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Review

Agroforestry: An Appropriate and Sustainable Response to a Changing Climate in Southern Africa?

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Received: 10 July 2020; Accepted: 18 August 2020; Published: 21 August 2020

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Abstract: Agroforestry is often discussed as a strategy that can be used both for the adaptation to and the mitigation of climate change effects. The climate of southern Africa is predicted to be severely affected by such changes. With agriculture noted as the continent's largest economic sector, issues such as food security and land degradation are in the forefront. In the light of such concerns we review the current literature to investigate if agroforestry systems (AFS) are a suitable response to the challenges besetting traditional agricultural caused by a changing climate. The benefits bestowed by AFS are multiple, offering ecosystem services, influence over crop production and positive impacts on rural livelihoods through provisioning and income generation. Nevertheless, knowledge gaps remain. We identify outstanding questions requiring further investigation such as the interplay between trees and crops and their combination, with a discussion of potential benefits. Furthermore, we identify deficiencies in the institutional and policy frameworks that underlie the adoption and stimulus of AFS in the southern African region. We uphold the concept that AFS remains an appropriate and sustainable response for an increased resilience against a changing climate in southern Africa for the benefit of livelihoods and multiple environmental values.

Keywords: food security; sustainable land use; conservation agriculture; carbon; environmental benefits; social development; climate-smart agriculture; trees; Southern African Development Community (SADC)

1. Introduction

The agricultural sector faces an unprecedented and daunting task of meeting global food requirements whilst dealing with climate change in a sustainable manner [1]. Since the formalisation of agroforestry systems (AFS) as a science and land-use system in the 1970s, there has been an increase in the attention of political and social discussions on its development and institutionalisation. AFS have frequently been framed as an important development concept that is able to augment and enhance existing agricultural systems to alleviate production deficits and risks in the light of a changing climate. The concept is integrally linked with the potential to address pressing land management problems, contribution to secure food production, the generation of diversified income for rural households, enrichment of biodiversity through the provision of ecosystem services, and as a potential for carbon (C) storage and other mitigation or adaptation practices [2,3].

AFS are deliberate combinations of at least two differing plant types, or in case of silvopastoral systems plants with animals, one component within AFS is always a woody perennial. This combination should interact within the same land management unit with distinguished spatial arrangements or temporal sequences, and have well-defined outputs [4–7]. The presence of trees on farmed land increases the ecological and aesthetical value of the landscape, and they have an important economic value for the farmer. To meet the demands of rural stakeholders, the aim of AFS is to combine ecological with economic returns, i.e., to integrate the cultivation of trees with regular farming activities representing a more natural and diverse ecosystem.

The southern Africa region, orientated on the Southern African Development Community (SADC) member states [8], and part of the commonly nominated sub-Saharan African (SSA) region, represents the southern geographical tip of Africa. Southern Africa is a region that is threatened by the effects of climate change that are intensified by increasing populations and food security issues [9–12]. In the light of such concerns, we intend to investigate if agroforestry can act as an appropriate and sustainable response to the challenges besetting agricultural production systems caused by a changing climate in this region.

2. Background

Despite the long-standing history of AFS around the world, a palpable re-emergence of interest in such land-use systems has been observed in recent times. Conventions formed following the 1992 Rio Earth Summit identified AFS as a land-use management system that could help rehabilitate degraded land and slow desertification processes [13]. Most recently, the state of the world's forests report 2018 [14] states as a key message that "It is time to recognise that food security, agriculture and forestry can no longer be treated in isolation", a statement that clearly recognises the importance of including trees in a farmed landscape. The FAO report further asserts that evidence supports the ideas that forests and trees also make significant contributions to the UNEP's Sustainable Development Goals (SDGs) through the informal sector, gender equality, climate change adaptation, and as part of an integrated solution for confronting land degradation and biodiversity loss [14–17].

Conventional agricultural systems are often simplistic in their spatial and temporal arrangement, often assuming the form of monocropping systems, such strategies can deliver high returns but can also be considered high risk. Due to its inherent complexity (multiple species within distinct special arrangements over a longer temporal scale), the utilisation of AFS adds a level of robustness to agricultural production facilitating a reduction in production risk. Nevertheless, this is not without trade-offs, often a more multifaceted system might make less economic sense, reducing yields, while increasing and complexifying management operations. AFS presents the opportunity for unlimited spatial and temporal arrangements optimising and modifying the three-dimensional composition of the system and adjustment of the mixture and proportion of components over time. Such flexibility allows the practitioner to utilise opportunities in the early years of AFS establishment to capitalise on light-, water- and nutrient-demanding crops, before the understory is transformed by the tree component over time. AFS adopters must acquire a longer-term perspective and an additional skill set for tree management over those practicing annual cropping alone; this, however, places a large dependence on knowledge transfer, access to material and secure land tenure to ensure successful adoption.

