. 2009), "RECORD" (Bergez et al. in Rapidel et al. 2009), and other approaches may

improve decision-making to strengthen the role of farmers' organizations for accessing markets and generating policy impact.

– Economic modeling approaches for the transition of a cacao-service tree to a cacao-timber tree agroforestry system (Navarro and Bermudez in Rapidel et al. 2009).
– Modeling of the impact of "payments for environmental services" in favor of rubber agroforestry systems over rubber monocultures (Villamor et al. 2013).

(C) **System models to simulate whole systems** and **economic performance and provide tools for decision-makers**:

– Epidemiological models, like the ones used for modeling coffee leaf rust (Avelino, in Rapidel et al. 2009), combine factors of the host, the pathogen, the environment, and the cropping systems, including management. However, they tend to be limited to statistically descriptive and predictive models; a call is made for developing more mechanistic models in the future.
– Modeling habitat quality and landscape connectivity for birds in silvopastoral and riparian systems (Sanfiorenzo et al. in Rapidel et al. 2009).
– Simulate the impact of biodiversity loss on ecosystem functioning (DeClerck et al. in Rapidel et al. 2009).

Obviously, these are but a few examples in this rapidly evolving field. Doubtlessly, the next steps will generate a better integration of individual modeling modules to expand the complexity of the models and, hence, improve the accuracy of predictions. One example of such new integrative tools was presented by Jackson et al. (2013) to identify synergies and trade-offs among the impacts of land use change on different ecosystem services. Other examples, both from the World Agroforestry Centre, are the model developed within the "Land Degradation Surveillance Framework (LDSF)" to study carbon dynamics, vegetation changes, as well as soil functional and hydrological properties at the landscape level (http://landscapeportal.org/blog/2/) and the *Negotiation-support toolkit for learning landscapes* (van Noordwijk et al. 2013) which provides a wealth of tools for fostering the development of landscapes that combine production with protection. Undoubtedly, these tools fill a key gap in linking field and farm level actions with ecosystem service provision at landscape scales.

Conclusions and Recommendations: Priorities for Research and Development

Over the past four decades, a solid body of research has revealed the potential of agroforestry for increasing or maintaining system productivity while protecting natural resources and providing environmental services (cf. Fig. 24). Thus, agroforestry is well suited as a central tool on the path toward "sustainable intensification" (The Montpellier Panel 2013), a new name for the quest of increasing production and conservation at the same time. The recent call by FAO in its 2014 "International Symposium on Agroecology for Food Security and Nutrition" that the future paradigm of land use should be based much more on biology and agroecology, rather than on chemistry and fossil fuels, endorses also a more widespread use of agroforestry and agroecological practices for food production. Now, it is up to us to apply the powerful tools at hand to design and custom-tailor agroforestry practices and systems to the needs of each particular ecozone or community.

In order to fine-tune the systems to the respective environmental and socioeconomic conditions, and rise to the challenge of sustainably producing more food that is less contaminated and less contaminating, we should advance in the following directions: (i) expand the species characterizations, (ii) widen the scope of crops and trees used by including "neglected and underutilized species" (NUS), (iii) strengthen work on "using" beneficial soil organisms for soil and plant health, (iv) optimize the system design and management to maximize resource use efficiency and minimize pest incidence, (v) create climate-smart and pest-suppressive landscapes based on an improved understanding on how different land use types interact at the landscape level to link production with environmental services, and, finally, (vi) advance toward more holistic socioeconomic assessments including an improved valuation of environmental services.

