21 The Need for Sustainable Agricultural Land-Use Systems: Benefits from Integrated Agroforestry Systems

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Abstract

This chapter introduces the different agroforestry systems (AFSs) as part of the diversification of agricultural landscapes and gives examples of their use in different related crop production systems in southern Africa. The introduction of trees into agriculture has several benefits and can mitigate the effects of climate change. For example nitrogen-fixing trees and shrubs contribute significantly to nutrient recycling and benefit soil conservation, which is particularly important for smallholder farms. In addition, shelterbelts play an important role in reducing

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wind speeds, and thus, evapotranspiration, and modifying the microclimatic conditions, which is an important factor for the adaptation of cropping systems to climate change. These integrated AFS landscapes provide important ecosystem services for soil protection, food security and for biodiversity. However, deficiencies in the institutional and policy frameworks that underlie the adoption and stimulus of AFS in the southern African region were identified. Furthermore, the following factors must be considered to optimise AFS: (1) selection of tree species that ensure maximum residual soil fertility beyond 3 years, (2) size of land owned by the farmer, (3) integrated nutrition management, where organic resources are combined with synthetic inorganic fertilisers and (4) tree-crop competition in the root zone for water.

21.1 Introduction

21.1.1 Land-Use Pressure

Agricultural production in sub-Saharan Africa (SSA) has been widely affected by the use of unimproved seed varieties, declining soil fertility, expensive inorganic fertilisers and, in some cases, poor pricing and marketing systems (Kuyah et al. 2021). In addition, continuous cropping with low inputs has resulted in devastating soil and land degradation effects. Amongst the major manifestation of land degradation are loss of soil organic matter (SOM), decline in fertility, elemental imbalances, deterioration of soil structure, as well as acidification and salinisation

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(FAO and ITPS 2015). Reports have shown that 24% of the global land area has suffered degradation within the last 25 years, with the cultivated land area directly contributing approximately 19% (Henao and Baanante 2006; Nkonya et al. 2016). Due to an increasing human population, the luxury of traditional fallowing consistent with former farming practices has been curtailed, leading to other land uses being exploited for agricultural expansion. For instance, in southern Africa, large forested areas have been converted to agriculture (Gondwe et al. 2020; Dziba et al. 2020). This is overwhelmingly the main cause of deforestation (Fisher 2010). In the Miombo region of southern Africa, FAOSTAT reported an increase in cropped area from 100,000 km^2 to 272,000 km^2 between 1961 and 2014 (Dziba et al. 2020). It is clear that agriculture is the main cause of woodland conversion in the ecosystem. The drivers of both small- and large-scale cropland expansion in the region vary greatly between countries, with widely varying degrees of land-use intensification and expansion (Ryan et al. 2016). Overall, however, cropped area per rural person has remained around 0.3 ha per head, whilst the rural population has increased from 31 to 111 million (1961–2020; data from FAOSTAT).

Whilst a small human population allowed land to lay fallow in order to rebuild and sustain the soil physical and chemical properties, this has not been possible in southern Africa due to the immense pressure to provide food for a rapidly growing population. Increasing productivity within small pieces of land has been at the mercy of continuous application of synthetic inorganic fertilisers by smallholder farmers, which are mostly costly and inaccessible. Consequently, several soil-improving interventions were promoted with a farming systems approach in agriculture including crop rotation with leguminous crops. In later years, a sustainable investment in soil fertility management programmes through the adoption of low-cost agroforestry (AF) technologies or practices that increase the resilience of agricultural production was promoted in different agroecological regions of the world, including in southern Africa (Kuyah et al. 2021; Muchane et al. 2020). Such soil-fertility-improving interventions are intended to make Africa achieve food and nutritional security (Chap. 20). Indeed, this addresses a wide range of Sustainable Development Goals (SDGs) of the United Nations including Zero Hunger (SDG 2), Health (SDG 3), Climate Action (SDG 13) and Life and Land (SDG 15).

21.1.2 Agroecosystems of Southern Africa

Most parts of southern African vegetation are generally referred to as the Zambezian phytoregion. The region covers ten countries in central and southern Africa between latitudes 3° and 26° south with a total area of 377 million ha (White 1983). The region falls within the tropical summer-rainfall zone with a single rainy season (November–April) and two dry seasons, a cool season from May to August and a hot season from September to November (Geldenhuys and Golding 2008). Annual rainfall is 500–1500 mm, with a decreasing gradient from north to south (Chidumayo 1997). Within the SSA region, savanna constitutes the largest ecoregion (Eriksen 2007). These are ecosystems that have been heavily influenced by both natural and anthropogenic factors such as fire, cultivation practices and wood extraction for charcoal production. Degradation of the agroecosystems in the region has been associated with not only a massive loss of soil material, but also a loss of fauna and flora. Additionally, anthropogenic influences have had an impact on the distribution of the woodland ecosystems in the region. For example the current distribution of Miombo woodland, the principal vegetation type in the region, is the result of fire regimes and anthropogenic practices (Tarimo et al. 2015).

Winter rainfall occurs predominantly in the Western Cape. The Cape Floristic Region, for example, is one of the world's 34 biodiversity hotspots and is recognised as a global priority area for nature conservation. Habitat loss has been accelerated by the ongoing transformation and fragmentation of landscapes. In large areas of SSA, soil structural degradation, low SOC concentrations and nutrient limitations are widespread in both natural and man-made ecosystems (Tamene et al. 2019). Agricultural land for crop production and rangelands takes up more of the land surface of southern Africa than any other type of land-use. Cereals and grains are southern Africa's most important crops, occupying a large area of cultivatable land (Chap. 20). Maize is the most common crop and a dietary staple, a source of livestock feed and an export crop in some countries. Other crops include sorghum, millet, wheat and rice grown for subsistence use and income generation. A larger number of small-scale farmers and commercial farmers also produce cassava, peanuts, sunflower seeds, beans, potatoes, pumpkins and soybeans. The Western Cape is traditionally the second largest wheat producer in South Africa, but also fruits, grapes and vegetables and oilseeds are important agricultural products. An overview on the agroecological regions in SSA is given by Roetter et al. in Chap. 20.

21.1.3 Impact of Land Use on African Savannas

In the African savanna, the most significant land-use practices include arable and pastoral systems as well as the harvesting of timber products. Agriculture is normally practiced and traditionally takes a form of shifting cultivation, which comprises interchanging between a short phase of cultivation and a period of fallow. In this way, shifting cultivation transmutes savanna into a mosaic landscape with croplands, fallows of different ages and non-arable savanna sites that are not used for cultivation due to unfavourable soil and habitat conditions. Characteristic for these mosaic landscapes is the preservation of some highly valued tree species such as *Adansonia digitata* (baobab), *Parkia biglobosa* and *Vitellaria paradoxa* on croplands. Besides natural fires, people set fires for various reasons such as to clear ground for agriculture, to achieve higher visibility and to stimulate an off-season re-growth of perennial herbs (Krohmer 2004). During the last decades, the African savannas were subject to high climatic variability and land-use changes (Hickler et al. 2005; Wezel and Lykke 2006; Brink and Eva 2009). Land-use changes account for 70–80% of the biodiversity changes in the African savannas (de Chazal and Rounsevell 2009). The percentage of land intensively used for agriculture has increased in Africa, and agricultural systems have been intensified due to the growing use of fertilisers and pesticides. Land-use changes are driving the loss of natural habitats, biodiversity and stored carbon and the loss of other ecosystem services (Brink and Eva 2009). The reduction of natural resource capital leads to an increased risk of soil erosion, land degradation and of natural hazards such as floods.

21.2 Developing Sustainable Land Management Strategies for the Savannas

21.2.1 Current Land Management Strategies

Agriculture remains an important engine for the growth of the southern African economy due to its backward and forward linkages to the economy. A changing climate is widely acknowledged as a threat to the agricultural sector; however, the sector holds a great potential in contributing towards the greening of the southern African economy. One approach advocated to support a transition to an all-inclusive green economy is climate smart agriculture (CSA). CSA is defined as agriculture that sustainably increases crop productivity, enhances resilience (adaptation), reduces or removes greenhouse gases (mitigation) and is leading to the achievement of national food security and development goals. A widely promoted CSA in South Africa is conservation agriculture (CA) which is defined as a farming system that promotes the maintenance of minimum soil disturbance, permanent soil cover and diversifies crops per unit area or time. Crop diversification includes practices such as intercropping, crop rotation, cover cropping and AF, which are key to the sustenance of CA. The practice of conservation agriculture with trees (CAWT) is a term recently used to describe the combined CA practices and AF, and it is believed to be an important CSA technique, but its benefits are not well documented. The worldwide acknowledgement of AF as an integrated approach to sustainable land use owing to its production and environmental benefits spans over several decades (Nair et al. 2021). In both CSA and agroforestry systems (AFSs), an on-field assessment plays an important role in the evaluation of access modalities and provides an understanding of characteristics that have a bearing on the beneficiaries' choice and preferences regarding adoption and the use of feasible technologies and management practices.