AFS are extensively practiced in developing countries and are already a major land use system in SSA [18]; moreover, at least 1.2 billion people around the world have been estimated to be dependent on such systems [19]. Farmers can benefit from the non-wood forest products (NWFP) provided by trees such as fruits, gum and nuts, AFS can also provide animal fodder and building materials, and increase household resilience [1,3,9,15,18,20,21]. Moreover, AFS can provide on-site and off-site benefits that contribute to sustainable land use [22,23]. On-site benefits include soil conservation, increased nitrogen fixation, nutrient input, increased water infiltration and reduced evapotranspiration rates of crops [3,18,24–26]. Off-site benefits include reduced runoff, reduced nutrient loading, and improved water quality [24,26,27]. In Africa, soil conservation and soil fertility management are arguably often the most important aspects to maintaining long-term agricultural land [9]. This paper aims to study some of these attributes (as highlighted in Figure 1) in greater detail.

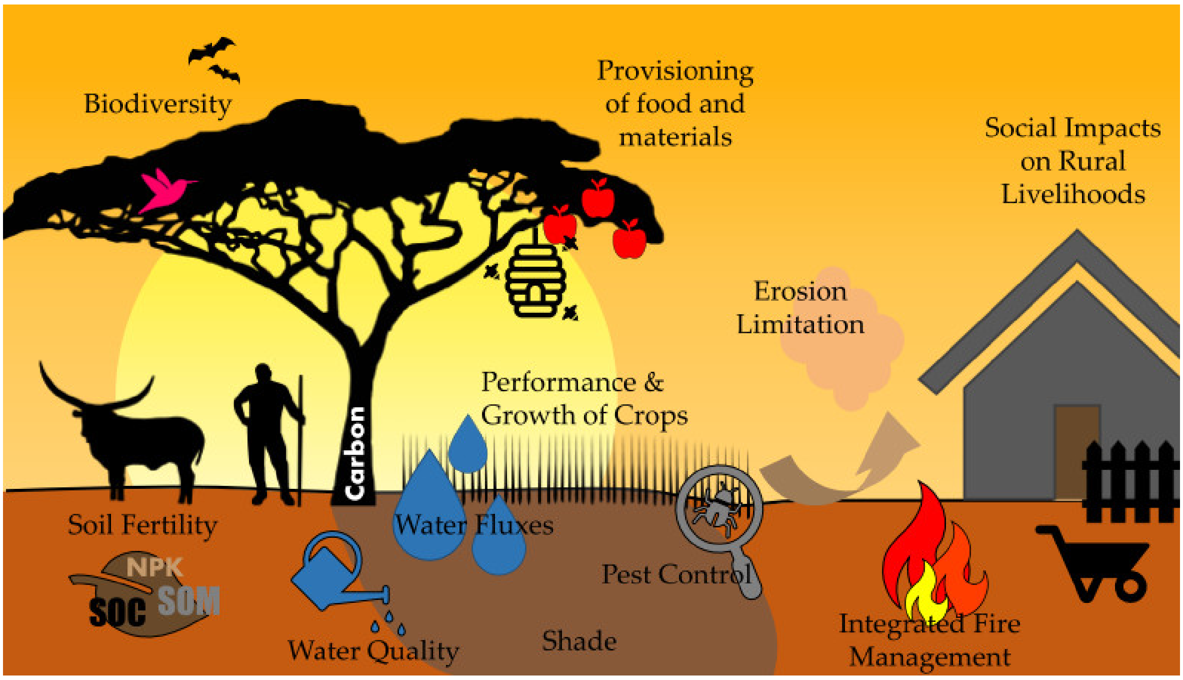

Figure 1. On- and off-site benefits of agroforestry systems (AFS) in the southern African region for direct and indirect mitigation of predicted climate change impacts.

Although the history of AFS in southern Africa is ancient, a milestone for the region was the formation of the Southern Africa Regional Agroforestry Programme, which was initiated in 1987, by the organisation now known as World Agroforestry (formerly International Centre for Research in Agroforestry; ICRAF) in partnership with national research institutions in Malawi, Zambia, Zimbabwe and Tanzania [28]. The program was aimed at addressing the problems common to most rural households in the region such as low soil fertility and consequent low crop and livestock production, low cash income, and shortages of fuelwood and timber. During the 1990s, nitrogen-fixing and fast-growing tree/shrub species (e.g., Sesban (*Sesbania sesban* L. Merr.) and Gliricidia (*Gliricidia sepium*

(Jacq.) Kunth ex Walp.)), intercropping of food crops with coppiced trees, tree fodder banks, rotational woodlots and research on indigenous fruits, were identified as key directives to provide solutions for many regional issues [9]. The state of the art of AFS research and development in southern Africa, by that time, was synthesised by Kwesiga et al. [28]. Here, they assessed the scaled-up adoption of AFS for food security, poverty alleviation and environmental sustainability, to be accomplished by key strategies. Such approaches included the provision of substitutes for costly agricultural inputs; production diversification; marketing strategies; processing of products; employment of GIS-based technologies; and information-sharing, training and collaborative partnerships in implementation and dissemination of AFS. In 2019 ICRAF merged with the Centre for International Forestry Research (CIFOR) to present a transformative agenda for forests, trees, people and the planet solution unifying a previously fragmented approach and aligning with the three Rio conventions, the SDGs and recent Intergovernmental Panel on Climate Change (IPCC), Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) and United Nations Convention to Combat Desertification (UNCCD) reports [29].

