Potential of Agroforestry to Enhance Livelihood Security in Africa

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Abstract

Agroforestry systems dot agricultural landscapes in sub-Saharan Africa (SSA), where they provide food, fuelwood, fibre, fodder and other products that are used at home or sold for income. Agroforestry also provides ecosystem services that are important and critical for improved livelihoods. By combining trees and/or shrubs with crops and/or livestock, agroforestry diversifies both farm and non-farm activities. This creates diverse livelihood strategies that help households to deal with recurrent shocks, such as droughts and lean periods, and can make livelihoods more sustainable over time. Based on the literature on agroforestry in SSA, we describe major tree-based systems that are widely practised in SSA and that have received much attention in terms of their contribution to sustainable livelihoods. We show that agroforestry systems are typically multifunctional, although the type of goods and services produced vary depending on the components of agroforestry and the way these are managed in the landscape. Broadly, agroforestry supports food production, health and nutrition, wood-based energy and income. We discuss the current state of knowledge, present case studies to provide the evidence base and highlight gaps in knowledge and barriers to harnessing agroforestry-based livelihoods.

Keywords

Biomass transfer · Fertilizer trees · Nutrition gardens · Rotational woodlots

4.1 Livelihood Systems in sub-Saharan Africa

4.1.1 Rural Livelihoods

Livelihood refers to the means by which people make a living. According to Chambers and Conway (1991), livelihood comprises people, their capabilities and their means of living, including food, income and assets. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future while not undermining the natural resource base (FAO 2019). In sub-Saharan Africa (SSA), rural livelihoods are directly linked to agriculture via small-scale processing and artisanal production and non-agricultural activities, such as wage labour, trading, hawking and service provision (Niehof and Price 2001). Agriculture, particularly farming and herding, is the main source of livelihood in rural Africa (Montpellier Panel 2013; Alliance for a Green Revolution 2017). Using 41 national household surveys from 22 countries in Africa, Davis et al. (2017) found that 92% of rural households are engaged in agriculture. In another study, on-farm sources of income accounted for 59–78% of the total household income in Malawi, Madagascar, Nigeria and Ghana (Davis et al. 2010).

Besides the above-mentioned two sectors, natural resources such as forests and woodlands play a central role in rural livelihoods in Africa. A review of the socio-economic contributions of non-timber forest products (NTFPs) to rural livelihoods in

SSA reported widespread reliance on NTFPs for subsistence and income (Timko et al. 2010). Examples of NTFPs commonly used in SSA include food and food derivatives (e.g. roots, fruits, edible seeds, kernels, edible leaves, mushrooms, insects and bush meat), medicines, fodder, gums and resins, and oils (Shackleton and Shackleton 2004; Timko et al. 2010; Hickey et al. 2016). People also collect bamboo, other grasses and palms for construction, weaving and handcraft productions (Timko et al. 2010). NTFPs are collected at minimum or no cost and provide a safety net during lean periods. However, they are seasonally available, collection is labour or time consuming and access to most forests is regulated.

4.1.2 Livelihood Diversification as an Option for Livelihood Security

Livelihood security connotes sustainable and adequate access to resources to meet basic needs (Frankenberger and McCaston 1998). Yet, approximately 70% of the people in SSA depend on land for their livelihoods (Montpellier Panel 2013; AGRA 2017) and have insecure livelihoods (Ellis 1998, 2000). Among these are the poor and marginalized communities whose survival is already at risk (Gray et al. 2016). Declining crop yields, production failures due to drought periods and lack of income are the leading causes of livelihood insecurity for these communities (UNEP 2015). Already Africa has the highest prevalence of undernourishment and food insecurity compared to other regions of the world (FAO et al. 2018). In 2017, an estimated 236.5 million people (23.2% of the population) were undernourished, while 345.9 million people (33.8% of the population) experienced food insecurity (FAO et al. 2018). It is at the heart of these eventualities that viable options for livelihood diversification are necessary for rural communities to attain their livelihood security.

Defined as the process by which rural families construct a diverse portfolio of activities and social support capabilities in order to survive and improve their standards of living (Ellis 1998), livelihood diversification is a common characteristic of rural smallholders in Africa (Ellis 2000). It occurs as diversification of the rural economy, which is a sectoral shift of rural activities from farm to nonfarm activities, or as individual or household diversification, which is an increase of the number of income-generating activities by individuals or households, regardless of the sector or location (Loison 2015). Livelihood diversification portfolios can consist of farming and nonfarming activities, include wage employment or self-employment, depend on how labour is compensated and accrue on-farm or off-farm, depending on the location where the activity takes place (Barrett et al. 2001; Loison 2015).

Asset, activity and income diversification are typical in livelihood strategies in rural Africa (Ellis 2000; Barrett et al. 2001). Most rural households have multiple sources of income (Ellis 1998), although agriculture remains important and, in most cases, the principal activity of poor households (Ellis 2000; Davis et al. 2010, 2017). In Africa, rural household diversification serves primarily as a strategy for coping with economic and environmental shocks but also as a means of enhancing income (Loison 2015). There is growing evidence that nonfarm sources contribute significantly to rural household income (Davis et al. 2017), in some cases up to 40% of average household income (Barrett et al. 2001; Haggblade et al. 2010). Nonfarm livelihood options that people resort to may include processing or transport of unprocessed agricultural and forest products (Barrett et al. 2001); small-scale business, such as trading and hawking; provision of services, such as transportation; and artisanal production (Niehof and Price 2001). Migration or transfers from networks in urban areas occur where there are no viable opportunities to diversify income activities (Loison 2015).

Livelihood diversification in Africa requires investment in improved farm practices and/or in nonfarm assets, depending on the options available for coping with shocks and income generation (Loison 2015). Currently, specialization in on-farm activities is common in rural Africa, practised by an average of 52% of households, and ranging from 33% of households in Kenya to 83% in Ethiopia (Davis et al. 2010). This means that the majority of rural households receive more than 75% of their income from a single source (Davis et al. 2017). Such households need to be able to generate cash, build assets and diversify across farm and nonfarm activities in order to use livelihood diversification to improve quality of life (Loison 2015). Agroforestry is one of the options that can diversify both farm and nonfarm activities. By creating diverse livelihood strategies, agroforestry can help households deal with recurrent shocks and lean periods and make livelihoods more sustainable.

4.2 Major Agroforestry Systems in sub-Saharan Africa

The variety of agroforestry practices found in SSA is wide. Agroforestry practices may consist of sequential practices in which trees and crops are grown in rotation (e.g. rotational woodlots and improved fallows) or annual relay fallows where fast-growing nitrogen-fixing leguminous shrubs are planted in a crop field at a time when annual crops (such as maize) have already been well established, usually within 2–4 weeks of crop sowing (Akinnifesi et al. 2010a), and tree crop intercropping—simultaneous practices in which trees and crops are grown together in various spatial arrangements (Cooper et al. 1996; Rao et al. 1998; Sileshi et al. 2007; Akinnifesi et al. 2010a). Simultaneous practices are the most common way in which trees are planted on farms. They may include trees on cropland (e.g. scattered trees on cropland or pastures, boundary planting and intercropping), hedgerow intercropping (alley cropping), multi-strata agroforestry systems (e.g. homegardens) and plantations of commercial crops under shade trees (Cooper et al. 1996; Rao et al. 1998; Sileshi et al. 2007).

Typically, agroforestry practices are multifunctional (Kuyah et al. 2016, 2017), although the type and magnitude of the goods and services produced vary depending on the components involved and the way these are managed in the landscape (Table 4.1). Based on the literature on agroforestry, major tree-based systems that are widely practised in SSA and that have received much attention in terms of their contribution to sustainable livelihoods are described.