Box 21.1 Case Study: Limpopo Climate Smart Agriculture
This study was initiated to address three objectives relating to CSA, namely: (1) to establish climate-smart (CSA) techniques and practices introduced and advocated with an understanding of factors that hinder farmer adoption, (2) smallholder maize farmers' perceptions and preference of specific CSA techniques and (3) document some dominant traditional AF practices for

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Box 21.3 (continued)
viable CSA interventions in the province. The study was carried out in Limpopo Province of South Africa. Limpopo Province was chosen as the study area due to its diverse farming activities, high climatic variability and largely arid to semi-arid nature, suggesting that CSA techniques and practices that reduce the effects of droughts, moisture stress and water scarcity are necessary. The province spans a total area of 20,011 km^2 and a population of 1,092,507, inclusive of a portion of Kruger National Park. In general, the bulk of precipitation in Limpopo Province occurs in summer with rainfall ranging between 400 mm and 600 mm.

Data Collection Methods

To achieve the research objectives, the study employed a combination of qualitative and quantitative methods which usually complement each other, as none of these methods are better than the other. Accordingly, in this study, literature review and semi-structured interviews with several groups of relevant stakeholders in the area of climate change, water management and agriculture were conducted using non-probability purposive sampling to identify factors impacted by water availability and climate change. Consequently, semi-structured interviews were held with farmers, NGOs and other stakeholders through both key informants and semi-structured interviews. The qualitative data was first transcribed by making memos and noting of main and key initial observations regarding the contextual information.

The Best-Worst Scaling (BWS) model was used to document farmers' perception and preferred CSA farming practices that are perceived as best and worst in sustaining crop productivity under climate change. This technique measures the relative importance that respondents attach to certain attributes. In developing the survey instrument for this objective, 15 farming practices suitable for dryland maize production based on literature were used (Table 21.1). The third objective on documentation of prevalent traditional AF practices in farmers' fields and home gardens was achieved by first reviewing a study on indigenous AF practices in the Limpopo Province carried out about 20 years ago (Ayisi et al. 2018) in the Mopane district. This was followed by site visits to farmers' fields across different rainfall regimes to assess dominant practices. Descriptive statistics was used to identify dominant systems and associated pros and cons of the practice.

CSA Technologies

Several technologies and practices consistent with CSA were noted, which included CA, DTSVs, infield rainwater harvesting (IRHW) and AF. For

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Box 21.3 (continued)
instance the adoption of seed varieties is anticipated to permit harvest even under adverse conditions, whilst helping farmers to deal with dry spells and mitigate against rain shortfall. Rainwater harvesting was also noted to have the potential to increase the rainwater productivity and yields with prospects to mitigate against the risk of crop failure associated with erratic and declining rainfall. AF was found to have prospects of improving soil fertility, whereas CA was an option for soil fertility improvement, whilst contributing to mitigation through limited tractor use and safeguarding soil carbon sequestration. To uncover the context within which the CSATIs are used, respondents revealed some key factors for adoption, which include proof of technology benefits, need for immediate benefits, involvement of end-users of the technologies and provision of support and complementary programmes, amongst others.

Farmers' Preference for Specific CSA Techniques

Report on the ranking farmers' preference for different CSA interventions in the Mopane District is presented in Table 21.1.

Traditional Agroforestry Practices

In general, AF in the Mopane district occurs in diverse forms in homesteads and farmlands. Fruit trees dominate the home gardens, whereas indigenous trees occur on the farmlands. However, planned or externally driven AF initiatives were found to be limiting, though few location-specific testing of species and systems had been carried out in the past. Leaving trees on farmlands as AF was prevalent in most agricultural production systems. AF in this sense is passive and has become a land management decision by which farmers choose not to remove specific trees when clearing land for farming. Farmers maintain trees with subsistence crops for several reasons amongst others (Tables 21.2 and 21.3).

Farmers within very high rainfall zones tend to focus on exotic fruit trees, grown in pure stands rather than in an intimate mixture with annual crops. However, AFS involving fruit trees such pawpaw, banana, mango and avocado planted with maize and vegetables can be found. The medium and drier localities are dominated by sparsely populated indigenous woody species mainly marula, Jackalsberry and acacia in association with maize. Interest in fruit tree production is largely encouraged by the favourable rainfall and availability of the local market for the fruits.

Conclusions

Whilst results have indicated some CSATIs with high prospects for the promotion of CSA in South Africa, high initial investment costs and additional labour required as well as management intensiveness associated with some CSATIs may render them unfavourable in the southern African context, particularly within smallholder agriculture. It is likely that a combination of

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Box 21.3 (continued)
technologies and practices will be necessary to achieve enhanced results with CSA attempts, so future research could unpack how this happens in practice. Diverse AFS occur in the study area, but the practice is more passive than planned interventions primarily and lowly ranked due to lack of information on the benefits of the practice.

Table 21.1 Respondents perceived the following attributes from best to worst

Ranking of practices	Description of practice
P1	Intercrop maize with legumes as nitrogen source.
P2	Apply maize residue as a mulch to bare soil.
P3	Changing planting date.
P4	Adopt drought-tolerant and fast-maturing maize cultivars.
P5	Changing maize plant density.
P6	Apply fertilisers according to maize fertiliser recommendations.
P7	Feed maize residues to livestock.
P8	Adopt ripper tillage for maize production.
P9	Apply fertiliser that releases nutrients slowly for maize production.
P10	Changing from maize to crops that require less nitrogen fertilisation.
P11	Intercrop maize with trees as the source fertilisers.
P12	Adopt no-till for maize production.
P13	Changing from maize production to livestock and dairy production.
P14	Changing from maize to sorghum production.
P15	Shift from farming to non-farming activities.

Table 21.2 Farmers' reasons for practicing agroforestry in the Mopane District

1	Food production for household consumption
2	Medicinal
3	Fodder
4	Material for building
5	Fuelwood
6	Fruit for sale and consumption

Table 21.3 Major limitations to the adoption of intensive agroforestry by farmers

Item	Constraints to adoption
1	Limited land area per household which cannot accommodate trees
2	Lack of land ownership for long-term investment in the woody perennial species
3	Lack of knowledge on agroforestry system
4	Inadequate water in drier areas for successful tree production

21.2.2 Low Input, No-Tillage Agriculture

Sustainable agriculture is an essential requirement to satisfy the needs of human beings, enhancement of natural resource base as well as environmental quality over a long period of time. The overarching purpose of sustainable agriculture is the conservation of the natural resource base, particularly soil and water by depending on the minimal utilisation of artificial inputs from outside the farming system. It ensures that land recovers from the disturbances caused by cultivation and the harvest of crops (Wezel and Lykke 2006; Francis and Porter 2011). Sustainable agriculture promotes the adoption of conservation practices such as crop rotation, integrated pest management, natural fertilisation methods, minimum tillage and biological control. Sustainable land management also requires an utilisation of techniques that reduces nitrogen loss (Küstermann et al. 2010). Sustainable agricultural practices can be effective in improving water use efficiency specifically in poor developing countries affected by water scarcity (Pretty et al. 2006). The use of agricultural practices such as no tillage or minimum tillage as some of the strategies to ensure sustainable land management has proven to be valuable in the reduction of soil loss and soil fertility restoration (Altieri 2002; Pretty et al. 2006; Lal 2007). These agricultural practices improve soil fertility by implementing farming practices such as using cover crops, leaving residues in the field, avoiding soil compaction, reducing the use of agrochemicals and unnecessary system inputs (e.g. World Bank 2008).

21.2.3 Perennial Crops

The cultivation of perennial crops has proven to reduce the detrimental effect of soil tillage, thereby promoting a sustainable management of land. Perennial crops have been reported to bring a valuable number of benefits. This is owing to the fact that their roots go beyond the depths of 2 m and can significantly improve the functioning of the ecological system such as conservation of water resources, nitrogen cycling as well as carbon sequestration. Compared to annual crops, perennial crops are reported to be more effective in the maintenance of the topsoil, that is to be 30–50 times more effective in the reduction of nitrogen losses, and to sequester between 300 and 1100 kg C ha^{-1} a^{-1}, compared to the 0 to 300 – 400 kg C ha^{-1} a^{-1} sequestered by annual crops (Cox et al. 2005). It is also believed that perennial crops could help restrain the impacts of climate change, reduce management costs, as they do not need to be replanted every year; hence, they require fewer passes of farm machinery and fewer inputs of pesticides and fertilisers. Perennial crops also require less harmful inputs such as the application of herbicides.

21.2.4 Usage of Crop Varieties

Sustainable land management requires an improvement of crop varieties as it becomes increasingly difficult to adjust the environment to the requirements of the plant. High yield plant varieties that are adapted to specific production environments and sustainable agricultural practices and that are resistant to specific pests and diseases will become increasingly important in the future. Livestock improvement will increase productivity and make more efficient use of scarce land and water. Biotechnology's potential as a tool for sustainable production systems should be evaluated and supported on a case-by-case basis (World Bank 2008).