In the crib of the Miombo woodlands ecotype, where agricultural systems consist mainly of continuous maize-mixed cropping and extensive production of cattle and goats, Luedeling et al. [30] differentiated the wide range of AFS being employed by farmers in southern Africa by specification of traditional (i.e., intensive intercropping) and improved practices, promoted by researchers and development aid agencies. AFS including trees with food or cash crops, relay fallow intercropping, rotational woodlots and permanent tree-cereal intercropping, received most of the scientific attention in the beginning of the 21st century [30]. Additionally, many benefits of AFS trees providing varied raw materials and ecosystem services, such as soil fertility, fuelwood, poles, fruits, or shade, were already investigated [9,31–33].

Highlighting many complementary practices supporting conservation agriculture in southern Africa (AFS being one of them), Thierfelder et al. [34] reviewed the multitude of studies that can contribute to better farming, considering regional edaphoclimatic conditions and socio-economic aspects. In this study they showed that smallholders, cultivating less than 5 ha, constitute the majority of farmers in southern Africa. Moreover, in terms of investments towards planting trees and establishing AFS, secured land-use rights and tenure systems were identified as key drivers for attracting (or dissuading) farmers' adoption of AFS in the region.

3. Predicted Changing Climate Effects on the Southern African Region

Southern Africa has experienced an increase in extreme weather events and inter-annual rainfall variability over the past 40 years, with intermittent droughts and rain seasonality changes [9,35,36]. Future climate change effects are predicted to further strongly influence the climate of southern African regions. Land surface warming is expected to exceed the global mean [37,38]. Moreover, an increase in drought events causing a loss or degradation of productive cropland is expected, particularly in the western and southwestern part of the region [37–42]. The continuing rainfall deficit in southern Africa has already resulted in food shortages due to poor production and rising food prices, meaning that 41 million people faced food insecurity in the peak lean season 2019/2020 [11]. Meanwhile, tropical regions have the potential to become wetter [38], while sub-tropical regions are more likely to be affected with shifts in current rainfall patterns [36,43–45].

The effects of climate change (see Figure 2) will change tree growth in the region [46]. But even more importantly, there will be profound consequences on crop yields on the African continent [18], an issue comprehensively reviewed by Zinyengere et al. [47]. Consensus suggests that under predicted climatic conditions, crop yield may decrease directly affecting food security and rural livelihoods. Staple food crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), wheat (*Triticum* spp.) and millet (e.g., *Eleusine* spp. and *Pennisetum* spp. et al.) are all forecast to deliver reduced yields [48–51] linked to factors such as reduced precipitation [52]. Likewise, climate changes were suggested to induce increased degradation and fragmentation of African rangelands [41] alongside increased drought events that bring about livestock losses through lack of drinking water and loss of fodder. Climate change may also lead to increased land degradation due to erosion processes, loss of soil organic carbon (SOC) and soil nutrients as well as a decrease in above and belowground biomass [26]. This is compounded by an increase in pests and diseases [36]. For these reasons, the employment of AFS has been widely lauded to be able to reduce the vulnerability of smallholder farmers and to increase their resilience to predicted climate change [21], the following section examines these issues in greater detail.