Characterization of Crop and Tree Species: Expanding the Passport Information

Based on the fundamental importance of using locally adapted, productive, and nutritious tree and crop species that can be associated in mutually beneficial ways, greater importance should be given to expand the species characterization beyond the standard botanic and agronomic attributes of crops and trees (cf. section "Information to Be Added to Crop and Tree Databases"). To facilitate the identification of the most appropriate crops and trees for designing climate-smart agroforestry systems, i.e., systems with minimal requirements for (unsustainable) external inputs (see section "Requirements for Sustainable Landuse"), the passport information for each species should be expanded by relevant attributes (preferably in quantitative terms translated to easily understandable categories for farmers and practitioners), including the following:

- **Shade tolerance** (at least in four categories: <25 %, 26–50 %, 51–75 %, >75 %)
- **Drought tolerance** (months without rain, seasonal minimum water requirement)
- **Heat tolerance** (preferred range, tolerated range)
- **Wind tolerance** (with an indication of strength; at least in three categories: not, moderate, strong)
- **Water logging tolerance** (days, weeks)
- **Disease- and pest-tolerance** (at least in three categories: high, medium, low)
- **Resprouting capacity** after inundation (to identify fast-start crops after environmental disasters)
- **Soil pH** preference and tolerance (preferred range, tolerated range)

– "**Anti-erosion effectivity**": the capacity of its root system to retain soil on slopes (at least three categories: weak, moderate, strong, and extreme, e.g., bamboo)
– **Productivity of edible parts** (kg/plant/year)
– **Nutrient and micronutrient profile** (including Fe, Zn, and vitamin A content)
– **Space requirement per plant** (m^2)
– **Shelf life** and storability
– **Ease of preparation and transformation** as human food (energy and time requirements)
– **Water use efficiency** (l water/kg edible product)
– **Compatibility** with other crops or trees (e.g., highly compatible with species A, B, C; not compatible with D, E)
– **Ease of reproduction** under tropical conditions (incl. number of seeds and storability)
– **Potential invasiveness**

With this information in a digitalized searchable database, the user can, then, easily choose the most appropriate plant components and "custom-tailor" their mix and arrangement according to the biophysical environment and the other plants in a specific place. While this information is currently not readily available for many crops or trees, its inclusion in standard databases would facilitate "filling in the gaps" as experiences around the world get analyzed. A comprehensive format is currently under development at CATIE.

Increasing the Scope for the Selection of Crops, Trees, and Animals

The scope of species should be broadened by strengthening work on neglected underutilized species (NUS), also called "orphan crops" or "Cinderella species." The increased passport information will facilitate finding the best niche for a particular species within the agroforestry system, integrated with compatible trees, crops, or animals around it. An interesting example is the widely promoted "drumstick tree" (*Moringa oleifera*) with highly nutritious leaves and pods, which can be planted in many arrangements and uses in agroforestry systems, including as a windbreak or living fence, in alley cropping, or as a support for climbing plants such as passion fruit, yams, or beans. Moringa can be intercropped with a wide range of vegetables such as cluster bean (*Cyamopsis tetragonoloba*), hot peppers, cowpeas, pigeon peas, and onions (Ebert 2014). The same holds for a long list of other species and NUS (see section "Lessons Learnt from Tree, Crop, and Animal Domestication: Widening the Search"), the selection and characterization of minor animal species for specialty systems (cf. section "Selection of Animal Species"), including bees such as the stingless *Melipona* and other insects of local importance, but also for warm-blooded animals and fish in their native setting. However, caution must be taken to avoid negative effects. As has been learned from the (ecologically) painful experiences in Lake Victoria after the introduction of the Nile perch (see the documentary "Darwin's Nightmare"[8]) or in many lakes in Central America after the liberation of Tilapia, the displacement of local fish species and the disturbance of local stability should also be considered before introducing exotic species. The same holds, of course, for invasive trees and shrubs (see section "Plant Selection for Agroforestry"), as well as other organisms.

Management of Beneficial Soil Fauna and Microorganisms for Soil Health and Fertility

For the next quantum leap in sustainable plant production, another group of organisms of central importance, yet largely ignored, should receive the attention it deserves: beneficial soil fauna and flora. The existing studies are but the tip of the iceberg (section "Selection and Use of Microbial Symbionts and Other Beneficial Soil Organisms"). Clearly, there is a great potential of using these organisms for maintaining or increasing soil fertility and even for rehabilitating degraded soils after decades of chemical-intensive monocultures, exposure to rain and sun, or following massive erosion as in Haiti and so many other places around the world with similarly adverse conditions. After decades of a predominantly chemical focus on soil fertility, more emphasis should now be given to study soil ecology and effective agroecological management interventions (Bardgett and van der Putten 2014). Particular attention should be given to systematically study how to manage soil health for better crop health and reduced pest incidence (Altieri et al. 2005; Altieri and Nicholls 2003) by learning about the effects of:

– *Soil fauna* on plant growth, demonstrated already as highly positive for trees, grasses, and perennial crops such as tea. Considering that only about 10 of the more than 6,000 species of earthworms have been studied in detail, more attention should be given to studying also native earthworms and their interactions with the soil and its fauna and flora (Brown et al. 1999; Lavelle et al. 1999). The importance of other groups such as dung beetles (Nichols et al. 2008) underlines the need for studying soil fauna.
– *Soil microorganisms*, including fungi, actinomycetes, and bacteria (Cardoso and Kuyper 2006; Stamets 2005; Margulis 1998). The active management of these microorganisms should be studied in more detail both in soils and on plant surfaces. In many organic production systems around the world, microbial ferments are applied to the foliage of crops to stimulate plant growth and to prevent the growth of diseases or to minimize their impact. The positive experiences from intensive organic agriculture from around the world (Martínez-Viera and Dibut-Álvarez 2012; Restrepo-Rivera y Hensel n.d.; Benzing 2001)

[8]Hubert Sauper 2004. Darwin's Nightmare. An Austrian-French-Belgian documentary. Nominated for the 2006 Academy Award for Documentary Feature. 102 min. https://www.youtube.com/watch?v=IV7Y9FHcdFk

should be adapted to optimize agroforestry systems and combat pests and diseases (Vázquez-Moreno 2014; Altieri and Nicholls 2003). Given that fungi are among the main decomposers and provide many essential products and services to their (mycorrhizal) symbiotic partners, greater attention should be given to their active use as inoculants for plant roots and for their conservation in agroforestry systems (Sieverding 1991). Unfortunately, the use of synthetic fertilizers, herbicides, fungicides, and other pesticides leads to a drastic impoverishment of the soil biota with large negative impact on the soil suppressiveness (Thuerig et al. 2009; Stamets 2005; Weller et al. 2002). The same holds for the symbiotic partners of N-fixing legumes. While the use of mycorrhizal fungi (such as *Glomus* spp.) or N-fixing bacteria is already a widespread practice in horticulture and some agriculture or forestry applications, this should also become a standard practice for improved agroforestry systems. A big part of the much needed "biological intensification" will have to rely on choosing and using the right inoculant for the crop and tree species of future agroforestry systems with decided attention on generating the appropriate soil conditions, particularly SOM, that favor their activity.

Optimizing the System Design and Management for Maximum Resource Use Efficiency

As mentioned in section "Design and Modeling of Agroforestry Systems," the appropriate design of agroforestry systems should aim for maximum resource use efficiency and combine high productivity with the provision of environmental services, including pollination, suppressiveness to pests and diseases, as well as adaptation and mitigation of climate change. The central tools for this are the right choice and management of crop, tree, and associated species as a function of the environmental and socioeconomic factors. Choosing the right amount of shade and the best spacing and arrangement of the trees are essential tools. While the interactions among the components within specific agroforestry systems are increasingly understood and documented (particularly for systems with coffee, cacao, tea, rubber, and animals), more work is needed to elucidate the roles and management of associated biodiversity, including birds, insects, and microorganisms which contribute greatly to providing essential ecosystem services. Furthermore, of particular importance for long-term resource use efficiency is the wider exploration of the great potential of biochar for reconstructing and maintaining long-term soil fertility, for carbon sequestration on the scale of decades to centuries, as well as for reducing the leaching of agrochemicals and the emission of green-house-gases (Cayuela et al. 2013; Lehmann and Joseph 2009).