Table 4.1 Major agroforestry systems and practices found in SSA and their contribution to livelihood benefits

System	Agroforestry practice	Goods and services	Contribution to livelihood benefits
Fertilizer tree	Alley cropping/ farming	Stakes, fuelwood and fodder; soil improvement, erosion control and pest regulation	Food production, income and fuelwood
	Relay fallow/ intercropping	Stakes, fuelwood, fodder and edible pulses (e.g. *Cajanus cajan*) and soil improvement	Food production, income and fuelwood
	Simultaneous intercropping	Timber, poles and fuelwood and soil improvement, wind regulation and microclimate improvement	Food production, income and fuelwood
	Sequential (improved) fallows	Fuelwood, stakes and fodder and soil improvement, pest regulation and erosion control	Food production, income and fuelwood
	Agroforestry parklands (perennial)	Food and food derivatives, fuelwood, timber, craft and medicines and soil improvement, microclimate improvement, shade for livestock and cultural benefits	Food production, cosmetics, health and nutrition, income, fuelwood, cultural benefits
	Biomass transfer (cut and carry system)	Stakes, fuelwood, fodder and soil improvement, pest regulation and erosion control	Food production, income and fuelwood
Fodder tree	Fodder (protein) banks	Fodder, stakes and medicines	Health and nutrition and income
	Silvopastures	Timber and shade for livestock and herdsmen, wind regulation and microclimate improvement	Health and nutrition and income
Fruit tree	Perennial crop orchards	Fruits and refugia for biodiversity	Health and nutrition and income
	Homegardens and agroforests	Food and food derivatives, medicines, cash crops, fodder, timber, fuelwood, refugia, in situ conservation of biodiversity, ornamental and shade	Food production, health and nutrition, income, fuelwood and cultural benefits
Firewood and timber	Rotational woodlots	Firewood, stakes and soil improvement	Fuelwood and income
	Smallholder timber	Timber and firewood	Fuelwood and income
	Live fences	Stakes and firewood and wind regulation, microclimate improvement, boundary demarcation, refugia and ornamental	Fuelwood, income and cultural benefits

(continued)

Table 4.1 (continued)

System	Agroforestry practice	Goods and services	Contribution to livelihood benefits
	Windbreaks	Timber, fuelwood and wind regulation, microclimate improvement, erosion control, refugia and ornamental	Income, food production, fuelwood and cultural benefits

4.2.1 Fertilizer Tree Systems

Fertilizer trees are defined as nitrogen-fixing woody perennials used for soil fertility improvement in arable lands and pastures (Sileshi et al. 2014). Fertilizer tree systems represent a paradigm shift in land use management by smallholder farmers: they exploit the ability of legumes to capture atmospheric nitrogen (N) and make it available to crops, permit growing trees in association with crops in space or time to benefit from complementarity in resource use and address most of the biophysical and socio-economic limitations identified with the earlier technologies based on using N-fixing tree legumes, such as green manures (Akinnifesi et al. 2010a; Sileshi et al. 2014). Fertilizer trees can be managed in alley cropping, intercropping, relay cropping and improved fallow as well as in traditional agroforestry parklands. The biomass they produce can be used ether in situ or in biomass transfer systems. As such, these trees play a key role in the diversification of agroecosystems and increasing the fertility and productivity of land. As they add large nutrient inputs to the soil, they can make a major contribution to sustainable agriculture by minimizing external inputs, particularly N fertilizers. Fertilizer trees have an added advantage, ensuring a multifunctional agriculture that provides timber, fodder, shade, soil improvement, carbon sequestration, watershed management and resilience to climate change (Luedeling and Neufeldt 2012; Sileshi et al. 2014). For example, leguminous trees and shrubs improve soil fertility through enhanced nutrient availability and nitrogen supply through biological N fixation, organic matter build-up, recycling of N from depth and improved soil physical and biological conditions (Akinnifesi et al. 2006b).

Alley cropping is defined as the planting of hedgerows of trees at wide spacing, creating alleyways within which agricultural or horticultural crops are produced (Kang et al. 1990). Alley cropping is synonymous with hedgerow intercropping. It is one of the common temperate agroforestry practices in South America, North America (USA and Canada), Europe, Asia and Africa (Oelbermann et al. 2004). In tropical Africa, it was developed as one of the alternatives to slash-and-burn agriculture (Kang et al. 1990; Kang 1993). Early work on alley cropping compiled by Kang et al. (1998) indicated that a large body of literature has been published on alley farming research and development in Africa. In the humid and subhumid tropics, alley cropping involves growing maize, beans or cassava between rows of perennial woody legumes of the genera *Albizia*, *Calliandra*, *Flemingia*, *Inga*, *Gliricidia*, *Leucaena*, *Senegalia* and *Vachellia*. The woody species may be regularly coppiced (Kang et al. 1999). Coppiced trees are periodically pruned, and their biomass is applied either as mulch or incorporated into the soil to improve soil fertility. Pruning reduces shading and below-ground competition with companion crops, besides providing N-rich mulch and green manure to maintain soil fertility and enhance crop production and provide protein-rich fodder for livestock. Results of on-station and on-farm trials have shown consistently that alley farming is efficient in reducing soil erosion, improving soil organic matter and nutrient status and sustaining crop yields under continuous cropping (Adesina 1999). Maize production under alley cropping has also been found to be socially profitable and financially competitive when compared to maize production relying only on chemical fertilizer (Adesina 1999).

Intercropping of fertilizer trees with cereal crops is an improvement building on the characteristics and advantages of alley cropping, but minimizing the biophysical limitations, such as "hedge effect", competition and tree management (Akinnifesi et al. 2006b, 2010a). In intercropping, fertilizer trees are managed by means of periodic pruning. The best-known example is *Gliricidia*—maize intercropping in southern Africa (Sileshi et al. 2012). Once planted, the trees are continually managed to supply green manure on the same piece of land. Fertilizer trees flourished in southern Africa because most of the potential constraints to the adoption of alley cropping, especially socio-economic factors, such as insecure land tenure, high labour costs for tree pruning as well as the area of land lost to trees (Adesina et al. 2000) were overcome in redesigned fertilizer tree systems, such as intercropping, relay and sequential fallows. Other technical issues overcome include tree management, choice of species and lack of adequate planting material and below- and above-ground competition between trees and crops. These have been variously documented in the reviews on fertilizer tree systems (Akinnifesi et al. 2010a; Sileshi et al. 2014). For instance, Akinnifesi et al. (2006b) showed scarcity of land, relatively low cost of labour and the high cost of mineral fertilizer improved the prospect for wide adoption of fertilizer trees in Malawi, with slight differences in uptake of different practices between regions. While *Gliricidia* intercropping and relay cropping are embraced in southern Malawi, the sequential fallow seemed to be preferred in northern Malawi and eastern Zambia (Akinnifesi et al. 2006b).

In relay intercropping, fast-growing nitrogen-fixing woody legumes are planted in a crop field at a time when annual crops such as maize have already been well established, usually within 2–4 weeks of crop sowing (Akinnifesi et al. 2010a). The legumes continue to grow after the crop harvest throughout the off-season. The tree-crop components only overlap for part of the growing season. Species such as pigeon pea and *Tephrosia* are recommended. As farmers prepare land for the next season, they clear-cut the legume and incorporate the biomass into the soil. Although the yield levels are usually lower than those of intercropping and improved fallows, relay intercropping works well on small farms, and the benefit of trees can be seen immediately after one season of tree growth (Akinnifesi et al. 2010a).

Biomass transfer is essentially moving green leaves and twigs of fertilizer trees from one location to another to be used as green manure (Kuntashula et al. 2004). This system is also known as "cut and carry system" (Ruhigwa et al. 1994). It has been demonstrated to be highly profitable in the production of high-value crops, especially vegetables, such as cabbage, rape, onion, garlic and tomato (Kuntashula et al. 2004, 2006).

Agroforestry parklands involve large canopy trees that are widely spaced in croplands (Boffa 1999). Parklands are the most widespread traditional land use system in Africa (Nair 1993) and the most extensive farming system (on a land area basis) found in the tropics (Boffa 1999). Agroforestry parklands are dominant in the savanna and Sahel biomes, where they provide socio-economic and ecological benefits (Dewees et al. 2011; Bayala et al. 2014b). In Mali, for example, agroforestry parklands occupy about ninety percent of the agricultural land (Kalinganire et al. 2007). Trees in agroforestry parklands are left following clearance of land for agriculture or they spontaneously germinate from dispersed seeds. The most common fertilizer tree in agroforestry parklands is *Faidherbia albida*. Reverse phenology in *F. albida*, which sheds leaves during the rainy season and is in leaf during the dry season (Roupsard et al. 1999), is responsible for a substantial increase of grain yield under its canopy (Bayala et al. 2012).