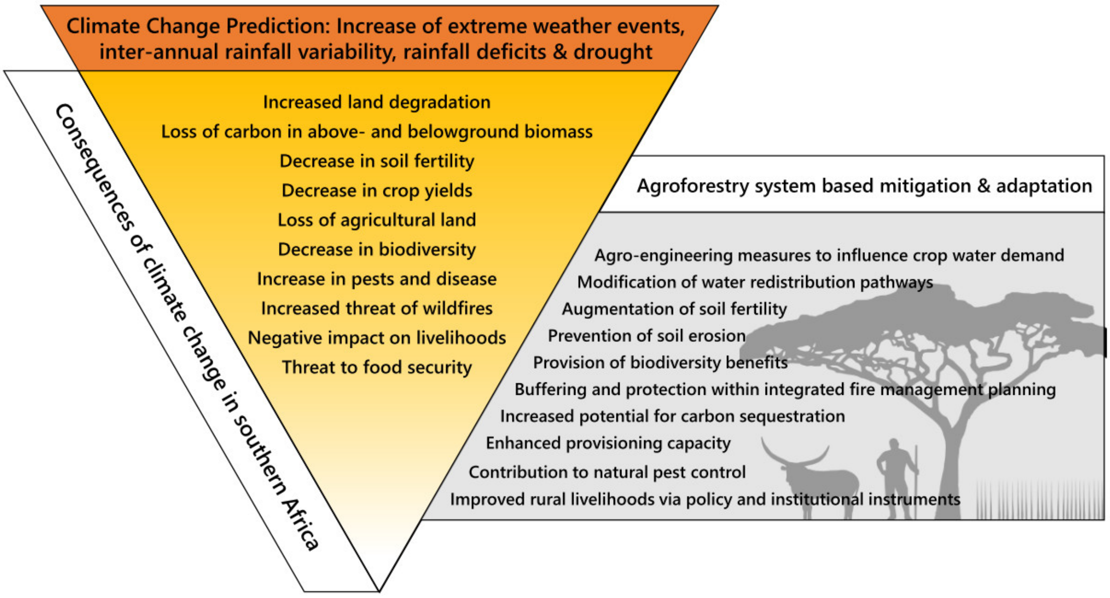

Figure 2. Consequences of a changing climate for southern African livelihoods with mitigation and adaptation solutions provided by agroforestry systems.

4. Consequences of Predicted Changing Climate Effects for the Southern African Region, Mitigation Offered by Agroforestry Systems

AFS is often discussed as a strategy that can be used both for adaptation to and mitigation of climate change effects [9,27,53–55]. Our aim is to find evidence of how AFS can be utilised as a means of buffering and mitigating the predicted climate change effects (See Figure 2) on agricultural production systems, rural livelihoods, food security and local microclimates. Moreover, we investigate which solutions AFS offers to improve both the yield and the resilience of existing production systems by presenting an increased range of cropping options, ecosystem services and the protection of vulnerable sites from degradation as a result of the above defined effects and consequences.

4.1. AFS as an Agro-Engineering Measure to Influence Crop Water Demand

In agriculture it is often important to reduce crop water demands through agro-engineering measures which directly influences soil evaporation and crop transpiration. The use of tree shelterbelts or windbreaks is a traditional measure to reduce wind speed, especially in commercial farming systems within regions with high wind speeds (e.g., in the Western Cape, South Africa). The introduction of obstacles within the air flow significantly influence the near-ground wind field and thermal energy, the addition of trees into a treeless landscape achieves just this. The physical processes of evapotranspiration are mainly driven by the saturation deficit of the air, dependent on temperatures, radiation balance and the near-ground wind speed [56]. Evapotranspiration processes are also dependent on turbulence and increase exponentially with wind speed over the canopy of a crop or stand. Various investigations have shown the reduction of wind speed on the downwind side of a shelterbelt as a function of distance, aerodynamic porosity and height [57,58]. Effective reductions of wind speed were measured to a distance of four to six times the height of the shelterbelt, minor reductions are effective up to 35 times the height [59]. While distance to a shelterbelt is a parameter dependent on height and porosity, it has great significance for the planning of field width between two rows of shelterbelts in an AFS. However, most existing empirical approaches applying such parameterisation focus on the reduction of wind erosion but do not consider evapotranspiration and crop performance. A recent study in the Western Cape, South Africa highlighted the positive effects of a poplar (*Populus simonii* (Carrière) Wesm.) windbreak on the combined reduction of wind speed and evapotranspiration in a vineyard [60]. Mean wind speed at crop height (2 m) was reduced by 27.6% over the entire year and by 39.2% over the summer growing season compared to a reference station. Furthermore, there was an observed reduction in crop evapotranspiration of between 18.4% and 20.4% during the main growing season, corresponding to other studies conducted within Mediterranean and temperate AFS [25,61]. Based on this finding, the underpinning concept lies on an optimal integration of hedgerows, or tree shelterbelts, within agricultural landscapes to optimise the interaction between trees and agricultural production focusing on the synergistic water use of crops.