21.2.5 Organic Farming

Organic farming has proven to be another approach for sustainable land management in the region. Conservation and enhancement of soil health is at the epicentre of organic farming. However, in order to conserve soil fertility, a number of farming practices that take full advantage of ecological cycles must be employed. This can be carried out by implanting practices such as crop rotation, intercropping, polyculture, cover crops and mulching. Long-term crop yield stability and the ability to buffer variations in yield against climatic adversity is critical in agriculture's capability to support society in the future. Sullivan (2009) estimates that for every 1% of soil organic matter (SOM) content, the soil can hold 10,000–11,000 L of plant-available water per ha of soil down to a depth of about 30 cm. Many studies have shown that, under drought conditions, crops within organically managed systems produce higher yields than comparable crops managed conventionally. This advantage can result in organic crops out-yielding conventional crops by 80% on average under severe drought conditions (Pimentel et al. 2005; Smolik et al. 1995). The primary reason for higher yield in organic crops is thought to be due to the higher water-holding capacity of the soils under organic management (Sullivan 2009). Nevertheless, other studies in the past have shown that organically managed crop systems have lower long-term yield variability and higher cropping system stability (Smolik et al. 1995).

21.2.6 Integrated Pest Management Systems

Integrated pest management (IPM) systems have been developed for many crops to control pests, weeds and diseases whilst reducing potential environmental damage from excessive use of chemicals. Scaling up IPM technologies is a challenge, as these management systems rely on farmers' understanding of complex pest ecologies and crop–pest relationships. Thus, although IPM messages need to be simplified, IPM systems require continuous research and technical support and intensive farmer education and training along with policy-level support (World Bank 2008).

21.2.7 Precision Agriculture

Precision agriculture improves productivity by better matching management practices to local crop and soil conditions. Relatively sophisticated technologies are used to vary input applications and production practices, according to seasonal conditions, soil and land characteristics and production potential (see Chap. 20).

21.3 Agroforestry Systems

21.3.1 Integration of Agroforestry into Sustainable Land-Use Systems

Under the conditions of global changes, there is an urgent need for alternative land-use systems and changes to current management to provide food security and resilient and climate-smart agricultural systems, as well as to combat desertification and the loss of biodiversity. In this context, the integration of AF is often discussed as a strategy that can be used both for the adaptation to, and for the mitigation of, climate change effects (e.g. Nair 2012; Zomer et al. 2016; Makate et al. 2019; Sheppard et al. 2020a). To effectively present AFS as a solution, we must present evidence of how AFS can be utilised as a means of buffering and mitigating the predicted climate change effects on agricultural production systems, rural livelihoods, food security and local microclimates.

21.3.2 What Is Agroforestry?

AFS can be defined as dynamic, ecologically based, natural resource management systems that, through the integration of trees on farms and in the agricultural landscape, diversify and sustain production for increased social, economic and environmental benefits for land users at all levels. The definition of AFS has evolved over the years and is now considered as a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. Trees in AFS provide a range of goods (fruits, timber, fodder, leaf litter and green manure, medicines, firewood) and ecosystem services (carbon sequestration, windbreak, improvement of microclimate, soil protection, habitat structure, food for animals etc.), thereby enhancing food and nutrition security and resilience to climate change. AF is already practiced by both small and large-scale farmers in the southern Africa region and there is evidence that the wider practice has been prevalent for many decades in different parts of the world (Nair et al. 2021). In Malawi for example, the prevalence on farms of AF tree species was already observed nearly 90 years ago by Hornby (1934, cited by Dewees (1995)). Today, regeneration (by planting or natural) and management of tree species on farmland (croplands and on rangelands) is now widespread in all the ecological regions of southern Africa. Broadly, there are three main types of AFS namely (1) agri-silvicultural (crops and trees), (2) silvo-pastoral (trees and livestock) and (3) agro-silvopastoral (crops, trees and livestock) (Nair et al. 2021). On most farms in southern Africa, trees are either established through (1) retention during land clearing for crops and pastures, (2) natural regeneration from stumps and roots in places where trees had been cleared (farmer managed natural regeneration) and (3) planted from seeds and seedlings (planted agroforestry systems). Each of these three methods of tree establishment has its own advantages and disadvantages. For example planting trees in drylands is a challenge due to low survival rates, and the high costs associated with accessing germplasm, nursery and out planting (Reij and Garrity 2016; Brancalion and Holl 2020). In this case (2) should be recommended.

21.3.3 Origin of Systems

Retention of Trees Retention of selected tree species during land clearing is a common method of establishing trees on farms. The method is cheap and effective. Tree species retained depend on farmers' preference and the ecological zone. In Malawi, for example, tree species retained on crop fields and pasture lands include *F. albida*, *Vachellia* spp., *Erythrina abyssinica*, *Markhamia obtusifolia*, indigenous fruit trees (*Uapaca kirkiana*, *Azanza gackeana*, *Parinari curatellifolia*, *Strychnos* spp., *Sclerocarya birrea, Ziziphus mauritiana*) and fodder trees (*Kigelia africana*, *Piliostigma thonningii*), depending on the ecological region (Dewees 1995). In northern Namibia, tree retained on farms include indigenous fruit tree species such as *S. birrea*, *Berchemia discolor*, *Diospyros mespiliformis*, *Strychnos* spp. and *Hyphaene petersiana*. Trees are retained on contour bunds, farm boundaries or in the field where they are intercropped with field crops or combined with pasture.

Farmer Managed Natural Regeneration (FMNR) FMNR is a low-cost method of establishing desired tree species on farms where trees had originally been cleared. Trees are established by natural regeneration from stump and root stock sprouting whilst keeping the land under the primary function of agricultural production, whether crops or livestock (Lohbeck et al. 2020; Weston et al. 2015). The FMNR practice is effective on landscapes where propagules (stumps, roots, seeds) can still be found. In the case of seeds, these are either deposited by wind or through animal dung. With FMNR, farmers select preferred tree species as they regenerate, removing undesirable ones whilst tending those preferred. Tending includes the pruning of branches and canopy and the thinning out of some trees and stems to achieve the desired tree density and protecting the seedlings and saplings from animal damage. Documented evidence shows that FMNR practice is widespread in southern Africa (Reij and Garrity 2016; Moore et al. 2020). In Tanzania, a study found as many as 69 tree species being managed on farms, although the average number of species selected and retained by farmers on crop lands was three, with umbrella thorn (*Vachellia tortilis* syn. *Acacia tortilis*) being selected most often by the farmers (Moore et al. 2020). A survey of trees on farms in the central plains of Malawi showed that mango (*Mangifera indica*) is the dominant tree species on agricultural land, accounting for one-third of the tree population. Other tree species with significant numbers are *Piliostigma thonningii* and *Erythrina abyssinica*, both indigenous trees (Dewees 1995). A recent study also found that more than 50% of indigenous trees regenerated on the farms are *Piliostigma thonningii* and *Combretum* spp. in the mid altitude sub-humid ecological zone. In the semi-arid lakeshore ecological zone, the dominant tree species regenerated by farmers are *F. albida* and *Vachellia polyacantha* (syn. *Acacia polyacantha*).

Planted Agroforestry Systems These AFS are established from either seedlings or by direct seeding. Some tree species such as *S. birrea* and *Gliricidia sepium* are also established from truncheons. There are many types of planted AFS which include systematic and dispersed intercropping with either coppicing or full canopy tree species, improved relay fallows (utilising, e.g., *Tephrosia vogelii, Sesbania sesban and Cajanus cajan*), protein fodder banks and windbreaks. If not intercropped, these trees can also be planted along contour bunds, farm boundaries and fallowed fields. If intercropped with coppicing tree species, trees are cut back repeatedly to prevent shading of crops. Generally, management of planted AFS depends on the species and the system objectives. In Malawi, the shrubs, *C. cajan*, are estimated to cover about 113,000 ha (Simtowe et al. 2010).

21.3.4 Typical Types of Agroforestry Systems in Southern Africa

The last decades have witnessed an increase in the promotion and a corresponding increase in the uptake of AFS in southern Africa. Several agri-silvicultural AFS (crops and trees), with different spatial and temporal arrangements, have been promoted and these include:

1. *Intercropping* systems can be described as those which combine multiple crops at different spatial and temporal scales, for example, relay intercropping which is considered as a cropping arrangement where the lifecycle of one crop overlaps with that of another crop. Fertiliser trees such as *G. sepium* or *S. sesban* can be established between the crops (Kwesiga et al. 2003);
2. *Improved fallows* or fallow rotations, where planted tree fallows are left for a short period (2 years) and are followed by 2–3 years of maize crop (Fig. 21.1a, b). Short-duration fallows with herbaceous legumes have been examined widely and were found to increase yields of subsequent crops compared to traditional grass fallows or continuous cropping systems (Nyamadzawo et al. 2012). The trees are left growing on residual moisture once the maize crop has been harvested. Improved fallow is a practice whereby a piece of land is dedicated to