4.2.2 Fodder Tree Systems

Fodder tree systems involve protein (fodder) bank and silvopastoral management (Chakeredza et al. 2007). Protein banks are stands of trees or shrubs established within a farm or pasture area to serve as a supplementary source of protein-rich fodder for livestock (Sileshi et al. 2014). They also bridge forage scarcity associated with the dry season. In the wet season, livestock graze on grass and herbaceous plants in pastures and woodlands. The quantity and quality of this forage normally decline in the dry season. To maintain animal health and avert loss of productivity, farmers supplement dry season forage with concentrates or fodder from trees and shrubs (Paterson et al. 1998; Bayala et al. 2014a). The latter has been shown to be economical in Kenya (Paterson et al. 1998). Forage is harvested by pruning the top and branches of fodder trees such as *Gliricidia*, *Calliandra* or various species of *Leucaena*, *Pterocarpus* and others that are grown in blocks on farmland. Livestock can also be allowed to graze directly on protein banks, but this can result in damage to the plants and wastage of fodder (Sumberg 2002; Hamer et al. 2007; Bayala et al. 2014a). Protein banks may also conserve soil on slopes, and if planted in strips along the contour they may serve as biological soil conservation measures.

Silvopastoral systems are defined as a land use system in which trees are integral parts of pastures, rangelands or other grazing systems (Sileshi et al. 2014). Silvopastoral systems are common in semi-arid areas, where they are used to overcome forage scarcity. In grazing systems, animals move freely and graze under trees scattered on pasture land. The trees provide shelter and shade for livestock and herdsmen and protect the animals from strong wind, and their branches can be lopped to provide pods (e.g. from *F. albida*) and twigs (e.g. from the African locust bean—*Parkia biglobosa* to feed livestock during the dry season (Teklehaimanot 2004). Provision of shade and fodder improves animal welfare and productivity. The livestock, in turn, are used to plough and provide manure to maintain crop productivity and milk and meat for human consumption. The trees in grazing systems can also be managed to provide timber and other wood and non-wood products for the farmers (Boffa 1999; Dewees et al. 2011).

In communal grazing land, overgrazing results in land degradation and low productivity. It causes the natural vegetation to disappear, and the resultant land with scant vegetation cannot support livestock, leading to conflict over resources. Rehabilitation of such land often involves exclusion of livestock by creation of exclosures (Mekuria et al. 2007) or enclosures (Nyberg et al. 2015; Wairore et al. 2016). These measures allow native vegetation to regenerate, providing fodder and wood, reducing soil erosion and increasing water infiltration (Mekuria et al. 2007, 2011; Wairore et al. 2016). The concept of rehabilitation of degraded lands by establishment of enclosures and agroforestry has been used successfully in West Pokot in Kenya. Establishment of living fences and intensive agroforestry within formerly degraded lands in West Pokot has increased vegetation cover, improved soil health and increased food production in the area (Wairore et al. 2016). Establishment of enclosures and agroforestry alleviated pasture scarcity and allowed the local Pokot pastoral community to participate in crop production (Wairore et al. 2016).

4.2.3 Fruit and Medicinal Trees

Fruit and medicinal trees play a significant role in the food, nutrition, health and income of millions of people in SSA (Akinnifesi et al. 2007; Jamnadass et al. 2011; Leakey and Akinnifesi 2017). Fruit- and nut-bearing trees are an important source of food, nutrition and income besides their potential to mitigate greenhouse gas emissions. Trees are usually planted and managed around homesteads and on farmland (as perennial crop orchards, semi-managed orchards with annual crops or dispersed trees in crop fields). The most prominent fruit trees in SSA include *Vitellaria paradoxa* (shea tree) in West Africa, *Mangifera indica* (mango) in East Africa and baobab in southern Africa (Rao et al. 1998; Teklehaimanot 2004). Many indigenous fruit tree species of Africa also produce edible fruits and nuts during the hunger period. Growth, fruit size, appearance and total yield of indigenous species can be improved through domestication (Akinnifesi et al. 2006a; Ofori et al. 2014; Leakey and Akinnifesi 2017).

Homegardens refer to a land use close to the homestead involving a mix of annual crops and perennial crops in combination with trees and sometimes in association with domestic animals. Homegardens have evolved through generations of gradual intensification of cropping in response to increasing human population and decreasing arable land (Kumar and Nair 2004). A review of the global distribution of homegardens suggests that people traditionally use trees in their homesteads to meet their needs of food, energy, shelter and medicines (Kumar and Nair 2006). Even though homegardens are highly heterogeneous, food plants (food crops and fruit trees) are the most common species in most homegardens throughout the world (Kumar and Nair 2004), suggesting that food and nutritional security is the primary role of homegardens (Kumar and Nair 2006). In homegardens, trees, shrubs, vegetables and other herbaceous plants are grown in dense and random arrangement (Whitney et al. 2018). Trees are also planted at specific locations to provide necessary shade or to avoid shading plants as appropriate (Kumar and Nair 2004) and to provide support for vines such as *Mondia whitei* (Hook.f.) Skeels and species of *Dioscorea* (yam). Akinnifesi et al. (2010b) showed that homegardens in Brazil help conserve biodiversity of native plant and animal species.

4.2.4 Fuelwood and Timber Trees

The demand for firewood, charcoal and timber has been rising and this is posing a serious threat to forests and diversity of some tree species in Africa (Santos et al. 2017). Advocacy for substitution of non-renewables with biomass-based materials will further increase the demand for wood. Fuelwood and timber trees can be planted in agroforestry arrangements, such as rotational woodlots, smallholder timber plantations, live fences and windbreaks. These practices provide integrated food-energy systems that maximize the synergies between wood and crop production. Regular pruning of the trees provides fuelwood for cooking and mulch or green manure for soil improvement. Production of timber and fuelwood on farms can reduce pressure on forests and woodlands and ease the task of fuelwood collection (Ndayambaje and Mohren 2011).

In the rotational woodlot system, food crops are intercropped with leguminous trees during the first 2–3 years. Then the trees are left to grow and harvested in about the fifth year, and food crops are replanted (Otsyina et al. 1996). Rotational woodlot systems utilize fast-growing tree species that can satisfy household and regional fuelwood demand while reducing harvesting pressure on local forests and the associated greenhouse gas emissions (Nyadzi et al. 2003; Kimaro et al. 2007). In Tanzania, species such as *Gliricidia sepium*, *Acacia crassicarpa*, *Acacia mangium*, *Acacia leptocarpa* and *Senegalia* (*Acacia*) *polyacantha* have been shown to produce large quantities of fuelwood (Nyadzi et al. 2003; Kimaro et al. 2007) and raise topsoil carbon above levels of 9–15 Mg C ha^{-1} obtained within 0–30 cm depth of fallowed miombo soils (Kimaro et al. 2007). The leaves and twigs, remaining after wood harvest, are usually applied as green manure to provide nutrients for the next crop (Nyadzi et al. 2003). By improving soil organic matter, rotational woodlots can increase post-fallow crop yield (Kimaro et al. 2007).

Live fences refer to lines of trees grown and used to delineate boundaries of farms or farm components, such as homesteads, crop fields, pasture plots and animal enclosures. Live fences are common among resource-poor farmers who lack cash to erect other types of fencing. When established with multipurpose trees, live fences can provide fuelwood, poles, timber, green manure or mulch, fodder and stakes for climbing beans. They can also stabilize the soil and control erosion. Trees in life fences are regularly pruned, pollarded or coppiced depending upon the species and type of product desired. For example, branches and twigs are pruned from live fences to provide fodder and fuelwood. Live fences are diverse in terms of species composition, although species with loose canopies are preferred, or dense canopies are pruned to minimize competition with crops (Ndayambaje and Mohren 2011). In East Africa, species, such as *Markhamia lutea*, *Grevillea robusta*, *Cupressus lusitanica*, *Euphorbia tirucalli* and *Erythrina abyssinica*, are established into hedges for wood production. In the Sahel, trees that provide fuelwood, e.g. *Ziziphus mauritiana* and *Balanites aegyptiaca*, are used together with other tree and shrub species to make live fences that protect crops against browsing animals (Kalinganire et al. 2007). Depending on the species planted, live fences also act as windbreaks (Kituyi et al. 2001; Ndayambaje and Mohren 2011). A windbreak is a row or multiple rows of trees or shrubs that block or redirect wind. Properly designed windbreaks can enhance and diversify income opportunities from timber production, modify microclimate and create refugia.

4.3 Agroforestry-Based Livelihood Options

There are four pathways through which agroforestry contributes to sustainable livelihoods: food production, health and nutrition, provision of wood-based energy and income generation. These pathways form agroforestry's basis for socio-economic and environmental development in SSA and are critical in shaping land use and management decisions in the region. Agroforestry contributes to household livelihood security by producing food and food additives, fuelwood, fibre, medicines, gums and resins, oils and fragrances and fodder for livestock. They also influence production of food from crops and livestock products, such as meat, milk and honey. These products can be directly used for home consumption or sold on the market to generate income. With income, it is possible to meet expenses related to other aspects of livelihood security, for example, housing, education, sanitation and even social integration.