Beside the reduction of the wind and its positive effects on evapotranspiration, the shade cast by trees in AFS has the potential to affect the growth of agricultural crops grown in the immediate vicinity, due to a reduction in direct radiation. For example, midday temperatures were reduced by 6 °C under Faidherbia (*Faidherbia albida* (Delile) A.Chev.) in Ethiopia in comparison with open fields [62]. Nevertheless, research to gauge the magnitude of such a shading effect of AFS and an appropriate crop selection is still lacking on a wider scale. In higher latitudes, light limitation and growth reduction become more pronounced in the near tree vicinity of AFS and there may be a tendency for crops to present a reduced yield when shaded [25,63]. Ghezehei et al. [64] studied the impact of hedgerow intercropping systems using a *Jatropha curcas* (L.)—*Pennisetum clandestinum* (Hochst. ex Chiov) system yield in KwaZulu-Natal, South Africa. Close to the trees the grass yield was reduced by 57–63% compared to the interspaces with an average yield of 7.03 t ha^{-1}. However, the reduction of the yield was a combination of the reduced irradiance and water competition between the tree and grass. Nevertheless, shading may also be beneficial to the intercrop depending from its shade tolerance and ecophysiological adaptation. In tropical and sub-tropical regions with higher irradiance input, trees have positive implication on the radiation and energy balances of the adjacent crops and can prevent the overheating of leaves and reduce light stress. Solar radiation levels common to tropical and sub-tropical regions are sometimes high enough to cause photo-inhibition of photosynthesis, especially under water limited conditions. In clear sky conditions solar irradiance is the main source of heat stress in crop systems [65], and therefore, commercial farmers often use shade nets (e.g., for citrus [66]) to reduce high radiation loads, leading to reduced crop temperatures and to increase growth performance. Furthermore, shade can result in longer moisture retention due to reduced evapotranspiration. However, better designed AFS systems which take the light and radiation conditions into account may be able to replace the artificial and costly shading nets in the future. Tree 3D-based applications modelling shade in high spatial and temporal resolution already exist [67], aiming at a quantification of solar energy losses on ground around a tree-cylinder-model. When appropriate shading effects can be further minimised by, for example, regular pruning treatments [68] or the establishment of tree rows in a northeast-southwest orientation to minimise shading effects and to increase self-shading against sunburn or sunscald effect on the trunks of trees [69]. In view of climate change, the small-scale climatic zones around the trees could be reassessed, as shading reduces heat stress and evaporation. Furthermore, the presence of shade trees alone has been linked to an increased amount of soil organic matter (SOM) [70] and when in combination with livestock, an increase in fertilisation. An optimal management and planting scheme and the selection of crops (e.g., vegetables), could thus, have a positive effect on the yields in smallholder agriculture. However, research on this is only just beginning.

In principal, the underlying processes of the plant-microclimate interactions (and here especially the windbreak functions of AFS) are well-investigated and understood. However, little information is available on the spatial impact of the microclimate on the ecophysiological processes of crops.

The complex connections between abiotic factors of the microclimate and the soil, which are influenced by the trees, lead to a spatial differentiation of cultivation zones in the vicinity of the trees. There is still a great need for research in this area, as it provides important information for the establishment of AFS. This also concerns the biotic interactions between the trees and the crops, which, in addition to positive effects, also include competition for water, nutrients and light. The special importance of AFS as an adaptation to climate change is highlighted by a large number of publications. However, there is a lack of concrete studies and simulation approaches, especially for drylands, that examine the feedback between trees, crops and microclimate. Here, a more systematic approach is needed.

4.2. Modification of Water Fluxes

Water availability in AFS is primarily determined by prevailing climatic conditions (e.g., temperature, precipitation, wind), especially potential evapotranspiration, site and soil characteristics, and the tree species and crops involved. Trees within AFS can significantly influence the water availability for agricultural crops: tree roots penetrate deeper into the soil than many agricultural crops, and thereby, potentially increase the water infiltration rate and capacity [18,24,71,72]. Trees can also increase evapotranspiration by transpiring water from deeper soil layers and redistribute water towards the surface [73,74], which can also increase competition for water.

Hydrological interactions between trees and crops in AFS range from mutually beneficial to critically competing, especially in dry regions where water can be a limiting factor for plant growth. Such competition for water can potentially outweigh the benefits of AFS [63,75,76]. For instance, a study by Odhiambo et al. [77] in an AFS system in Kenya consistently found more soil water in control plots (without trees) than in plots with trees. Furthermore, volumetric soil moisture content was higher with greater distance from the trees. The same outcome was also found under Calliandra (*Calliandra calothyrsus* MEISSNER) trees where a soil moisture decrease of 15% was recorded [78]. Conversely, in a study in Zambia, Chirwa et al. [79] found higher soil water content under *Leucaena leucocephala* ((LAM.) DE WIT) and *Flemingia macrophylla* ((WILLD.) MERR.) hedgerows compared to the maize rows in the alleys. Similarly, Siriri et al. [78] reported an increase in soil moisture of 18% under Alnus (*Alnus acuminata* KUNTH) in an AFS in Uganda compared to plots without trees. Such contrasting results emphasise the importance of the difference in tree water requirements between species which must be acknowledged during the planning phases of AFS implementation or recommendation.

The concept of hydrological niches (cf. [80]) is necessary when considering the belowground interactions between plants and their environment and the temporal dynamics of these interactions. The concept describes that plant species which compete for the same resources (in this case water) have niche differences, which allow their coexistence. A first review on hydrological niche segregation was published by Silvertown et al. [81]. They proposed three types of constraints (an edaphic, a biophysical and a structural one) that lead to the trade-offs underlying hydrological niche segregation (HNS) and found evidence of HNS in 43 out of 48 field studies. However, the mechanisms behind HNS could not be distinctly identified as many aspects of hydrological interaction contribute to the overall picture. This is similarly unclear for AFS.