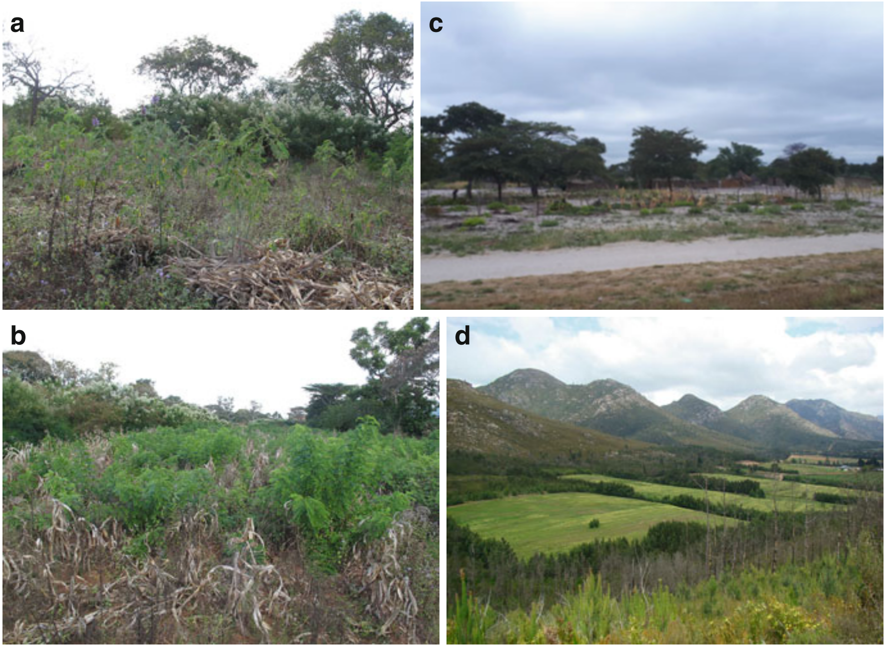

Fig. 21.1 *Tephrosia candida* (**a**) and *Gliricidia sepium* (**b**) are used in AFS to improve fallows in Malawi, (**c**) AF as part of a home garden in Caprivi, Namibia and (**d**) shelterbelts in the Western Cape Province, South Africa (Photos Rebekka Maier **a**, **b** and Maik Veste **c**, **d**)

fallowing with fast-growing nitrogen-fixing trees or shrubs. Improved fallows are an improvement over natural fallows, with the capability to attain the objective for using natural or traditional fallow systems more quickly, through careful choice of species, management of tree density, spatial arrangement, and pruning. From ecosystem perspective, the main function of the fallow is the transfer of mineral nutrients from the soil back to the woody biomass, which is then made available through burning, decomposition, and nutrient turnover from the organic biomass. These fallows also come in different forms depending on the size of the land holding: They can be non-coppicing fallows/rotational fallows or coppicing fallows (Akinnifesi et al. 2007). Several tree species have been used in these systems including *Sesbania sesban, Tephrosia candida*, *T. vogelii*, and *Crotalaria* spp. (Fabaceae), for rotational fallows. For coppicing fallows, species include: *Leucaena* spp., *Calliandra calothyrsus*, *Gliricidia sepium, Senna siamea*, *Flemingia macrophylla* and *Vachellia* spp. (Kwesiga et al. 2003; Mafongoya et al. 2006). Furthermore, woody biomass and nutrients can be provided also from intercropped pigeon pea (*Cajanus cajan*). The nutrient levels such as nitrogen are influenced by the species, their coppicing ability and the biomass production.

3. *Parkland systems*, for example, where *F. albida* is intercropped with crops. With its reverse phenology the tree-crop competition for resources is reduced, whilst enhancing crop yields and soil health (Barnes and Fagg 2003); The term fertiliser trees is premised on the impact of the various soil fertility improvement practices on key ecological functions including nitrogen fixation, soil fertility improvement and soil conservation (Sileshi et al. 2014). Essentially, these practices are modifications of the natural fallow and traditional shifting cultivation systems, which have become unsustainable in southern Africa (Akinnifesi et al. 2008). As indicated earlier, trees have the potential to improve soil fertility through nutrients contributed from decomposition of biomass or leaf residues, nutrient flow, atmospheric nitrogen fixation (legumes only), root turnover and nutrient cycling processes, as well as the influence on soil microclimate and associated faunal activities.
4. *Biomass transfer* is essentially moving green leaves and twigs of fertiliser trees or shrubs from one part of a farm to another to be used as mulch or green manure (Kwesiga et al. 2003; Sileshi et al. 2020a, b). The effect of biomass transfer is also dependent on the amount and quality of leaf manure. To improve the system, appropriate nutrient-rich tree species have been selected. Amongst the legume species tested for biomass transfer, so far *G. sepium* has shown superior performance in southern Africa. *Leucaena Leucocephala* and *T. vogelii* have also been used in biomass transfer technologies (Place et al. 2003; Kuntashula et al. 2004).
5. *Fodder banks*, which are concentrated units of forage legumes established and managed to provide additional protein for selected cattle during the dry season. They involve the establishment of high-quality fast-growing leguminous trees or shrubs, and often leguminous species with an objective of providing supplements to livestock to achieve high productivity and are mostly used during the dry season to bridge periods of forage shortage.
6. *Alley cropping* or hedgerow intercropping is an AF practice in which perennial, usually leguminous trees or shrubs are grown simultaneously with an arable crop. Alley cropping involves growing crops in alleys formed between planted hedgerows of widely spaced woody species that are regularly coppiced to reduce shading and below ground competition with companion crops, and to provide green manure and mulch (Kang and Wilson 1987). Tree species that have been tested in southern Africa include *L. leucocephala* and *G. sepium* (Kwesiga et al. 2003). In general, alley cropping is more promising in the humid tropics than in the drier areas, mainly due to below- and above-ground interactions between trees and companion crops, and the climatic conditions. The literature on the effect of alley cropping on crop yields in southern Africa is generally contradictory. In northern Zambia, alley cropping with *L. leucocephala* increased the yield by 90% compared to limed control after 6 years whilst *G. sepium* had no effect in the same trial (Matthews et al. 1992).

7. *Multi-story plantations*, which are characteristic AFS that involve growing several (tree) crops in different layers of a shaded perennial cropping system. Multi-story cropping will alter the light and radiation environment of understory species more than their nutrient relations.
8. *Tree/Home gardens*, where perennial agricultural crops and livestock are grown in association with seasonal multipurpose AF trees and shrubs within the compound of individual houses, under the management of family labour (Fig. 21.1c).
9. *Shelterbelts*, which are barriers that are erected to break down or slow down the ravages of wind which are placed on the windward side (Fig. 21.1d). Wind breaks consist of trees or shrubs maintained and arranged in such a way that they work as a protective measure against destructive winds and cold fronts.

Several of these AFS have been adopted in southern Africa ranging from improved fallows, alley intercroppings, parkland systems, biomass transfer systems and shelterbelts amongst others. These have resulted in increased crop productivity through improved soil organic matter and soil physical properties, water storage, soil fertility and soil biodiversity at farm level and landscape scale (Akinnifesi et al. 2010; Sileshi et al. 2014, 2020b).

21.3.5 Benefits and Limits of Agroforestry

AFS present the potential capacity to contribute to climate change mitigation and adaptation by enhancing agricultural landscape resilience, improving the microclimate, sequestering carbon, and reducing greenhouse gas emissions. AFS are one of those few land-use systems that provide adaptation and mitigation services in an integrated and synergistic manner (Duguma et al. 2014). AFS provide the potential to adapt and modify existing land-use management strategies to external pressures providing a stable long-term solution that is able to meet environmental and socio-economic needs as a replacement for unsustainable agricultural activities. AFS contribute to a wide range of important ecosystem services for protection of soils, optimise agricultural production systems, and provide additional income by forest and non-forest products (Sheppard et al. 2020b; Nair et al. 2021).

Mechanisms for Soil Improvement in AFS

AF practices have been demonstrated to increase soil fertility through benefits from fallowing using annual, biannual or perennial nitrogen fixing trees or ‘leguminous fertiliser trees’ which are either planted in rotation (e.g. improved fallows) or intercropped with crops (Kwesiga et al. 2003; Mafongoya et al. 2006; Sileshi et al. 2014). Leguminous trees such as *G. sepium* and *Acacia angustissima* and others such as *S. sesban and C. cajan* can fix nitrogen that can be of use to the crops that are grown after the fallow period (Sileshi et al. 2014, 2020a, b). Chikowo (2004) estimated that the total annual fixed nitrogen in *A. angustissima* (non-woody components + leaf litter) was 122 kg N ha^{-1} during the 2-year fallow period, whilst

C. cajan, S. sesban and cowpea (*Vigna unguiculata*) fixed 97, 84 and 28 kg N ha^{-1}, respectively.

AF practices also sequester more carbon compared to other agricultural land-use systems (Kumar and Nair 2011; Sileshi et al. 2014). However, the amount of biomass and SOC added is not the same between different systems and varies with tree species, soil type, rainfall and environmental conditions. Several studies have estimated biomass buildup in AFS. Nyamadzawo et al. (2008a) reported that improved fallows of *A. angustissima* and *S. sesban* accumulated 26.3 and 25.4 Mg ha^{-1} in leaf litter and twigs after 2 years of fallowing and resulted in 3.7–9.1 Mg ha^{-1} more SOC compared to continuous maize cropping. Fallowing also improves soil structure, build-up of soil organic matter and its carbon stocks, thus contributing to carbon sequestration. Build-up of SOM is critical to soil productivity and generally corresponds to nutrient build-up. The increase in SOM increases the cation exchange capacity (CEC) of the surface soil, which is especially important in kaolinitic soils and other light textured soils with low CEC. The associated benefits of high SOM include reduced phosphorus fixation in soils with high iron and aluminium oxide contents, buffering of soil against pH changes, improved water retention and nutrient retention against leaching and reduced mineralisation rates (Nyamadzawo et al. 2009).