Creating Climate-Smart and Pest-Suppressive Landscapes

Since many ecosystem services, such as the protection of soils, water, and biodiversity, but also pollination and the suppression of mobile pests, are emergent properties of a landscape, we need to greatly expand our understanding on how different land use types interact at the landscape level. This knowledge is essential to strike the right balance between production and environmental services (Vaast and Somarriba 2014). Undoubtedly, the emerging tools for mapping and valuing ecosystem services (Kareiva et al. 2011; Rapidel et al. 2011) and for facilitating community-driven processes (van Noordwijk et al. 2013) will help greatly with the transition toward truly sustainable landscapes that satisfy the needs of production and protection.

Biophysical Research Methods and Improved Experimental Design

One of the central lessons of early agroforestry research is that tree roots reach much further than expected from standard agronomic experiments. In some cases, roots of adult *Erythrina poeppigiana* and other trees absorbed nutrients from adjacent "control" plots without trees (sometimes at distances of more than 20 m), causing spurious and distorted results (Somarriba et al. 2001). This realization had fundamental implications for the appropriate design and analysis of agroforestry research as summarized by Coe et al. (2003). The most obvious result is to drastically increase the dimensions of the experimental plots (sometimes to more than 50 m of net plot dimensions); another one is to work with artificial root barriers or to practice root pruning. Unfortunately, the need to establish agroforestry plots on sufficiently large tracts of land (depending on the tree species, planting density, and tree pruning, individual plots may require often 0.25 ha or even more) and the need to manage them under the experimental regimes for many years, sometimes decades, put severe financial and biophysical constraints to such work. Besides the great difficulties to obtain funding for such endeavors, it is difficult to assure access to land of appropriate dimensions and homogeneity. Today, there are very few examples of such long-term studies. One successful example is the long-term experiment to test the effects of different tree species and fertilization regimes on coffee, which was set up at CATIE in 2000 with long-term funding from Norway (Box 3). A sister experiment is running in Nicaragua.

Box 3. The "Mesoamerican Scientific Partnership Platform" (PCP) at CATIE, Costa Rica: Technical Backstopping for Regional Development

In order to pool research capacity for studying agroforestry systems with coffee and cacao, six organizations (Bioversity Int'l, CABI, CATIE, CIRAD, INCAE, and PROMECAFE) established in 2007 the "Mesoamerican Scientific Partnership Platform" (PCP) at CATIE. Today, this consortium provides essential technical information on productivity, product quality, disease and pest management, nutrient and gas flows, environmental services, and economic performance of different systems. The clients include national and regional institutions, as well as development projects working on systems with perennial

(*continued*)

crops. In the photo below, a team of experts visited a strategic experiment at CATIE for studying the interactions between tree species, shade, and different input levels on organic and conventional coffee production. Information on nutrient budgets and flows is essential for optimizing the systems and for mitigating greenhouse gas emissions in coffee production. Costa Rica's pioneer project on "Nationally Appropriate Mitigation Actions" in coffee production (NAMA-Café, started in 2014 with key support by GIZ, Germany) will receive central inputs from this and related strategic experiments (Fig. 29).

Fig. 29 *Top*: in 2000, CATIE established its "coffee systems experiment" in Turrialba, Costa Rica. This experiment, scheduled to run for at least 20 years, is designed to study the interactions among three tree species (*Erythrina poeppigiana*, *Chloroleucon eurycyclum*, *Terminalia amazonia*, full sun as control), five fertilization regimes (with synthetic and/or organic fertilizers at different levels), and two varieties of coffee. The dimension of this project reflects the need for controlling the root and shade interactions among neighboring plots: the experiment occupies 9 ha and each plot occupies about 1,500 m^2. Early results indicate that a significant portion of synthetic fertilizers can be substituted by organic sources, reducing nutrient losses and the emission of nitrous oxides to the atmosphere. A "sister" experiment is being run in Nicaragua. Both projects are financed by NORAD. *Bottom*: a 30 m tall tower in a commercial coffee farm (Cafetalera Aquiares) allows to monitor C flux at high resolution, essential information for measuring C sequestration. Scientists of CATIE, CIRAD, and other partners pool their capacities in the "Mesoamerican Scientific Partnership Platform" (PCP) (Photo credits: R. Muschler)