A favourable interaction of trees and crops within AFS is hydraulic lift. Deeply established root systems of woody perennials can lift water from deeper soil layers towards upper, drier soil horizons, making water available for surrounding crops, a feature especially useful during dry periods for AFS in semi-arid regions [75,82–85]. The wider term of water redistribution includes not only the upward water movement during dry spells but also the movement and storage of excess water in the sub-surface to deeper soil layers, making the root system a mechanism for the balancing of soil water gradients [73,86–90]. However, when water is being redistributed it is not necessarily available for neighbouring plants. A study by Fernández et al. [75], for instance, reported that the water use of pines (*Pinus* spp.) in AFS consisted of about 20% of water from the upper 20 cm of the soil, implying a degree of competition with the crops. Therefore, new management strategies have been developed, for instance, a so-called water safety-net. Competition for water is minimised by complete shoot removal, thereby preventing transpiration. These plants still perform a support role, raising water from lower soil depths, and they increase dry biomass production despite water limitations [90,91].

The term water use efficiency describes the balance of water needed for plant metabolism and growth and the water loss through transpiration. In an AFS context, it sometimes describes the complementary use of water by different plants in the sense that water is taken up at different times or from different depths, and hence, more water is being used in total, even though there is no nursing effects from trees to crops (e.g., [92–95]). Under typical rainfall conditions in southern Malawi, Chirwa et al. [93] showed that there was sufficient water stored in the soil profile during the dry season to support growth of Gliricidia and pigeon pea (*Cajanus cajan* (L.) Millsp.). The case study demonstrated temporal complementarity resulting from the use of residual water by deep-rooted trees after the maize was harvested. Furthermore, Gliricidia pruned before and during the cropping season did not deleteriously compete for water with associated crops, while tree-based systems appeared with higher water use efficiency than in a pigeon pea and maize consortium, and in sole maize treatments.

Hydrological fluxes in AFS are defined and regulated by soil characteristics. The various studies reviewed in Sileshi et al. [96], demonstrated the role of fertiliser trees modifying water fluxes by improving the physical properties of soils (i.e., bulk density, aggregate stability, porosity) in AFS in Zambia, Zimbabwe, Malawi and other countries. Kuyah et al. [97] found a more pronounced effect of AFS on water infiltration characteristics than on actual soil water content, since the latter is subject to tree uptake and transpiration.

Additionally, hydrological fluxes are time-variant. They shift on the scale of days, vegetation periods, years and between years, and are influenced by land use and changing climatic conditions. With respect to AFS, hydrological benefits to agricultural crops are, for example, changing with time since AFS establishment. In early stages, the superficial root systems of young trees increase belowground competition as they share soil layers with cash crops and tend to consume more water and nutrients than mature trees [98].

Positive examples of AFS systems with hydrological benefits can be found throughout different climatic regions and are not limited to specific rainfall patterns, soils or other influences. It appears that suitable systems can deliver positive feedbacks and enhance yields and soil hydraulic properties. However, many open questions remain. Hydrological benefits need to be evaluated in relation to the species combination, soils and management practices for different regions. Kuyah et al. [97] started disentangling this issue in their review. Based on a meta-analysis, the authors related environmental conditions of AFS systems with yield results and water availability. The principle trade-offs were low available phosphorus concentrations and low soil water content vs. increased crop yield. They concluded that, on average, the utilisation of AFS in SSA can increase crop yield while simultaneously maintaining delivery of regulating ecosystem services [97].

4.3. Augmentation of Soil Fertility

Land degradation runs hand-in-hand with the nutrient depletion of soils and is a serious threat to food security. AFS can provide a wide range of opportunities for smallholder farmers without the need to access expensive fertilisers [18,99]. The majority of smallholder farming systems in SSA are without or under sub-optimal use of fertiliser, e.g., N input of less than 1 kg ha^{-1} yr^{-1} [100]. Yet, farmers acknowledge the environmental role of trees (aside from erosion control and thus lower fertility loss, salinity decreasing, drought prevention, fire control and others) as a method of nitrogen fixation. Nitrogen fixing trees and shrubs (e.g., *Acacia* spp., *F. albida*, *Casuarina* spp. and others) have important ecological potential in dryland forestry and are often integrated into AFS (for example, within many silvo-pastoral systems, e.g., [101]) contributing to sustainable agriculture by restoring and maintaining soil fertility and productivity [102]. Their inclusion is an effective way to increase nutrient use efficiency and to improve soil health parameters [103]. The actual state of knowledge provides little information on specific conditions where AFS are successfully established [3]. Experiments with different nitrogen-fixing tree species under different climatic and site conditions would, therefore, provide important information on suitability and benefits of specific legume trees.