In southern Africa and most of the tropical regions, the soils are acidic and deficient in phosphorus; hence, there is a need for inorganic P supplements. However, in most smallholder areas, mineral phosphorous is available but very expensive. In addition, in some soils, P may be present in the soil, but it is not available for plant uptake because of low bioavailability due to the high binding capacity of P to Al and Fe minerals in acidic soils. The use of AFS can be an option as some trees enhance P bioavailability to subsequent crops (Chikowo 2004; Mweta et al. 2007). Trees improve the P availability through secretion of organic acids and an increased mycorrhizal fungi population in the soil.

Impact of Fertiliser Trees on Soil Improvement and Crop Yield

Research has shown that the use of organic amendments may be a better and more sustainable option to improve soil health amongst resource-constrained smallholder farmers in SSA. However, the challenge of using organic amendments is that the range of the organic resources available to smallholder farmers is narrow, and in most cases, there are just animal manures and a few plant residues left after grazing and leaf litter collected from woodlands. The major challenge is to widen the range of organic nutrient resources in farming systems and increase quantities of those already in existence. Systems such as AF fertiliser tree systems, which mimic natural processes and make effective use of soil nutrients, rainfall, sunlight and natural resources are possible sustainable options. AF fertiliser tree systems encompass practices such as crop rotations, intercropping, no or low use of chemical fertilisers, composting, little or no tillage and direct seeding, maintenance of soil cover, maximisation of water infiltration, monitoring crop and water status (Garrity et al. 2010a, b; Sileshi et al. 2014). The application of these methods aims at using water, land, nutrients and other natural resources in a manner that prevents deterioration of the land and provides examples of sustainable farming systems that can be utilised in the smallholder farming sector. AF fertiliser tree system could potentially serve as a reliable and cost-effective alternative to increase soil carbon and nutrient stocks in southern Africa soils (Sileshi et al. 2014; Bayala et al. 2018).

In southern Africa, traditionally farmers grow crops under scattered trees, and thus, the region has both, traditional fallow and mixed intercropping systems as well as improved AFS. These include parkland systems, improved fertiliser tree systems, and green leaf biomass transfer systems (Akinnifesi et al. 2008, 2010).

Trees in the parkland are retained in order to improve the yield of understory crops. The most common species in the landscape in the drylands is *F. albida* (Box 21.2). According to a recent meta-analysis by Sileshi (2016), soil organic carbon (SOC) was increased by 46%, total nitrogen by 50%, available phosphorus by 21%, exchangeable potassium by 32%, and grain yields of maize and sorghum by 150% and 73% respectively, under the tree canopy compared to the open area. Larger increases in SOC and nutrients were observed on inherently nutrient-poor sites than on nutrient-rich sites (Sileshi 2016). The improved crop growth under tree canopies can be explained in terms of a combination of different factors: (1) increased nutrient inputs including those from biological nitrogen fixation, manure and urine from livestock grazing or resting under the tree, and birds that take shelter under or perch in search for food; (2) increased nutrient availability through enhanced soil biological activities and rates of nutrient turnover; and (3) improved microclimate and soil physio-chemical properties (Akinnifesi et al. 2008). The *F. albida* was promoted in Malawi (Amadu et al. 2020) Other traditionally systems include shifting cultivation such as “chitemene” in northern Zambia (Kwesiga et al. 2003).

Soil Biodiversity

AF also increases the diversity and population of soil biota, thus ensuring a healthy ecosystem (Barrios et al. 2012; Muchane et al. 2020). Under improved fallow systems, the microbial biomass is higher (Nyamadzawo et al. 2009), the microbial community is much more diverse and the rate of plant material decomposition is much faster (Sileshi and Mafongoya 2006a, b), thus ensuring nutrient recycling and timely release of N and other nutrients as pointed out before. The fungi that are associated with increased P availability in agricultural soils are the arbuscular mycorrhizal (AM) (*phylum: Glomeromycota)*. Reported that N-fixing legumes resulted in better colonisation of cereal roots and an increase in AM fungal populations in the soil in addition to alleviating P-deficiency whilst enhancing N-fixation at the same time.

Fig. 21.2 Anatrees (*Faidherbia albida*) embedded in a parkland AFS with maize fields in Malawi (Photo: Rebekka Maier)

Box 21.2 The Anatree: A Key Species for Agroforestry in Africa

As leguminous nitrogen-fixing anatree (Faidherbia albida syn. *Acacia albida*, Fabaceae) is common in the Sudano-Sahelian region of sub-Saharan Africa, forming "parklands" (Fig. 21.2; van Wyk and van Wyk 2013) and grows in a wide range of ecological conditions either scattered or gregarious, in closed canopy woodlands or open savanna It grows on the banks of seasonal and perennial rivers and streams on sandy alluvial soils or on flat lands. *The tree species* is the most promising utilised 19 tree species in southern Africa and is one of the most recognised trees utilised for intercropping. The species is widespread within millions of farmers' fields throughout the eastern, western, and southern regions of Africa especially amongst low-lying areas (Barnes and Fagg 2003). It is highly compatible for cropping with food crops unlike other indigenous trees because it sheds its nitrogen-rich leaves during the early rainy season and remains dormant throughout the crop growing period, a phenomenon known as reverse phenology.

These leaves will start growing again at the beginning of the dry season. This reduces tree crop competition for resources, whilst enhancing crop yields

(continued)

Box 21.4 (continued)
and soil health (Barnes and Fagg 2003). *F. albida* creates a unique opportunity for increasing smallholder productivity by input of high-quality leaf residue for increased soil fertility (Garrity et al. 2010a, b; Sileshi 2016), thus reducing the amount of inorganic N fertiliser needed. The coincidence of litterfall and rainfall season ensures the timely decomposition of the tree leaves which releases nutrients, particularly N, one of the most deficient nutrients in the smallholder farming sector. However, when promoting this system, there is need for targeting certain areas, especially those places where the trees are naturally adapted.

F. albida also increases livestock production through supplying high-quality fodder and nutritious pods. The trees also produce seeds that can be used as food by humans during periods of food shortages (Barnes and Fagg 2003). In addition, it enhances carbon storage in farmed landscapes through increased carbon sequestration (both above and below ground). It is drought tolerant; hence, it can be considered a keystone species for climate-smart agriculture in much of Africa (Garrity et al. 2010a, b). In Malawi, maize yields under *F. albida* trees increased by 50% compared with maize alone (Saka et al. 1994). *F. albida* trees also resulted in a yield increase of between 10% and 100% for various other crops (Hadgu et al. 2009; Sileshi 2016). To show the importance of *F. albida*, for example the government of Ethiopia has launched an initiative to plant 100 million *F. albida* trees (Beedy et al. 2014).

Soil Physical Properties and Soil Water Availability

In most smallholder farming areas of southern Africa, conventional tillage is the most common method of land preparation before planting crops. The challenge is that conventional tillage has resulted in increased runoff losses and soil erosion. However, the use of fast-growing AF trees that fix nitrogen has been reported to increase soil organic matter, improving soil physical conditions. Improved soil physical conditions can result in better soil aggregation, lower bulk density, lower resistance to penetration (Lal 1989), improved soil porosity and reduced surface sealing. Improved soil structure also increases hydraulic conductivity, infiltration rates and water holding capacity (Lal 1989). Trees also break up plough layers and increase infiltration rates since they have deeper rooting systems (Nyamadzawo et al. 2008b). Nyamadzawo et al. (2003) reported that plots under *A.angustissima* maintained high infiltration rates of over 35 mm h^{-1} 2 years after fallow termination, because of the addition of biomass from the re-growth of cut stumps in the second cropping season and the presence of an active tree root system. In addition, AF trees also reduced the raindrop impact on the soil and, hence, reduced structural degradation. Trees may affect soil water content by reducing its due to high water consumption or competition with another tree (Bayala et al. 2008). However, trees act as water “pumps” and “safety nets” through hydraulic lift mechanisms. Hydraulic lift means that trees with access to deeper soil layers lift water through their roots or capillary forces to higher soil layers where crop roots can access it (Sakuratani et al. 1999; Liste and White 2008). Hydraulic lift from trees ensures water availability and, thus, enhances productivity of crops in AFS (Sileshi et al. 2014, 2020a). In general, available water can be used more efficiently in a tree–crop system than a sole crop system owing to favourable microclimate and improved water use efficiency (Beedy et al. 2014). Although trees can increase the potential soil-water-holding capacity, they can also have negative effects on the actual water volume available in the tree–crop–soil system. Tree roots can use water accumulated deeper in the soil profile, which can benefit crop growth, resulting in water deficit for shallow rooted crops and can use residual available water outside the crop growing season (Garcıa-Barrios and Ong 2004). Highly soluble nutrients such as N, K^+ and Ca^{2+}, which are leached into deep soil layers, can be brought to the surface through the deeper rooting habits of AF trees (Sileshi et al. 2020a). Beside the manifold positive aspects, root competition needs to be considered, for example in windbreaks where roots of *Casuarina* ssp. grow into the adjacent irrigated orchards and root pruning is often applied.