4.3.1 Food Production

Agroforestry enhances food and nutritional security by supporting crop production and through provision of edible tree and livestock products (Dewees et al. 2011; Jamnadass et al. 2013; Franzel et al. 2014).

4.3.1.1 Cereal Productivity

Trees improve growth and yield of crops when the appropriate species are planted in optimum densities and appropriate pruning regimes are applied (Bayala et al. 2002, 2015). According to recent meta-analyses (Kuyah et al. 2019), average yields of staple crops were almost twice as high in agroforestry compared to yields in treeless systems. Agroforestry practices with the highest increase in crop yield are those that improve soil fertility: alley cropping, biomass transfer and planted fallow (Fig. 4.1).

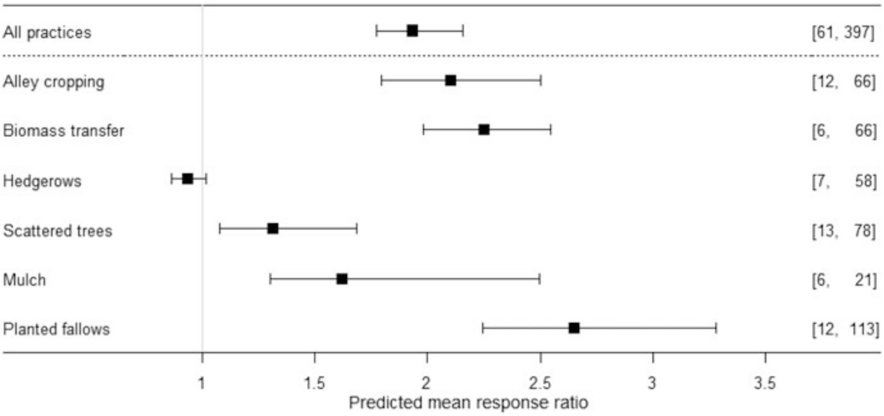

Fig. 4.1 Effects of different agroforestry practices on crop yield. Error bars represent 95% confidence interval (CI). Numbers in parentheses indicate the number of papers reviewed and the number of observations, respectively. Effects are significantly different from 0, if the 95% CI does not include 1 (grey line). Adapted from Kuyah et al. (2019)

There is an abundance of literature on how trees improve soil fertility, e.g. by increasing nutrient inputs through organic matter and nitrogen fixation or by reducing the loss of organic matter and nutrients through erosion control and promotion of nutrient recycling (Rao et al. 1998; Bayala et al. 2006; Akinnifesi et al. 2010a; Sileshi et al. 2014). Trees and shrubs that are used to improve soil fertility on degraded lands are those that can grow on poor soils and build up large amounts of biomass. There is evidence that trees improve crop yield on relatively fertile soils with enough rainfall, but tend to compete with crops when moisture is limiting and soils are inherently infertile, thus requiring appropriate management to minimize trade-offs (Cooper et al. 1996; Rao et al. 1998; Bayala et al. 2002, 2015).

Agroforestry practices, such as fertilizer tree systems, can increase cereal yields and reduce risks of crop failure by increasing soil fertility, improving microclimate and soil moisture (Bayala et al. 2012; Sileshi 2016) and reducing pest problems (Pumariño et al. 2015). One of the benefits of these practices is their ability to diversify the production system and reduce the risks especially for less resource-endowed and vulnerable households. According to Kamanga et al. (2010), maize intercropped with pigeon pea or *Tephrosia* was less risky for resource-poor farmers compared to fully fertilized maize, which had acceptable risk only for resource-endowed farmers in central Malawi. Maize intercropped with pigeon pea was found to be the least risky technology for all resource groups (Kamanga et al. 2010). Similarly, Sirrine et al. (2010) found that the most vulnerable households in southern Malawi were better off intercropping pigeon pea or *Tephrosia* with maize than growing maize with the recommended fertilizer. Using historical rainfall records and simulated yield in northern Malawi, Snapp et al. (2013) also showed that pigeon pea-maize intercropping can meet the household food needs (calories and proteins) in 73–100% of the years across variable rainfall patterns, while fully fertilized maize can achieve this in only half the households.

4.3.1.2 Fruits and Vegetables

Fruits and vegetables common in homegardens provide food security because they mature at various periods throughout the year. Some trees found in agroforestry parklands [e.g. the African locust bean, the shea tree, the tamarind (*Tamarindus indica*) and the baobab—*Adansonia digitata* (Kalinganire et al. 2007; Kehlenbeck et al. 2013; Gebauer et al. 2016)], in homegardens [e.g. the bush mango (*Irvingia gabonensis*) or njangsa (*Ricinodendron heudelotii*) (Dewees et al. 2011; Kehlenbeck et al. 2013)] and shrubs used in improved fallows [e.g. pigeon pea (Jamnadass et al. 2013)] produce edible seeds, fruits, nuts, kernels, leaves and oils. These are consumed fresh or cooked or processed into juice, cakes and other products, such as chutney, curries, pickles and sauce (Kalinganire et al. 2007). By diversifying food sources, agroforestry protects poor households during stress conditions, such as drought and preharvest periods, when staples are in short supply. Trees survive adverse weather conditions that often result in crop failure for most staple crops and, therefore, can provide food in cases of shortage, following crop failure. They also vary in phenology, meaning they can be harvested at different times of the year. For example, a fruit tree "portfolio" based on nine indigenous species in Malawi showed that at least one species was ripe every month (Akinnifesi et al. 2004; Jamnadass et al. 2013). Thus, by growing a collection of exotic and indigenous fruit species, households can access year-round fruit supply (Jamnadass et al. 2013; Kehlenbeck et al. 2013). Income from the sale of tree products can also be used to buy food.

4.3.2 Health and Nutrition

Contrary to the dietary simplification associated with conventional agricultural intensification with cereals (Fanzo et al. 2013), agroforestry can diversify diets by increasing the variety of available foods (Jamnadass et al. 2013; Kehlenbeck et al. 2013). Empirical evidence shows that dietary diversity increases with tree cover (Ickowitz et al. 2014). This suggests that the number of food groups consumed in a day could be increased by increasing the number and diversity of fruit trees and vegetables on farms. A diversified diet contributes to health and nutrition in several ways.

First, fruits, nuts, kernels, oils, condiments, vegetables and medicinal and aromatic plants are a major source of dietary minerals that ensure nutritional security (Kalinganire et al. 2007; Kehlenbeck et al. 2013). Some of these products have higher micronutrient, vitamin, fibre and protein contents than staple crops (Whitney et al. 2017). For example, ~ 50% of vitamin C needs of an adult human in Malawi can be met by daily consumption of 100 g of fruit pulp of either *Azanza garckeana* or *Strychnos cocculoides* available from November to March and 25 g of baobab fruit pulp from March to September (Jamnadass et al. 2013). Nutritional security alleviates deficiencies such as iron and vitamin A that are prevalent in most parts of SSA (Fanzo et al. 2013). With an appropriate portfolio of tree species, households can, therefore, access a year-round supply of vitamin-rich fruits and vegetables.

Many communities used to collect fruits and other edible tree products from forests and woodlands, which have become degraded or which are protected, so they are no longer (legally) accessible. Agroforestry allows the communities to access these products through domestication of indigenous shrub and tree species (Akinnifesi et al. 2007; Ofori et al. 2014). Priority indigenous food trees identified for domestication in SSA include *Allanblackia* spp., baobab, tamarind, bush mango, *Ziziphus mauritiana*, *B. aegyptiaca*, *Sclerocarya birrea* (marula), *Dacryodes edulis*, *Chrysophyllum albidum* and *Uapaca kirkiana* (Akinnifesi et al. 2007; Ofori et al. 2014). Having such a range of trees on farms can increase the range of edible tree products available for households in SSA, where low fruit and vegetable consumption is the main cause of micronutrient deficiencies (Ruel et al. 2005). Domestication can also provide fodder to support dairy and meat production in silvopastoral and agrosilvopastoral systems (Ofori et al. 2014).