For studying the complex relationships between trees, crops, and soils, Schroth and Sinclair (2003) collected fundamental concepts and research methods, which remain of great relevance to date. This multiauthor landmark publication covers standard and advanced methods for studying soil organic matter, soil nutrient availability and acidity, decomposition and nutrient supply from biomass, nutrient leaching, nutrient capture, nutrient exchange with the atmosphere, soil structure, soil water, root systems, biological nitrogen fixation, mycorrhizae, rhizosphere processes, soil macrofauna, and, finally, soil erosion. For research on coffee and cacao systems, research methods were reviewed by Somarriba et al. (2001). Methods for measuring and valuing ecosystem services were compiled by Rapidel et al. (2011). For the way ahead, it is imperative to not only optimize the systems ecologically but also to transform the ecological benefits at medium and long time scales into tangible economic payments and incentives.

Socioeconomic Aspects: Paying for Externalities and Services

A wealth of studies exists on the economic performance of different agroforestry systems. Examples from around the world and tools for "financial and economic analyses of agroforestry systems" were compiled by Sullivan et al. (1992) and Current et al. (1995). The assessment of the trade-offs between crop losses due to tree-crop competition or harvest damages from tree felling, on the one hand, and economic benefits from harvesting high-value timber species, on the other hand, has shown a positive balance for the agroforestry systems, particularly for coffee (Somarriba 1992) and cacao (Ryan et al. 2009). Similar benefits are often generated when fruits, medicinal plants, and other crops are included in the economic evaluations. However, due to the complexity of measuring and valuing non-tangible products or services, most of the economic studies have ignored nonmarket benefits and environmental services of agroforestry (Mercer and Miller 1998). This frequent shortcoming of economic analysis, a fundamental limitation when considering the essential importance of conserving natural resources (see sections "Setting the Stage for Agroforestry: Lessons from Monocultures" and "Agroforestry: Evolution, Definition, Practices and Systems"), is only recently receiving more attention with the evolution of metrics for measuring such services (Rapidel et al. 2011). Clearly, for a more holistic assessment of the full benefits of agroforestry systems, it will be important to strengthen the quantitative assessment of all the services provided by agroforestry systems, including their capacity to reduce agronomic and financial risks, to improve the system resilience to extreme climate events, and to contribute to biodiversity conservation and climate change mitigation.

The recognition of these benefits drives the current evolution of different schemes of payment to compensate land stewards for the services they provide to society at large. For example, based on experiences from Africa, Reid et al. (2004) concluded that carbon credits for maintaining trees in savanna grasslands could contribute around 15 % of additional income to pastoralists. For many pastoralists, this was a sufficiently high incentive to retain and protect the trees. Another successful example is the evolution of "payments for environmental services" (PES) as implemented in Costa Rica since 1997. In this country, a tax is levered on gasoline which is used to pay for environmental services such as the protection of biodiversity, soils, and water through forest conservation and reforestation and, recently, also through the establishment for trees in agroforestry systems. For details about the performance of the PES scheme and the possibilities for sustaining such a program, please consult the "National Forestry Financing Fund" (www.fonafifo.go.cr) and the evaluations by Robalino et al. (2011) and Murillo et al. (2011).

As demonstrated by Villamor et al. (2013), there is a significant potential for PES also in Asian rubber plantations to increase the attractiveness of biodiversity-rich systems. Together with additional benefits from certified products for specialty markets and increased support of farmers to transform and sell their products, the overall benefits can favor the adoption and maintenance of more species-rich systems. However, integrative work is urgently needed on the best ways to combine public and private payments not only for the products but also for the increasingly important environmental services of biodiverse agroecosystems within climate-smart territories. A third example of the effectiveness of PES comes from their highly beneficial application to silvopastoral systems in Central and South America (Box 4).