Modification of Microclimate by Shelterbelts

The improvement of the microclimatic growth conditions for crops is important especially in times of a changing climate. For that purpose, tree shelterbelts and AFS can be a suitable tool to mitigate climate change effects in agriculture. The coastal regions of the West Coast and the Overberg regions in South Africa as well as the Winelands of the Western Cape Province are characterised by high mean annual wind speeds of 5–8 m s^{-1} at 10 m above ground. High wind speeds are a threat for cultivated crops. Plantations of tree shelterbelts and hedges are traditional eco-engineering measures to reduce lee-side wind speed near the ground or near the crop canopy. In the Western Cape mainly, fast-growing tree species, including *Alnus cordata*, *Casuarina cunninghamiana*, *Pinus radiata, Populus simonii* and various *Eucalyptus* species, are used for the wind protection of fields, vineyards and fruit orchards (Fig. 21.3). The design and orientation of the windbreaks are arranged perpendicular to the prevalent wind directions and are modified by local topography.

Fig. 21.3 Windbreak with (**a**) *Casuarina cunninghamiana* for the protection of a citrus orchard and (**b**) with *Populus simonii* in a vineyard, Western Cape, South Africa (Photo Maik Veste)

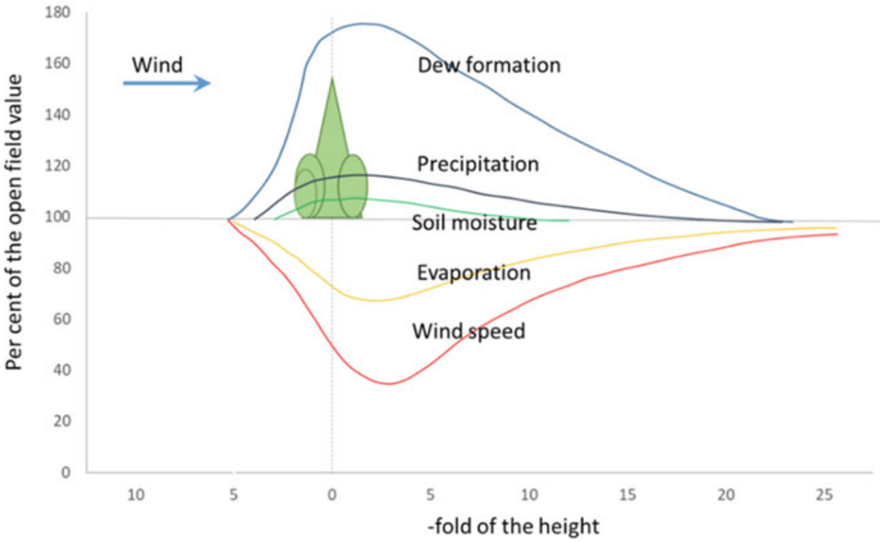

Fig. 21.4 Influence of a shelterbelt on microclimatic conditions

Trees can improve microclimatic conditions by reducing air temperature and wind speed and reducing evaporation from soils by shading crops, thereby increasing the availability of water in the soil. The microclimatic effects of linear windbreaks are summarised in Fig. 21.4.

The reduction of wind speed on the downwind side of a shelterbelt is a function of distance, aerodynamic porosity and tree height. Since in wind-prone areas, wind disturbs the laminar layer of crop plants and leads to a significant increase in transpiration, wind shelter from trees is able to reduce transpiration and, consequently, soil water losses significantly (Veste et al. 2020). A poplar windbreak (see Fig. 21.3b) was demonstrated to reduce the mean wind speed at an 18 m distance from the hedgerow at 2 m canopy level (Fig. 21.5a) by 27.6% over the entire year and by 39.2% over the summer growing season compared to a reference in the open field. This effect leads to a parallel reduction of evapotranspiration of 15.5% during the whole year and of 18.4% over the growing season (Fig. 21.5b).

Furthermore, in the fruit growing regions of the Western Cape, shelterbelts are essential to minimise fruit damages of citrus and other wind-sensitive fruits. In a recent study, Geldenhuys et al. (2022) could show that the fruit quality was significantly affected by the presence of a windbreak, whilst it had no significant effect on citrus fruit yield. The increase of peel wind scar damage with increasing the distances from the windbreak resulted in a reduced export quality by 17.7% and the associated economic losses. In this case, the citrus orchard was protected by a windbreak built up by evergreen beefwood (*C. cunninghamiana*). Beside the wind effects, trees also reduce exposure to heat stress, which minimises tissue temperature to optimise the phenology and productivity of understory crops (Monteith et al.

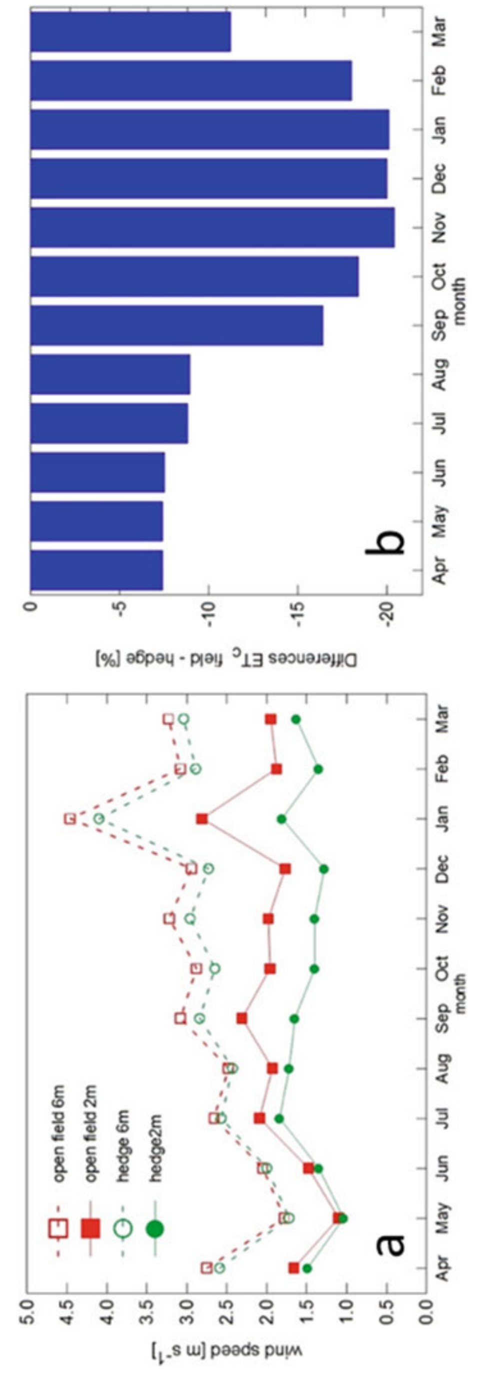

Fig. 21.5 (**a**) Monthly average of wind speed at 2 m and 6 m above ground near a poplar hedge (height 5 m) in 18 m north and as a reference in approximately 100 m distance and (**b**) monthly differences in crop-specific evapotranspiration by the hedge in the open vineyard, Western Cape (after Veste et al. 2020)

Fig. 21.6 Single trees providing shades for livestock (Western Cape, South Africa, Photo: Elbé du Toit)

1991; Vandenbelt and Williams 1992). In AFS, shading of crops by tree crowns is an essential feature (Bohn Reckziegel et al. 2021, 2022) and beneficial for crop productivity due to delayed stomatal closure under shade. Shading can be also beneficial for livestock, preventing over-heating during the daytime (Fig. 21.6).

21.4 Innovations of Land Management Strategies

Sustainable utilisation and conservation of savanna ecosystems requires an urgent intervention. This can be accomplished by encompassing human land use via the formation of protected areas, the introduction of management systems in human land-use areas that guarantee the sustainable use of the natural resources and by improving agricultural efficiency in forest peripheries. Protected areas, according to Adams and Hutton (2007), have been the backbone of international conservation strategies since the beginning of the twentieth century, even if their history is much older. In spite of their spatial limitation, protected areas play a vital role, specifically in the tropics, in protecting ecosystems within their borders, precisely by preventing land clearing arising from various land-use activities (Bruner et al. 2001;). Evidence of high diversity of fauna and flora species has been observed in a number of regions. Such examples have been observed in Zambia (Banda et al. 2006) where communal areas are characterised by a high heterogeneity, the ultimate source of biodiversity (Pickett et al. 2003). Hence, the maintenance of traditional land-use