Second, agroforestry contributes to health and nutrition by providing fodder and shade or shelter that improves the welfare and productivity of livestock. The livestock, in turn, provide milk, meat and eggs for human consumption. These are important sources of proteins, fats, vitamins and minerals, such as zinc, iron, selenium, calcium and phosphorus (Fanzo et al. 2013), given the dominance of carbohydrate-rich foods in diets of some households in Africa (Ruel et al. 2005). In East Africa, trees and shrubs scattered on farms, in hedgerows and on erosion control structures contribute substantial amounts of high-value fodder for livestock during the dry season (Angima et al. 2002; Kinama et al. 2007; Mutegi et al. 2008; Gachuiri et al. 2017). The fodder supplements grass forage, and some species (e.g. *Calliandra calothyrsus*) can be used as substitutes of commercial feeds (Franzel et al. 2014). In the Sahel and in drylands of Ethiopia, leaves, twigs and pods are lopped from *F. albida* in parkland agroforestry to provide fodder when other sources of forage are not available (Bayala et al. 2014a).

Third, trees and leafy vegetables, with medicinal value, contribute to the health of the people. This can directly provide cure and healing for some sicknesses, reducing the cost of healthcare. Some poor communities in Africa depend on medicinal plants for their primary healthcare. They cook parts of plants, such as roots, bark and leaves, and serve them with regular meals or prepare pastes and concoctions. The latter can be taken in dried form or applied externally to the hurting part of the body. A survey of priority functions of agroforestry parkland trees and shrubs in Burkina Faso, Mali, Niger and Senegal found that nearly all 116 species listed by 425 informants in 45 villages provide food (90%) and medicines (93% of the species) in addition to other benefits (Faye et al. 2011). A variety of trees and shrubs have been documented as serving as both food and medicine (Kalinganire et al. 2007; Jamnadass et al. 2011; Dimobe et al. 2018). For example, *R. heudelotii* found in homegardens is used to treat constipation, dysentery and eye infections; its kernels and seeds are also used in stews and the oil industry, respectively (Jamnadass et al.

2011). Income from sale of agroforestry tree products can contribute to meeting the cost of nutrition and household healthcare (Dimobe et al. 2018).

4.3.3 Wood-Based Energy

Production and use of fuelwood are important livelihood strategies in SSA where about 81% of the households (excluding South Africa) rely on wood fuel as their primary source of energy (World Bank 2011). The main fuelwood in SSA is charcoal and firewood. Charcoal is mainly used in urban areas while firewood is used by rural households for cooking and heating and in cottage industries for brickworks, tea processing and tobacco curing (Ramadhani et al. 2002; World Bank 2011; Iiyama et al. 2014). The demand for charcoal and firewood is projected to increase (Global Environment Fund 2013) in many countries in SSA, as they remain the most readily available sources of energy and the most affordable alternatives to kerosene, liquid petroleum gas and electricity (Iiyama et al. 2014). More fuelwood must, therefore, be produced on agricultural land if the fuelwood demand is to be met on a sustainable basis (Ndayambaje and Mohren 2011).

Approximately 20% of fuelwood in Africa is produced in agroforestry systems (Sharma et al. 2016). Agroforestry fuelwood production can provide more sustainable alternatives compared to forest and woodlands sources (Iiyama et al. 2014). For example, firewood from agroforestry is often harvested by selecting branches or collecting deadwood from trees. Woodlots are also sometimes established on farms for charcoal production. Having fuelwood in the farm is important for women and children, who are responsible for all tasks related to fuelwood collection for cooking in most SSA countries. The literal translation of a woman getting married (*okhutekha*) in the Luhya community in Western Kenya is “to cook”. As this terminology suggests, women in the region devote a lot of time to gathering firewood and cooking while men may be involved in the production and sale of fuelwood. This situation is also observed in some countries, such as Burkina Faso, Togo and Benin in West Africa, indicating that in SSA, the collection of firewood by women and production or sale of fuelwood by men are common. In some parts of western Kenya, women spend about 2–5 hours per day collecting firewood (Bishop-Sambrook 2003). Reducing the time used to collect fuelwood can allow youth to allocate more of their time to their education and women to reallocate time to other activities.

Experimental studies and inventories of fuelwood across SSA report substantial amounts from various species under different agroforestry practices (Fig. 4.2a). The quantities produced vary with agroforestry practice and region, but are generally sufficient for meeting the fuelwood need of 486–500 kg per person per year for up to ten households of 3–7 people (Fig. 4.2b). This production is equivalent to the current 0.67–0.69 m^3 per capita per year (Ndayambaje and Mohren 2011; Iiyama et al. 2014). Exceptions are noted for hedgerow intercropping with *Daniellia oliveri* or *G. sepium* in Benin (Böhringer and Leihner 1996) and windbreaks with *Bauhinia rufescens*, *Acacia holosericea*, *F. albida* and *Vachellia nilotica* in Niger because of

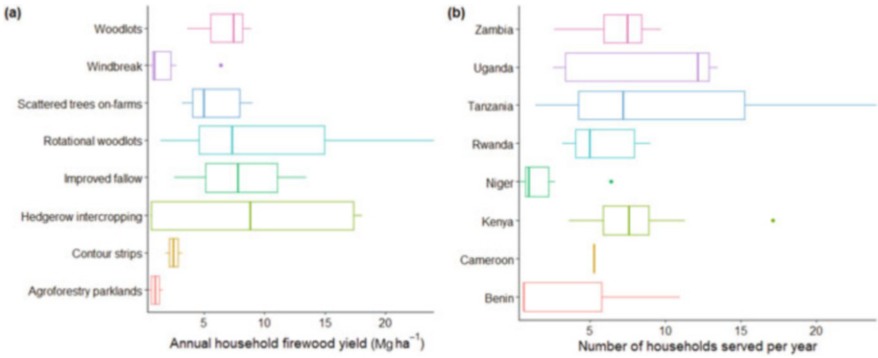

Fig. 4.2 Annual production of fuelwood from different agroforestry practices in sub-Saharan Africa (**a**) and the number of households served by fuelwood from agroforestry per year (**b**). Plot in (**a**) based on means reported for the agroforestry practices in Lulandala and Hall (1987), Jama and Getahun (1991), Kwesiga and Coe (1994), Lamers et al. (1994), Böhringer and Leihner (1996), Nyadzi et al. (2003), Siriri and Raussen (2003), Harmand et al. (2004), Kimaro et al. (2007), Jama et al. (2008), Avohou et al. (2011) and Ndayambaje and Mohren (2011)

larger household sizes with an average of 7.1 persons (United Nations 2017) and low amounts of fuelwood produced (Lamers et al. 1994).

Even though almost all agroforestry practices can provide fuelwood, the main fuelwood production technology in agroforestry is rotational woodlots. These are found to be the most promising agroforestry practice for fuelwood production in semi-arid areas (Ramadhani et al. 2002; Nyadzi et al. 2003; Kimaro et al. 2007). When used with fast-growing nitrogen-fixing species, they allow intercropping without compromising crop yield in the first 2 years. They produce large amounts of wood for charcoal and twigs for livestock after 5 years and improve crop yield after the wood harvest (Nyadzi et al. 2003; Kimaro et al. 2007). In Tanzania, wood productivity in rotational woodlots was about three times higher than that of local miombo woodland vegetation and was sufficient to meet household firewood demands for 7–16 years (Kimaro et al. 2007). However, adoption of rotational woodlots is low (Nyadzi et al. 2003) as farmers instead prefer planting trees for commercial timber or maintaining a diversity of species for multiple benefits. For example, in Rwanda, western Kenya and Ethiopia, farmers often maintain small monospecific woodlots of eucalypts or other fast-growing species, which supply fuelwood and utility poles or timber (Kituyi et al. 2001; Ndayambaje and Mohren 2011). The woodlots are found at homesteads and on slopes (normally highly degraded land) in Rwanda and Kenya or as communal hillside plantations in Ethiopia.

Firewood production has also been reported in agroforestry systems whose primary objective is to improve soil fertility, such as improved fallows and hedgerow intercropping (Jama and Getahun 1991; Siriri and Raussen 2003; Jama et al. 2008), and multipurpose agroforestry systems, such as agroforestry parklands (Boffa 2015). Fertilizer trees grown in relay intercropping can also produce substantial amounts of fuelwood. For example, over 90% of the domestic fuelwood needs were met from a hectare of 2–3-year-old *Sesbania* trees in Malawi (Kamanga et al. 1999). Pigeon pea production has also been successfully integrated with energy-saving stoves, and this has reduced the frequency of buying and collecting fuelwood in parts of Malawi (Orr et al. 2015). Fuelwood is also reported as a priority use of on-farm trees in many surveys on farm agrobiodiversity or livelihood benefits of trees (Tabuti 2012; Reppin et al. 2019).