Box 4. "Payments for Environmental Services" (PES) for Silvopastoral Systems in Central and South America

In a project funded by the "Global Environment Facility" (GEF), the Tropical Agricultural Research and Higher Education Center (CATIE) in Costa Rica evaluated, together with FAO, the World Bank, Nitlapan in Nicaragua, and the Centre for Research on Sustainable Farming Systems (CIPAV) in Colombia, the impacts of PES on the adoption of silvopastoral systems. From 2003 to 2006, cattle farmers from Colombia, Costa Rica, and Nicaragua received between US$ 2000 and US$ 2400 per farm (equivalent to 10–15 % of their net income) to implement silvopastoral systems. Overall, the program led to a 60 % reduction in degraded pastures in the three countries, while increasing the land under silvopastoral systems, such as improved pastures with high-density trees, fodder banks, and live fences. The environmental benefits associated with the project included a 71 % increase in carbon sequestration (from 28 M t CO_2-eq. in 2003 to 48 M t in 2006). At the same time, milk production increased by 10 % and farm income by 115 %, while herbicide use dropped by 60 %, and the use of fire to regenerate the pasture is now less frequent (FAO 2010). These positive changes give ample evidence that PES can be a viable avenue to foster positive change.

While the mentioned benefits and their economic equivalents should reach all members of the families and communities providing the services, there is also a great challenge to foster gender equality. Analyzing gender issues in agroforestry in Africa, Kiptot and Franzel (2012) have recommended to (i) empower women by forming or strengthening women's associations, (ii) help women improve the productivity and marketing of the crops and animals under their responsibility, and (iii) foster women's access to information. Obviously, these recommendations also apply to Asia and Latin America where gender inequality prevails. Undoubtedly, much remains to be done to foster gender equality in development initiatives. So, how can we put all of these biophysical and socioeconomic aspects together?

Integrative and Cross-Disciplinary Work: Stitching it all Together at the Landscape Level

In order to address the challenges of food insecurity, poverty and inequality, climate change, ecosystem degradation, and biodiversity loss at the same time, it is critical to put all our tools for sustainable use of natural resources to work to create "multifunctional agriculture" subject to "integrated landscape management" (UN SDSN 2012; Milder et al. 2012). For the past 50 years or so, despite local and temporary relief generated by punctual efforts (e.g., green revolution and monocultures in agriculture), individual uncoordinated efforts in agronomy, livestock farming, forestry, or ecological engineering were not able to sustain environmental services, which are emergent properties of landscapes (Pope Francis 2015; Kimbrell 2002). Consequently, the development paradigm has to change and integrate the advances in all these fields. Agroforestry and agroecological practices have much to offer in the creation of such "climate-smart landscapes" (Gliessman 2015; Leakey 2012; Nair and Garrity 2012).

Our focus must widen to encompass all actions, despite their immense complexity and our resulting lack of mechanistic understanding. When trees, crops, animals, and their respective microbial symbionts interact with the atmosphere and the pedosphere, complicated by nonlinear relationships over different scales of time and space, predictions based on linear dose-response curves for the application of individual nutrients are often inappropriate, no matter how hard we like to cling to them. Add extreme climatic events and increasing population pressure to upset the systems, plus the global spread of pests and diseases to other continents (cf. coffee leaf rust, coffee berry borer, or the existence-threatening diseases of bananas and cacao), and we can easily see how "business as usual" with its reliance on technological quick fixes in the form of pesticides or genetically modified crops not only has contributed greatly to the dimensions of our current problems (Kimbrell 2002) but will also likely impede effective solutions to overcome them. Clearly, a new paradigm is needed to substitute the ineffective reductionist approaches of linking individual factors often with (mostly inappropriate) linear relations for the sake of modeling.