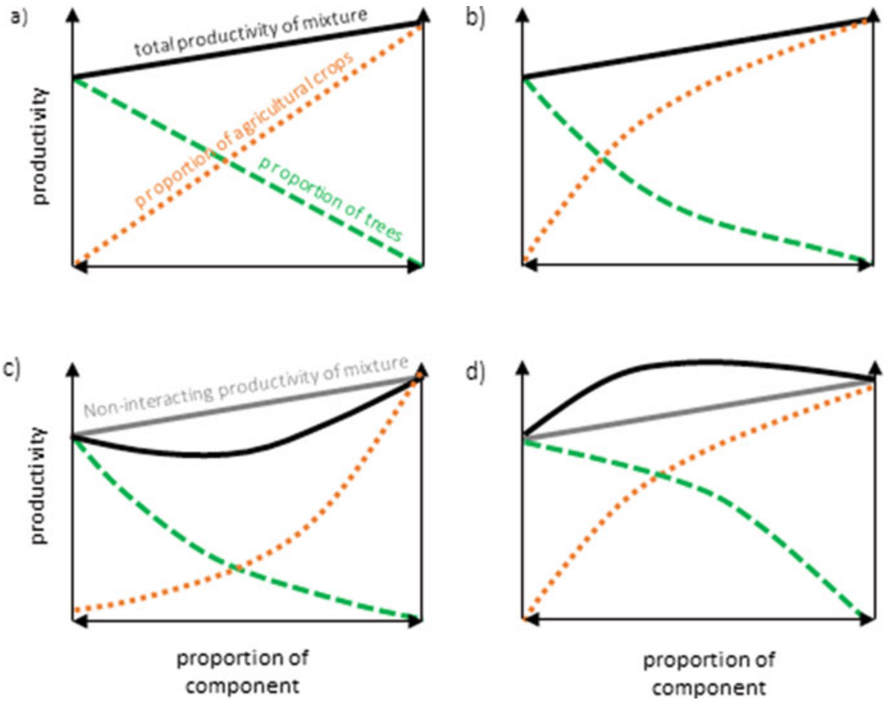

Fig. 21.7 Different effects of mixing agricultural crops and trees in agroforestry systems on the total productivity of the land-use system (solid line) and the individual productivities of the participating agricultural crops and the trees (dotted/orange and dashed/green lines, respectively). The figure shows four scenarios (**a-d**) where one system component is gradually replaced by the other towards full forest cover or pure agricultural cropping (after Sheppard et al. 2020a)

practices resulting in a mosaic-like distribution of various land units is the key to the maintenance of biodiversity in communal areas of the African Savannas (Augusseau et al. 2006).

Figure 21.7 depicts a land-use system replacement series applied to a conceptual and vastly simplified two-component AFS. This applies the conceptual ideas of production ecology to AFS exploring the idea of plant community mixtures as presented by Harper (1977) and nowadays applied to different forestry systems (Pretzsch et al. 2017). Within this conceptual example, the density of the AFS tree component is the same as in the monoculture cropping system and always totals 100%. Figure 21.7 describes four scenarios where one system component is gradually replaced by the other towards either full forest cover by increasing the proportion of trees or pure agricultural cropping with an increase in proportion of agricultural crops. In the given example, it is assumed that the agricultural crop is more productive than the tree culture and productivity is independent of external variables such as climate and site characteristics.

(**a**) The proportion of trees decreases at the same linear rate as that of agricultural crop increase. There is no interaction between the two AFS components. The effects of the inter-system competition (competition between the two systems) and the intra-system competition (within the two systems) are equal. Total productivity of this scenario results in an *additive effect* of the productivities of the individual components. This scenario is unlikely, as the interaction effect between trees and crops is generally proven to provide an influence on growth for one or more components of the system.

(**b**) The change in component proportion is non-linear. The agricultural crop benefits from the interaction, for example, by means of facilitation or competitive reduction factors. The intra-system competition for the agricultural crop is higher than the inter-system competition with the tree culture; the reverse applies to the tree culture. However, these effects compensate each other so that the net effect of the combination is *additive* and equal to scenario (**a**).

(**c**) Interactions between the two land-use systems are incompatible, decreasing proportion of one AFS component results in an opportunistic increase in the other. Intra-system competition is high, leading to an *under-yielding* scenario. This may be reflected by incompatible species choice or an influence of a biased management of individual components.

(**d**) Interactions between the two land-use systems are synergistic or mutualistic and non-linear, a combination of components provides an increased yield. Intra-system competition is higher than inter-system competition for both systems. This may result from facilitation, competitive reduction, and/or niche complementarity of both agricultural crops and trees (agricultural crops and trees utilising different soil resources). This leads to *over-yielding* at the level of the mixture and is the scenario that is most often touted as a benefit of AFS (i.e., increased land equivalent ratio (LER)).

Nevertheless, applying a simplified concept does not fully reflect the complexity of the interactions that occur within functioning AFS. Figure 21.8 is based on the work by Van Ittersum and Rabbinge (1997) presenting both the yield potentials and yield gaps between agricultural production systems and AFS. This further conceptual description highlights the actual, achievable and experimental yields when compared to a potential yield which is limited by growth-defining factors including temperature, CO_2, incoming direct solar insolation, individual plant physiology and phenology. This potential is further modified by site-based growth-limiting factors such as water and nutrient availability, growth-reducing factors such as biotic (e.g. competition from weeds, diseases, pests) and abiotic (e.g. drought, storm) influences, and also highlights an experimental yield gap which accounts for yield differences between field trials and practice.

In real life, such conceptual models must be tested and modified to provide elevated productivity over simple agricultural production methods accounting for species mixture and for limiting or reducing factors that prevent the full potential of AFS being realised. This is especially important within the southern African region where the effects of predicted climate change are multifaceted and far-reaching and are suggested to hit southern African communities hardest. The predicted instances of decreased rainfall can lead to loss of crops and land degradation and represent

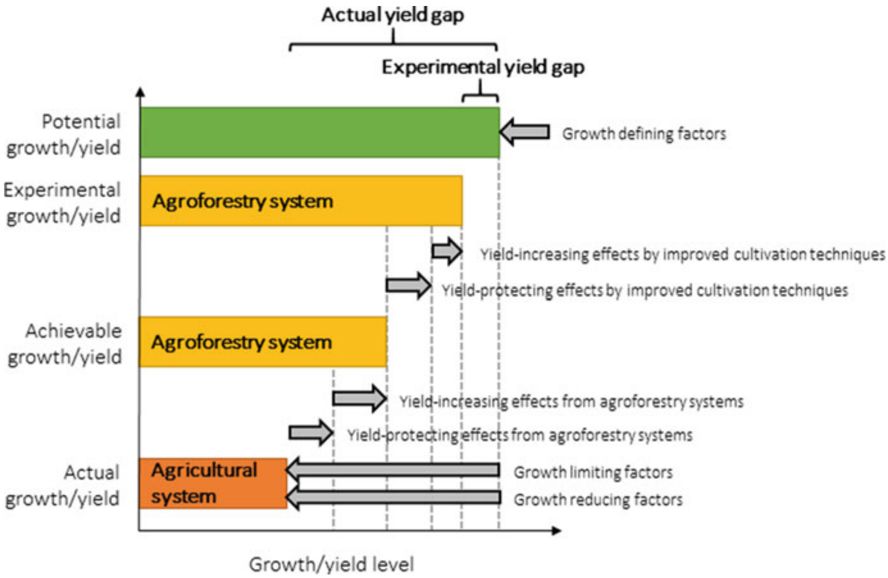

Fig. 21.8 Yield potentials, yield gaps and relationships amongst yield levels and growth-defining, growth-limiting and growth-reducing factors, as well as yield-increasing and yield-protecting measures (after Sheppard et al. 2020a)

a real and serious growth reduction factor. Increased frequency and severity of extreme weather events can also affect the viability of crops and can bring disruption and loss of profitability widening the gap among actual, achievable and potential yield (Fig. 21.8). As discussed in the sections above, the increased support and employment of AFS within southern Africa can help increase sustainability and resilience of smallholder farmers, brought about by integrating the benefits of suitable multipurpose tree and shrub species and adequate AFS practices to existing subsistence farming systems. It is not just subsistence farms either; the integration of trees within general agricultural practices can boost the productivity of the land and thus the economy of an area, providing employment, security and prosperity, laterally reducing investment risks supplying supplementary food and a variety of raw materials to trade a benefit that can also filter down and benefit individuals within the community.

21.5 Implications for Land Management Systems on the African Savannas

Sustainable land management is commonly considered as the main approach to prevent, mitigate and reverse land degradation, but it can also serve as an integral climate change adaptation strategy, being based on the fact that the healthier and more resilient the system is, the less vulnerable and more adaptive it will be to external changes and forces, including climate. In that regard, sustainable land management can be considered a land-based approach, which includes the concepts of both Ecosystem-Based Adaptation (EBA) and Community-Based Approach (CBA) land management practices, if widely adopted, help to prevent, reduce or reverse land degradation in an area. Land-use and climatic changes may more strongly affect savanna vegetation and diversity patterns in future. Therefore, adapted management and conservation strategies in the communal as well as in the protected area are required to ensure the availability of natural resources for local people and to protect ecosystems and biodiversity in the long term.

Overall, AFS have been shown to improve the productivity and resilience of farming systems. Specifically, integrated AFSs provide nitrogen-rich green manure, protein-rich fodder, fruits, nuts, firewood, flowers for foraging bees, microclimate, windbreak, timber, shade and many other ecological services. AF leguminous fertiliser tree systems are mostly managed for soil fertility improvement through nitrogen fixation, and production of copious amounts of nitrogen-rich leaf litter and green manure that is incorporation. When optimally established and managed, crop yields increase by between two and four times the yield of unfertilised plots (Garrity et al. 2010a, b). In Malawi, *F. albida* parklands, for example, enable an additional 150,000–300,000 metric tons of maize to be produced, thereby improving the food security of families farming under the systems and generating surpluses for sale. Besides direct benefits of increased crop yields, soil of AF plots shows a high diversity of soil biota (Sileshi and Mafongoya 2005), a highly desirable attribute of good soil. AF fertiliser trees also provide firewood which indirectly contributes to reduced deforestation. Other AFSs, for example coffee, can be used integrated with bee keeping and results in increased coffee yields. Fruit and nuts AFS provide nutrition and income generation from sale of fruits and nuts. The fruits and nuts contribute to family nutrition security and diversify farm income streams. In drylands, trees provide fodder, which is critical during the long dry season, whilst in smallholder dairy farming, trees provide cheaper but high-quality protein-rich fodder, enhancing milk production at lower costs.