4.3.4 Income

Agroforestry supplements household income through sale of surplus staples or vegetables, livestock or livestock products and trees and tree products. Salable tree products include fruit, nuts, kernels, edible leaves, oils, condiments, gums, resins, building poles, stakes for climbing beans, timber, fuelwood, fodder and medicines (Kalinganire et al. 2007; Dewees et al. 2011; Place et al. 2016). Some of these products and services such as improvement of soil fertility substitute what farmers would otherwise have to buy.

Using national household surveys, Miller et al. (2017) found that more than 30% of all rural households in SSA cultivate trees on their farms and that these trees account for an average of 17% of the total annual gross income for tree-growing households and 6% for all rural households in Ethiopia, Malawi, Nigeria, Tanzania and Uganda. In Burkina Faso, Mali and Senegal, close to 50% of households obtained income from agroforestry, with fuelwood, fodder and fruits contributing between 10 and 24% of the total household income (Binam et al. 2015). In these countries, tree products were second only to crop production in terms of income generation (Binam et al. 2015). A study in Maradi, Niger found that adopters of farmer-managed natural regeneration (FMNR) had around 30% more income than corresponding non-adopters (Haglund et al. 2011). In another study in the same region, Rinaudo (2012) found an increase in household income by at least 140 USD per year. In West Pokot, Kenya, income from agroforestry products ranked fourth in total household income (Wairore et al. 2016). Opportunities for agroforestry to contribute to household income are projected to increase with population growth and economic development in SSA (Dewees et al. 2011).

4.3.4.1 Income from Non-wood Products

Non-wood tree products provide regular income to farmers. The value of these products varies considerably by species and region. Most species maintained by farmers in agroforestry parklands are preferred because of their income-generating values (Place et al. 2016). For example, fruits and leaves of baobab (Pye-Smith 2013), cakes processed from fruits of *Detarium microcarpum*, seeds of the African locust bean, fruit pulp of tamarind and *Z. mauritiana* and the nuts of shea tree generate substantial income for households in West Africa (Teklehaimanot 2004;

Kalinganire et al. 2007; Pye-Smith 2013; Binam et al. 2015). Mangoes (the third largest group of fruits produced in SSA, after bananas and citrus fruits) provide a major source of income for smallholders. A survey of 121 households in six villages in Mangwende, Zimbabwe, found that 82% of the households had one or more mango trees, most of which were planted in homegardens and around the homesteads (compounds); 94% of the households sold mangoes from their farms (Musvoto and Campbell 1995). In Hoima, Uganda, farmers intercropping fruit trees with food crops earned enough income to meet household needs (Recha et al. 2017). Gum from *Senegalia senegal* contributed significantly to incomes in Sudan (Aymeric et al. 2014), similar to marula in southern Africa (Shackleton and Shackleton 2004).

Agroforestry also provides opportunities for households to generate income through processing and value addition for tree products and establishment of tree nurseries (Asaah et al. 2011). Value addition allows farmers to obtain high prices, for example, from shea nuts, cashew, mangoes, gum and resins (Place et al. 2016). Shea butter is both sold at both local markets and exported for use in the chocolate, cosmetics and pharmaceutical industries within Africa and in Europe (Kalinganire et al. 2007; Place et al. 2016). Post-harvest processing of shea nuts yields greater returns than sale of raw shea nuts and provides large quantities of husks and cakes that are used as compost and fuel (Boffa 2015). Fruits and nuts from *B. aegyptiaca* can be processed into oils (Pye-Smith 2013). Processing and value addition can increase availability of tree products throughout the year, creating opportunities for new markets and off-farm employment.

4.3.4.2 Income from Fodder Trees

Silvipastoral and agrosilvopastoral systems produce livestock and livestock products (e.g. milk, meat and manure) that can be sold for cash. Increasing livestock densities have raised the demand for fodder in SSA, especially during the dry season when grass forage is scarce. Fodder from trees is rich in proteins, vitamins and minerals like calcium. It can help to bridge times of forage scarcity, increase milk production and can be used to substitute dairy meal (Place et al. 2009; Paterson et al. 1998). For example, milk production can be increased between 0.6 and 1.3 kg per day by feeding animals an additional 2 kg of *C. calothyrsus* (Place et al. 2009). Farmers can also earn income from the sale of fodder or seeds of fodder trees (Paterson et al. 1998; Place et al. 2009; Ayantunde et al. 2014; Bayala et al. 2014a). Analysis of economic impacts of fodder shrubs in East Africa projected a net income between USD 101 and 122 per year from 500 bushes of *C. calothyrsus* after 2 years (Place et al. 2009). In the Sahel, the price of browse (*Combretum micranthum*, *Piliostigma reticulatum*, *Pterocarpus erinaceus* and pods of *F. albida*) has been estimated to evolve from 95 FCFA F in November to 298 FCFA F in January (1 USD = 500 F CFA) (Ayantunde et al. 2014).

4.3.4.3 Income from Wood Products

Farm production of wood, including timber and poles, for local markets is increasing in Africa (Place et al. 2016; Sharma et al. 2016), making significant contributions to improving rural livelihoods through income generation (Kiplagat et al. 2011). In Kenya, much of the timber from farms is produced in woodlots (e.g. *Eucalyptus* spp. or *Vachellia* spp. in western Kenya and *Melia volkensii* in eastern Kenya) or along boundaries (e.g. *G. robusta* in central Kenya) (Kiplagat et al. 2011; Place et al. 2016). Trees in woodlots are often selectively harvested and sold. Agroforestry systems that include high-value trees (e.g. *G. robusta* in perennial tree crops such as coffee and tea or shea trees in cereals in agroforestry parklands) provide incomes when harvested. Timber species common in pasture, windbreaks and homegardens provide cash when the trees are cut and sold.

Charcoal and firewood provide income to a wide range of beneficiaries along the value chain, including people who harvest trees, produce charcoal, collect charcoal or firewood or transport or retail the commodity (Iiyama et al. 2014). Farmers practicing FMNR in four West African countries obtained higher income from sales of firewood (Pye-Smith 2013). In Niger, wood collected at the roadside and from farms contributed between USD224 and US 256 per household per year (Pye-Smith 2013). In West Pokot, sale of wood products from agroforestry, including firewood, ranked fourth in importance among all sources of household income (Wairore et al. 2016). In Tanzania, the net present value of rotational woodlots was 6.3 times higher than that of maize-fallow (Ramadhani et al. 2002). Species used to control soil erosion on slopes and to improve soil fertility via planted fallows also provide firewood that can be sold.

4.3.4.4 Income from Increased Crop Production

Economic studies of farm returns to land and labour [net present values (NPV) and benefit cost ratios (BCR)] indicate that fertilizer trees are either comparable or better than inorganic fertilizer (Ajayi et al. 2009; Kamanga et al. 2010). In central Malawi intercropping maize with pigeon pea had consistently positive returns across the farmer resource groups, indicating its suitability to a wide range of environments and for the poorer farmers (Kamanga et al. 2010). Over a five-year cycle, the discounted net benefit of maize grown with species of *Gliricidia* (USD 327 per ha), *Sesbania* (USD 309 per ha) and *Tephrosia* (USD 233 per ha) compared favourably with maize grown with the recommended inorganic fertilizer (USD 349 per ha) in eastern Zambia. In eastern Zambia, fertilizer trees generated better returns per investment (BCR: 2.8–3.1) than with the recommended fertilizer purchased at market price (BCR, 1.8) or with the 50% government subsidy for fertilizer (BCR, 2.6) (Ajayi et al. 2009).

Franzel (2004) assessed the financial returns to farmers of three agroforestry practices, namely, fodder shrubs in Kenya, rotational woodlots in Tanzania and improved fallows in Zambia. He found that full adopters of these practices earned USD 68–212 per year more from these practices than from alternative available practices. Some studies (Phiri et al. 2004; Quinion et al. 2010) also indicated that farmers who take up the improved fallows in Zambia and Malawi have higher welfare, measured in terms of outcome parameters, such as increased asset base, among others.

4.4 Case Studies

4.4.1 Ex Ante Impact Analysis of Fruit Trees in Southern Africa

Many rural households rely on indigenous fruit trees as sources of cash and subsistence in southern Africa. Until the late 1980s, there was little effort to cultivate, improve or add value to these fruits. In 1989, the International Centre for Research in Agroforestry (ICRAF: now the World Agroforestry) initiated research-and-development work on indigenous fruit trees in southern and western Africa (Akinnifesi et al. 2006a). Studies suggest that the cultivation of wild fruit trees will become more important as rural households move from subsistence to a cash-oriented economy. During the season of food abundance, the collection, utilization and commercialization of indigenous fruits become important for household income portfolio diversification.