The role of fertiliser trees and their contributions towards food production and security issues were addressed by Sileshi et al. [96], with many reported cases in southern Africa, including records of cereal and vegetable yields in response to the presence of fertiliser trees, condensed from studies in AFS across SSA. Coulibaly et al. [104], investigating the adoption of fertiliser trees by 338 farmers in Malawi, found that implementation is ruled by a perceived effectiveness of this technology in restoring fertility on degraded land, by previously acquired knowledge in management practices for AFS and the existence of farm assets. In an experiment in southern Malawi, the integration of legume trees as fertiliser trees within AFS could reduce the need for artificial N-fertilisation by 75% [33]. Experiments in Zambia and Malawi, where Faidherbia trees are commonly planted in unfertilised smallholder farmlands, were reported with an increased maize yield in up to three times on the plants neighbouring trees when compared to ones outside tree canopy coverage [100,105]. Likewise, Akinnifesi et al. [106] and Beedy et al. [107] showed in a research trial in southern Malawi that significantly higher maize yields can be achieved in intercropping systems with biological N fixation (BNF) compared to single crop maize cultivation. Considerably increased chemical soil fertility parameters, such as cation exchange capacity, nitrogen and phosphorous concentrations, were observed after a 14-year intercropping period. A study conducted in Zambia showed no significant changes of basic chemical soil quality parameters (i.e., nitrogen and phosphorus content, cation exchange capacity, soil organic carbon), after twelve years of conservation agriculture with no tillage and on-site remaining harvest residues, probably due to small net input of organic carbon [108].

The BNF of trees in drylands leads to the question of how one can maximise and/or optimise their effects, especially under the pressures of a changing climate, and how we can manage BNF and the transfer of nitrogen to associated soils. Understanding the functional adaptations of nitrogen and phosphorus nutrition in BNF trees and shrubs is crucial for understanding soil-plant interactions and to optimise tree growth in nutrient-poor and water-scarce ecosystems. Still, the understanding of N-fixation in different AFS and its effects on crop yields must be studied further in southern Africa to fulfil this knowledge gap.

4.4. Prevention of Soil Erosion and the Degradation of Agricultural Land

Soil erosion is the main reason for land degradation in southern Africa and a serious threat to agricultural productivity and sustainability [109]. Montanarella et al. [110] identify erosion as the greatest threat to African soils. Agricultural soils, mostly tilled and with temporarily bare soil surface, are particularly at risk [111]. The susceptibility of soils to erosion is described as erodibility and is controlled by various soil characteristics, whereas aggregate stability and soil structure play an important role [112]. AFS provide the opportunity to improve both soil properties on agricultural lands [113]. Tree and crop residues are continuously added to the soil, boosting the formation of soil aggregates and soil structure [114]. A connection between the capacity of soils to stabilise organic matter and soil structure is scientifically proven [115].

Besides the organic matter input, physical soil properties are just as important to reducing soil erodibility and are often neglected [116]. A number of studies showed that the aggregation process is more influenced by soil texture and site-specific soil minerals than by organic matter input [117,118]. Therefore, AFS research should focus more on aggregate formation and aggregate properties [53]. Knowing more about the part carbon actually plays in these processes would help to better understand site-specific susceptibility of soil to erosion and conservation measures could be better addressed. It is often assumed that the implementation of AFS potentially reduces soil erosion [3,15,119,120], although very little specific data are available on erosion control and soil conservation with reference to southern Africa.

Aeolian sediment transport is a natural phenomenon leading to environmental issues in many landscapes worldwide. Wind erosion is responsible for more than 46% of global soil degradation in arid regions [121–123]. In northern Africa, the process of wind erosion on the agricultural landscape has been researched and documented; studies in southern Africa are largely lacking [124], very likely because wind erosion is not widespread in the region; however, increased tillage and continuous cultivation accelerate land degradation and the risk of erosion through combination of reduced input of organic matter, high temperatures and reduced rainfall [125].

The geological processes of wind erosion and dust emission are driven by an interaction of climate, vegetation properties and human interference [126]. When wind velocity exceeds a threshold for movement of certain soil particle sizes, it results in wind erosion, while the surface roughness has an influence on the aerodynamic turbulence. Roughness elements range from macro- to microregional scales, consisting of landforms, the predominant soil surface structure and vegetation [127]. As wind erosion is also a very effective sorting process, dust emission or deposition significantly influence the carbon and nitrogen balances of soils [128]. Lessons learnt from other regions have shown that the emitted dust removes the most valuable parts of a soil, as particles in the silt and clay fraction and the SOC in its particulate form. Soil dust from agricultural land can be enriched in SOC up to 17 times compared to the original soil [129,130]. These losses are not considered in most matter balances although the lost quantities represent a disproportionately high loss of soil quality [131]. Due to the low net primary production of most regions affected by wind erosion, removed SOC can be regarded as an irretrievable loss at the eroded site [132].