21.6 Agroforestry in Policy Implementation

21.6.1 Challenges in Policy Coordination

In general, policies play an essential role in human–environment interactions as they define priorities, remove barriers, create capacities and potentially ensure the availability of key resources for the implementation of different programmes. Within AF, clear policies are also a necessary precondition in ensuring its wide-scale adoption and consequent harnessing of the proclaimed benefits. Over the last decade, there has been a growing interest in AF from a policy perspective. In a number of countries, national agencies are developing objectives and strategies that integrate AF into their policies and programmes. However, it is particularly important to note that despite a high-level policy recognition of AF, there is little knowledge on how policy aspects of AF are actually being integrated and implemented in different contexts. Policy and institutional factors with their connections have implications on how AF is approached. The cross-sectoral nature as well as the existing institutional dispositions can aggravate the difficulties for proper design, coordination and implementation of AF projects. These problems become more apparent and challenging to overcome when linked with complex issues such as land-use planning and administration, in particular issues such as land ownership and rights of use (including rights of possession, inheritance, use, usufruct and disposition). The cross-sectoral nature of AF also means that it is impossible for just one single institution or agency to implement proposed AF programmes without collaborating and coordinating with other sectors. Although coordination and collaboration are important ingredients for effective policy implementation, their potency is however fraught with challenges as they depend on contextual factors, such as the policy environment, existing policies, administration institutions, international pressure, the economy and other actors. Very few studies have detailed how these factors play out in AF implementation. Given that AF as a concept sits squarely between a number of complex policy fields, such as agriculture, forests and climate change, where coordination and collaboration play a huge part in its success, it is also worthy to focus on this strand of knowledge.

In pursuit of this knowledge, 15 interviews with different actors who are in the forefront in implementing AF and related technologies in Malawi were conducted. A policy document analysis was carried out to establish the prominence of AF. In the following section, four key challenges that they have encountered whilst trying to implement AF are reported. These include the lack of a clear framework for AF, lack of trust amongst actors, lack of resources and political interference.

1. Lack of harmonisation/no clear framework on agroforestry

   Malawi has different policies and strategies that incorporate AF, and to a greater extent most of these policies emphasise that policy coordination and collaboration is vital for policy implementation. For instance this is mentioned in 71% (10/14) of the policies that we reviewed. The Food Security Policy of 2006 states, "If we are to guarantee the implementation of the policies and programmes of food security, it is necessary to guarantee the coordination, not only of government institutions, but also of all actors involved in the food economy."

   Despite the existence of these policy documents, most interviewees expressed that in relation to the coordination of activities, the documents are vague and difficult to interpret. The interviewees mentioned that some of the policies are not sufficiently connected (integrated) across sectors and lack supporting instruments and resources to implement different activities. Additionally, there are no plans or measures to overcome these siloed coordination challenges.
2. Lack of mutual trust amongst organisations

   Effective coordination and collaboration also depend on the level of trust amongst actors. Essentially, it improves relations, generates mutual understanding, legitimacy and commitment for a particular activity. One major reason for the lack of trust emanates from different philosophical and work approaches. These different approaches are usually related to donor organisations who exert influence in ideologies, power and resources. Although donors provide resources to supplement work efforts in AF, their influence consequently determines how each organisation engages with others. This eventually causes some projects to collapse, since they bring in new elements that might be different or contrary to what other actors are pursuing.

Although there are existing platforms and systems that have been created by both state and non-state actors to overcome these challenges and coordinate activities, some organisations still bypass these platforms. This has also led to different challenges: for example the introduction of black wattle (*Acacia mearnsii*), a tree species that is considered an alien invasive species in Malawi and other parts of southern Africa.

3. Lack of Resources/capacity for joint action

   There is a lack of an effective and sustainable financing mechanism for the implementation of AF activities. AF is rarely a priority in national or sectoral budgets and it competes with other activities for the same resources. Although the agriculture sector receives more budgetary support from the government and over half of this allocation goes towards subsidy programmes, particularly maize seeds and inorganic fertilisers for smallholder farmers. Consequently, other programmes have to share the remainder—this includes AF activities. The remaining budget is usually only sufficient to pay staff salaries with very little resources left for other projects. Without project resources, no one is willing to take up AF activities. Most of the resources that support AF usually come from bilateral and multilateral donor arrangements. However, because of the low uptake of AF innovations by farmers, it has become difficult to get funding that is solely directed to AF as most donors seem to prefer other strategies and ideas.

4. Politicisation in agroforestry

   According to the respondents, politicians attempt to gain political mileage by ignoring sustainable and long-term projects in favour of those that offer immediate benefits to the populace. Usually, these politically motivated projects are masked as pro-poor development programmes and very appealing to the farmers who cannot wait to witness the benefits of AF over a long time. These political projects present significant barriers in attempts to scale up as they discourage farmers from implementing AF activities. One of the causes of this challenge is that AF does not get enough political support. This scenario can be contrasted with the European Union's (EU) Common Agriculture Policy where AF enjoys EU-level recognition and support.

21.6.2 Policy Research in Agroforestry

Whilst supportive institutions and targeted policies are lauded as important towards upscaling and the wider adoption of AF, there is also a need to acknowledge that policies are not always implemented as envisioned and do not necessarily achieve intended results. It is therefore important to appreciate the role of policy research in policy implementation. Research can significantly contribute towards the development and implementation of effective policies for the adoption of AF technologies. Between August 2019 and June 2020, Ndlovu and Borrass (2021) conducted a literature review to assess the status of policy research in AF with a focus on the SADC region. Key to their findings was that most of the research has a strong bias towards the biophysical aspects and technical attributes of AF. However, in the last two decades, there is also a clear increase in studies that have a socio-economic orientation: mostly those with the intention to address the challenges of upscaling and adoption of AF in different contexts.

Whilst much literature is available, on the different barriers associated with adoption of AF, there is little research addressing policy and institutional aspects. There are few articles that have pursued to engage in understanding how different national and local policies influence the advancement of AF. In addition, the research community with a focus on policy issues is rather narrow and most articles are published by authors from specific institutions with a very direct interest in the propagation of AF. Critical perspectives are generally missing, and the variation of theoretical and conceptual approaches to the study of AF in the policy arena is very limited. Interestingly, none of these shortcomings have deterred scientific articles from presenting bold social scientific claims or defining institutional pre-requisites for a "successful" implementation or adoption of AF.

21.7 Conclusions

AF can make an important contribution to the diversification of agricultural landscapes and to increase resilience against a changing climate in southern Africa. The introduction of trees can also provide additional products, offering multiple ecosystem services, influencing crop production, and generates additional incomes for smallholder farmers. Protection against erosion and conservation of soil fertility are important arguments for the introduction of AFS. To optimise the benefits of AFS in terms of soil protection, the following critical factors must be considered: (1) selection of tree species that ensure maximum residual soil fertility beyond 3 years, (2) size of land owned by the farmer, (3) integrated nutrition management, where organic resources are combined with synthetic inorganic fertilisers and (4) tree–crop root competition for soil water. This is particularly important for the nitrogen and phosphate cycle, as it has a high savings potential and can contribute to sustainable soil development. The development of catch crop strategies in combination with the inclusion of N-fixing trees is important for closing the nitrogen cycle in AFS and enables an optimised nutrient cycle. This is an important aspect for the future development of sustainable agriculture in southern Africa. Furthermore, research can contribute to the adoption of AF by focusing on understanding the processes of policy interventions. Additionally, policy recommendations that actually reflect on the policy conditions of a particular context are likely to be accepted and actioned

(Sikora et al. 2020). Research and analysis on AF should tackle this assertion more frequently with the aim of effectively communicating with policy actors. Consequently, this calls for a shift towards a context-specific policy research agenda on AF.

In general, shelterbelts and alley-cropping systems are major eco-engineering measures to reduce water demands and influence directly soil evaporation and crop transpiration in the neighbouring fields. The redesign of the agricultural landscape by the introduction of specially designed obstacles to airflow will significantly influence the near-ground wind field. Further detailed information about tree water use is needed to optimise the water use efficiency and ecohydrological implications of the combined tree–crop interactions under climate change conditions. The integration of managed AFS, tree shelterbelt and hedges into climate-smart agriculture can mitigate the effects of climate changes to a certain extent and improve the growth conditions of crops and contribute to a resilient livelihood. Still an open scientific gap is the importance of AF for biodiversity and conservation. Not in all cases can the introduction of trees be seen as positive for the development and conservation of ecosystems in southern Africa. Invasive trees are of major concern for natural ecosystems, due to their drastic impacts on water resources and biodiversity. Further research and development of integrated landscapes combining different land uses and natural ecosystems are needed.

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