In southern Africa, several studies were conducted concerning the contribution of miombo fruits to the livelihood portfolio of the rural communities. Mithöfer et al. (2006) quantified the contribution of indigenous fruit trees towards reduction of vulnerability to food insecurity and poverty, using a multiperiod stochastic household income model. The results show that rural households in Zimbabwe are highly vulnerable to seasonal fluctuations in income, thereby identifying a critical period where households run high risk of being food insecure. The report recommended diversified season-specific income-generating portfolios of which indigenous fruit trees have an important role to play. The probability of rural households falling below the poverty threshold is at 70% during the critical food-insecure season during growing season of food crops, if no indigenous fruits are available, and this reduces at harvesting time. If indigenous fruit area available, the vulnerability can be reduced by about 30% during the critical period. This suggests that indigenous fruit trees can serve as an important risk-coping strategy, which can be further complemented by other livelihood strategies during the agricultural off-season and, thus, provide a cushioning effect to annually occurring poverty and hunger (Mithöfer et al. 2006).

An ex ante impact analysis in Zimbabwe showed that household consumption of indigenous fruits represents 42% of a family's food intake during the fruiting seasons. In addition, the marketing of these fruits contributed substantially to household income, keeping families above the poverty line during critical hunger periods (Mithöfer 2005). A household food security survey conducted in 2002 showed that an estimated 60–85% of all rural households in Malawi, Zambia and Mozambique lack access to food for as much as 3–4 months per year, especially during December to February (Akinnifesi et al. 2004). During this critical hunger period, 26–50% of the respondents relied on indigenous fruits as a coping strategy (Akinnifesi et al. 2004). In South Africa, 30% of households were reported to have planted new trees in their homesteads as a coping mechanism for hunger periods (Akinnifesi et al. 2006a).

4.4.2 Vegetable Production Using Biomass Transfer

Vegetables are valuable as sources of vitamins and minerals in the largely maize-based diet of rural households, especially in eastern and southern Africa. Vegetables also have high market value and can help generate income throughout the year (Kuntashula et al. 2006; Tschirley et al. 2009). Smallholder vegetable production has become a fast-expanding enterprise due to the increasing demand from rapidly increasing urban populations. The vegetables are often produced in nutrition gardens, promoted by non-governmental and church organizations targeting the poor and the sick, especially HIV patients, with the aim of improving their standards of living through improved nutrition and income generation. Nutrition gardens are often located close to water sources wherever possible, and this often tends to be in wetlands. Vegetable production is restricted to the dry season, mainly due to the high incidence of vegetable pests, diseases and waterlogging (Kuntashula et al. 2006). Declining soil fertility is one of the major factors limiting smallholder vegetable production in the wetlands.

Biomass transfer using fertilizer tree species has been proposed as a more sustainable means for maintaining soil nutrient balances in vegetable-based production systems in the wetlands in southern Africa (Kuntashula et al. 2004, 2006). In that regard, two separate studies were carried out in Zambia to assess the agronomic and economic feasibility of biomass transfer. In the first study the biomass transfer using *Gliricidia* and *Leucaena* in the production of cabbage, onion and a subsequent maize crop during the dry season was evaluated on the fields of 43 farmers (Kuntashula et al. 2004). In that study biomass transfer recorded higher net incomes than the control and required lower cash inputs than fertilized crops. Net income derived from cabbage and onion grown using *Gliricidia* at 12 Mg ha^{-1} was comparable with that from fully fertilized cabbage (Kuntashula et al. 2004). There were also additional benefits from the maize crop planted after vegetable harvests. The *Gliricidia* biomass treatments produced maize grain yields as high as those from the fully fertilized treatments (Kuntashula et al. 2004). *Gliricidia* leafy biomass produced vegetable yields comparable with those obtained from chemical fertilizers (Kuntashula et al. 2006). For instance, the increase in yields of cabbages grown on soils amended with leafy biomass of *Gliricidia* ranged between 85 and 167% relative to no soil amendment (Kuntashula et al. 2006).

In Zimbabwe, Muchecheti and Madakadze (2016) determined biomass accumulation and nitrogen recovery rates of rape (*Brassica napus*) as influenced by different legume tree pruning and the effect of combining these pruning with inorganic N fertilizer. The authors found that the application of the different pruning and inorganic fertilizer, alone or combined, increased total biomass yields of rape relative to the control. The sole pruning of *Vachellia karroo* increased the total biomass yield of rape by 1.09 Mg ha^{-1} on dry matter basis relative to the yields of the non-fertilized plots. The corresponding increases in biomass yield of rape following soil amelioration with sole pruning of *C. calothyrsus*, *Senegalia angustissima* and *Leucaena leucocephala* were 2-, 3.2- and 7.5-fold, respectively. The total biomass increases over the control plots following supplementation of pruning with a quarter of the recommended inorganic N were 13.31, 9.49, 6.81 and 5.23 Mg ha^{-1} on dry matter basis for *L. leucocephala*, *S. angustissima*, *C. calothyrsus* and *V. karroo* each with quarter recommended N, respectively. Similarly, Makumba and Phiri (2008) reported that *G. sepium* and *Tephrosia candida* biomass increased cabbage yields by 7.48 and 12.60 Mg ha^{-1}, respectively.

The profitability of the leguminous leafy biomass depends on the synchrony between N released from the decomposing organic matter with the demand for N by the crop (Myers et al. 1994) as well as the structure of the inputs, especially the labour costs (Kuntashula et al. 2004). Kuntashula (2004) found that the structure of costs differed between the full fertilization and the leafy biomass applications. The biomass transfer technologies recorded higher net incomes than the control and required lower cash inputs than the fully fertilized crop. Net incomes of the biomass treatments were substantially reduced by the labour costs for pruning and incorporation of the biomass. This is an important implication for the African farmer since cash resources to obtain external inputs are the major impediments to production. In rural set-ups of most African countries, the opportunity cost of labour is very low because most of the family labour cannot find alternative payable jobs. This family labour can, therefore, be deployed in the use of leafy biomass without serious consequences of resource misallocation.

One of the key benefits of this practices is the improvement in soil fertility. Mafongoya and Jiri (2016) found high residual fertility terms of inorganic nitrogen (nitrate and ammonium) after harvesting vegetables, especially in plots treated with 12 Mg ha^{-1} of *Gliricidia* pruning. The high levels of nitrate after onion and cabbage harvest could lead to nitrate leaching during the rainy season if not utilized. Farmers grow maize crop after harvesting the vegetables (usually in September) using the residual soil fertility. The maize is harvested in the middle of the hunger period (December–January) in southern Africa. The sale of green maize is a good source of income and food security to farmers during this hunger period (Mafongoya and Jiri 2016). Measurements after maize harvest showed that the residual N in the soil was reduced to undetectable levels (Mafongoya and Jiri 2016). This shows that this cropping system can minimize the environmental problems associated with N leaching.

4.4.3 Cereal Production in Agroforestry Parklands

Using 64 observations from 15 studies conducted in Burkina Faso, Mali, Niger and Senegal, Bayala et al. (2012) found that parkland trees increase crop yield between 0.14 and 0.24 Mg ha^{-1} depending on tree species. The most limiting factor for the associated crops in parklands being light (Kater et al. 1992; Bayala et al. 2008; Bazié et al. 2012), yield increase magnitude can be enhanced through crown pruning for C_4 cereal crops (Kater et al. 1992; Bayala et al. 2002) or by using shade-tolerant crops (Bazié et al. 2012; Pouliot et al. 2012; Sidibé et al. 2017). Root pruning has also been tested but the associated increase in yield was less than the one due to crown pruning (Jones et al. 1998). These management actions are not needed for shrubs intercropped with cereals (Dossa et al. 2012) and some tree species like *F. albida* because of its atypical phenology (Roupsard et al. 1999; Kho et al. 2001).