Increasingly, farmers and land managers are reaching out across traditional sectorial boundaries to forge partnerships with conservation and development organizations, researchers, local governments, businesses, and others to address these interconnected problems. According to the UN SDSN (2012), more than 200 such initiatives have already been documented in Latin America, Africa, and Asia. Our future efforts should facilitate and build on such multi-actor and multidimensional initiatives as illustrated by the following examples from UN SDSN (2012): in Lari-Kijabe in Kenya, smallholder farmer organizations are partnering with local governments, banks, and conservation groups to expand agricultural markets and protect high conservation value forests and watersheds. In the Maasai Steppe land of Tanzania, commercial avocado producers, pastoralists, and conservation organizations are partnering to raise incomes and food security, while protecting wildlife. In Tigray, Ethiopia, restoration of highly degraded watersheds by community-government-NGO partnerships has enabled irrigation and water access, increased food production, and greatly reduced the need for food aid during droughts. From Latin America, where agroforestry is increasingly important (Somarriba et al. 2012), another highly successful example is CATIE's "Mesoamerican Agro-environmental Program" (MAP), which has, over the past 10 years, facilitated positive changes in many communities throughout Central America. This multi-actor platform (http://map.catie.ac.cr/web_en/) has provided central tools for promoting effective practices for improving agroforestry systems with cacao, for promoting the agroecological production of vegetables in homegardens and integrated production systems, and for strengthening local governments in their quest for combining production and income generation with the effective protection of natural resources.

The creation of climate-smart territories for food security and, where possible, food sovereignty requires the judicious integration of agricultural, livestock, agroforest, and forest ecosystems in a way that maximizes productivity on the most appropriate lands for production while guaranteeing the essential ecosystem services by protecting critical areas. As indicated in Fig. 30 (and recalling Fig. 2 from the beginning of this chapter), efforts should be strengthened to develop tools which help us design landscapes as a mosaic of land use patches whose species composition, management, dimensions, and spatial distribution foster the effective functional integration of production and conservation objectives. Obviously, the conservation must include cultivated and wild biodiversity (from micro- to macroscales), as well as soil fertility and water resources, the three key elements for sustainable production (Frison et al. 2011; Jackson et al. 2007).

In 2012, a global coalition of more than 50 agriculture, environment, and development organizations came together to implement the "Landscapes for People, Food and Nature Initiative" (www.landscapes.ecoagriculture.org). The target is to combine sustainable development in food production, ecosystem health, and human well-being. The top priority is to strengthen the capacity of existing landscape initiatives and mobilize cross-site learning, coordinated investment, and documentation. To accelerate the scaling up of integrated landscape approaches, the initiative is assisting countries to put in place supportive policy frameworks, encouraging businesses to pursue sustainable sourcing through landscape partnerships, expanding financing for integrated landscape investments, and promoting science and knowledge systems for landscape solutions. Undoubtedly, this is an illustrative example of what is needed.

Another example is the evolution and success of the Cuban programs on agroforestry, reforestation, and knowledge-intensive urban agriculture over the

Fig. 30 At the landscape level, it is essential to put the different agroforestry practices to work in a "climate-smart" mosaic. In this example from the Central Highlands of the Dominican Republic, we see the integration of different agroforestry practices that are (or should be) incorporated in order to protect the natural resources (Photo credit: R. Muschler)

past 25 years. Productivities exceeding 10 kg of organic vegetable production per m^2 (INIFAT 2011) illustrate the potential from pooling effective agroecological practices, even under a demanding climate and on lateritic soils. This is remarkable and the accumulated know-how should be applied to many similar situations (Niggli et al. 2007). Undoubtedly, there is now a wealth of effective agroecological practices which can help reduce the yield gap of 5 to 34% between high-chemical input and organic production systems even further (Seufert et al. 2012). Finally, as illustrated by the examples in sections "Principal Agroforestry Practices" (Fig. 11) and "Roles and Potential of Agroforestry for Sustainable Land and Landscape Management," decided community efforts to build artificial lakes and establish agroforestry systems around them can bring about the effective rehabilitation even of degraded landscapes subject to high population pressure like in Haiti. As these examples illustrate, when the tools of agroforestry and agroecological management are used to their full potential to contribute to sustaining multifunctional landscapes, the title of the recent review *Agroforestry – The Future of Global Landuse* (Nair and Garrity 2012) may be well justified. In fact, the creation of climate-smart landscapes with agroforestry at its core offers substantial benefits over the model of continued agricultural intensification and land sparing (Perfecto and Vandermeer 2010). While agroforestry is not a magic wand for solving all human and environmental challenges, it clearly provides powerful tools to address many of them.

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