As trees in parklands are not planted in most cases, a common way of renewing them is through FMNR, where farmers protect and nurture trees and shrubs that naturally grow on farms (Box 4.1). FMNR in Niger exemplifies successful application of agroforestry on degraded lands for improved livelihoods (Haglund et al. 2011; Binam et al. 2015; Place et al. 2016) in a country where tree plantation (forest) programs have low seedling survival rates, about 20%, and agricultural intensification had failed to improve food security and incomes (Pye-Smith 2013). The success of FMNR in Niger is attributed to preserving "the right tree in the right place", focusing on native species and involvement of local communities (Pye-Smith 2013). People willingly invested time, labour and available resources once they noticed significant impacts of trees on soil fertility, crop yield, wood supply, animal welfare, income and food security (Haglund et al. 2011; Binam et al. 2015; Place et al. 2016).

Box 4.1 Farmer-managed Natural Regeneration in Niger

Farmer-managed natural regeneration (FMNR) is a practice of actively managing and protecting non-planted trees and shrubs in order to increase the quality or quantity of woody vegetation on farmland. Whether such achievements materialize depends on the existence of living root systems or seeds in the soil. Farmers protect and manage trees that regenerate spontaneously on their farms, contrary to the usual practice where sprouts are slashed or burned down before each planting season. After emergence, farmers select the most vigorous stems of the sprouts, which they prune so that the stems grow into a straight trunk; the rest are culled. In 2005, 5 million hectares of treeless, highly degraded land in Maradi and Zinder had been transformed into green landscape through FMNR. FMNR added to the landscape more than 200 million new trees since 1985 and prevented further land degradation.

FMNR improved food security and incomes in Niger. In Zinder and Maradi, trees on farms increased crop yields by 15–30%. At the national scale, annual agricultural production on restored croplands increased by about 500,000 Mg. Crop yields improved significantly because of improved soil fertility and microclimate (reduced wind speed and decreased local temperatures). The trees also produce fruits and leaves for human consumption, fodder for livestock, fuelwood, traditional medicine and other products and services. Surplus from trees can be sold on the market allowing farmers to pay for household needs and buy food on the market in case crops fail. Farmers who adopt FMNR and practice it continuously can increase their gross income per month by around 72 USD per year. Multiple benefits of trees compensate for possible losses in cereals where tree density and canopy cover are high.

Co-benefits from FMNR include improved social well-being. Improved access to fuelwood and fodder reduces the daily workload for women. For

(continued)

Box 4.1 (continued)
example, the presence of trees on cropland reduced the time spent gathering firewood from 2.5 hours per day to an average of half an hour per day. High tree cover on the landscape can control wind speed, reduce airborne dust and have a cooling effect. The trees provide other environmental services, such as watershed protection and carbon sequestration. Provision of wood and fodder can reduce the pressure of firewood collection and livestock grazing in adjacent forests.

Further reading: Faye et al. (2011), Haglund et al. (2011), Bayala et al. (2012), Luedeling and Neufeldt (2012), Binam et al. (2015) and Gray et al. (2016).

Insights from FMNR in Niger have been replicated and scaled up across Africa, where agroforestry has transformed degraded lands into fertile farmlands by increasing on-farm tree densities, for example, in Mali (500,000 hectares), Ethiopia (1 million ha), Burkina Faso, Malawi and Senegal (Gray et al. 2016). Farmers in these countries have benefited through higher crop yields, increased provision of fodder, firewood and other tree products, income from sale of these products, surplus staples and employment (Gray et al. 2016).

4.4.4 Fodder Banks

A review of work carried out in Tanzania, Malawi and Zimbabwe has provided substantial evidence for improvement in smallholder dairy production (Chakeredza et al. 2007). Data on the profitability of fodder shrubs in zero grazing, cut and carry systems are available from Tanzania, Kenya and Uganda. In Tanzania, Otsyina et al. (2001) calculated that by using either *Leucaena pallida*, *Leucaena collinsii* or *Leucaena diversifolia* as substitutes to dairy concentrate, a farmer could save about USD 310 per cow per year. In central Kenya, Franzel (2004) found that when *Calliandra* was used as a substitute to the basal diet, annual net returns increased by USD 142. Farmers who planted 500 *Calliandra* seedlings could increase their net income by 101–122 USD a year from the second year of planting onwards. By using *Calliandra* as a supplement (6 kg fresh leaves per day) to an existing basal diet (with 2 kg dairy meal), the calculations in East Africa show that a farmer's net income increases by USD 62–115 (Chakeredza et al. 2007). Fodder banks have also been experimented and introduced in farmers' fields in West Africa (Hamer et al. 2007; Bayala et al. 2014a).

4.5 Knowledge Gaps and Barriers

4.5.1 Knowledge Gaps

A gap in knowledge relates to a lack of holistic valuation of the benefits of agroforestry. So far, the evidence on livelihood benefits of agroforestry is scattered within primary studies. Published syntheses are limited to specific ecosystem services—especially certain provisioning ecosystem services and the role of agroforestry in supporting food production. This gap persists in the literature because researchers prioritize economic benefits or tools for measuring non-economic livelihood benefits are not well developed. Studies on livelihood benefits of agroforestry in SSA mainly focus on market benefits, such as crop yield, timber, fuelwood and non-wood tree products (Kuyah et al. 2016). Those studies that consider non-market benefits limit research to tree cover and associated agrobiodiversity. Non-market livelihood benefits of agroforestry are, therefore, undervalued or omitted altogether in many studies. However, livelihood security is not just linked to income, but to a much broader set of relationships, conditions and physical factors.

The cultural role of agroforestry or its products is often overlooked. A recent review identified an apparent lack of studies on cultural benefits of trees on farms in SSA (Kuyah et al. 2016), although some of the trees documented to provide cultural benefits in forests are also found on farms. Many tree species found on farms have a central place in peoples' traditions and ceremonies. For example, beer from marula is shared with neighbours, helping to build and maintain social networks (Shackleton and Shackleton 2004); shea butter is presented as a gift among women to celebrate marriage, births or dowries (Boffa 2015); homegardens provide fruits for sharing, and they also play a role in cultural festivals and religious activities. The majority of rural people traditionally use wild species for medicine and other purposes. Harvesting and processing medicinal plants, e.g. shea butter and other tree products, entail traditional knowledge passed on across generations. Understanding the contribution of trees to various aspects of livelihoods is needed to support informed decision-making and evidence-based land use management in SSA.

4.5.2 Overcoming Barriers

Beyond physical suitability, such as favourable sites, appropriate tree and crop germplasm and adoption of suitable land management practices (Cooper et al. 1996; Rao et al. 1998; Akinnifesi et al. 2007; Kalinganire et al. 2007), successful agroforestry systems require enabling conditions, such as governance, gender synergies, secured land tenure, investment, markets for agroforestry inputs and outputs (Mbow et al. 2014). This underscores the complex nature of factors that hinder the ability of agroforestry to provide livelihood security. They include political, social, cultural, economic and ecological factors. Barriers related to adoption of agroforestry have widely been documented. Nevertheless, there are barriers that directly relate to harnessing livelihood benefits from agroforestry. On the political front, policy frameworks in many countries determine the ownership and, thus, realization of monetary value from trees on farms.

Ecological factors include low productivity and suboptimal management. Agroforestry systems include many species that grow in different places. Suitability of some species has been evaluated and, in some situations, farmers are able to identify species that best match the conditions of the planting site and know where to get the seed for those species. However, many other species are yet to be domesticated, and information on the characteristics of each species, their management and productivity is lacking. Domestication of indigenous species can lead to productivity gains and preserve those species that are threatened by overharvesting. This requires knowledge on the reproductive biology of potential agroforestry species, the correct densities that are compatible with different crops and the kind of management required to sustain productivity gains. It is not clear how climate change will affect trees, since as plants they have specific environmental and climatic requirements. In some cases, lack of experience with trees, and lack of time and knowledge required for management can limit livelihood benefits derived from agroforestry. In other cases, there is need for awareness creation for agroforestry practices that produce high-value products. ICRAF and other partners have played a significant role creating awareness for agroforestry opportunities in Africa. There is rising interest on public-private partnership with a focus on making agroforestry profitable. The involvement of the private sector is likely to lead to development of value chain that is critically needed for many agroforestry practices.

Economic factors that limit harnessing livelihood benefits of agroforestry include limited capital for investment, long payback period and limited market opportunities for agroforestry products. Agroforestry requires investment in inputs (e.g. seedlings) and time. The many benefits (co-benefits, products and services) of agroforestry are often not realized until after some years. Delayed return on investment demotivates farmers to invest in agroforestry and, therefore, incentive schemes during the establishment years can be catalytic. Some of the current schemes focus on conservation of trees (in forests) in order to limit deforestation, which leaves out management of trees on farms. Another barrier is that markets and value chains for agroforestry products are generally underdeveloped.

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