The main usage of vegetative windbreaks as an applied form of AFS is the reduction of wind velocity on the leeward side [60,133]. Learning from studies in the Sahel, where soil and climate conditions are similar to the semi-arid regions of southern Africa, the effectiveness of shelterbelts is dependent on height, porosity, incident wind angle and by the leeward crop itself [134]. While the effect of the height is up to 40 times leeward [135], the influence of porosity is in the immediate vicinity. A high porosity on ground level allows air flow and prevents a build-up of pressure differences, which would lead to increasing turbulence leeward, diminishing the extent of shelter. The maximal protective effect is with an incident wind angle of 90°, while a reduction of wind speed in the order of 10–25% is still feasible with parallel structures. During the growing season, there is a shift of the zone of maximum shelter towards the windbreak, caused by the change of porosity, variation in climatic conditions, as well as the growth of the crop [134,135].

4.5. Provision of Biodiversity Benefits

Biodiversity is by default a multi-dimensional subject, covering genes, species, functional forms, adaptations, habitats and ecosystems, as well as the variability within and between them [136]. All these are closely interwoven and affect the stability, resilience and productivity of the ecosystem and its services. Functional diversity of biodiversity refers to the richness of the functionally different types of organisms with their different niches, habitats and positions on the food web. Functionally diverse populations are seen as more resilient against stress and shock and less likely to change their behaviour [137]. Species differ in their ability to influence and modify ecosystem processes and some species with certain functional traits are more able to do so than others. Forest plantations and AFS have a high potential for the augmentation of biodiversity in a given area with increased species variety and structure [18]. Understanding the interplay between the different levels (types) of biodiversity is significant when assessing the value of biodiversity in combination with alternative land-use management strategies.

Acknowledging the role played by forest resources in influencing and shaping practices in AFS, De Cauwer et al. [138] provided a clear picture of woodland resources, management and utilisation in southern Africa. With the exception of Afromontane forests, the region features three main forest types; Miombo, Mopane and the Zambezian Baikiaea woodlands; these are found in the northern reaches of the southern African region (generally > −20° latitude). These forest types have a predominantly deciduous forest formation, which allows enough light to reach the ground, enabling the growth of a rich grass layer. Forests cover on average 32% of the southern African countries but are mostly situated in the tropics. Southern Africa possesses an area covered by forest plantations of 1.95 million ha, equivalent to 1.5% of the total forest cover and 0.4% of the total land area [138]. Forest loss and degradation is an issue within these areas, regeneration through coppicing is swift, but lacking structural diversity [139–141]. However, it is also reported that fire presents a greater threat to forest cover in this region [142].

The Global Drylands Assessment [143], carried out by means of visual interpretation of satellite images, provides results on the extent and spatial distribution of dryland vegetation, including trees, shrubs, grasses and crops, for eastern and southern African regions as a baseline for monitoring changes in dryland forests, tree cover and land use by aridity zone. In the region, drylands cover a total area of 224 million hectares, representing 84% of the region's land area and 3.6% of the world's drylands. Trees outside forests (TOF)—defined as trees on lands other than forests and other wooded land—are present on 28% of the drylands area not covered with forest and woodlands in southern Africa. Yet, 47% of the southern African dryland area has no tree cover. Such evidence serves as basis to support decisions on land-use planning and on the implementation of strategies to enhance climate change resilience, biodiversity conservation and the maintenance of ecosystems services. This information can assist in the prioritisation of investments related to the restoration and rehabilitation measures for the drylands, bringing new possibilities to the implementation of AFS.

AFS increase structural diversity and support a greater faunal diversity with many positive effects on food webs and pollinators. Arthropods, for example, are indicators of a wide range of ecosystem services, such as pollination, biological pest control and decomposition in natural and agricultural ecosystems. Only a few studies investigated the biodiversity in southern Africa under different land uses including AFS. In [144], an increase in various soil invertebrate groups was shown in AFS in eastern Zambia, while Magoba and Samways [145] studied the biodiversity of arthropod communities around native and non-native trees in vineyards and natural South African Fynbos vegetation. For biodiversity conservation, AFS should be integrated into the ecological corridor concept and linked to the natural ecosystems [146], while AFS providing natural heterogeneity and edges in forest-like patches in open agricultural fields for faunal elements [147].

Invasive, alien trees [148] are of major concern for natural South African ecosystems, e.g., in the Fynbos in the Western Cape due to their drastic impacts on water resources and biodiversity [149,150]. In general, it is assumed that indigenous trees use significantly less water, but they grow more slowly than exotic, non-native tree species. Despite first studies on water consumption and water-use efficiency of native vs. introduced tree species in southern Africa (e.g., [151]) there is still a lack of information. The same is true for effects of non-indigenous and non-invasive trees on ecological processes, including the provision of these ecosystem services. Despite a growing body of publications on the relations of trees and ecosystem services (see [152–160]), knowledge in this field is still far from complete. However, the use of native tree species can potentially lead to better production while decreasing costs for management and decreasing hydrological impacts especially on problematic locations with, e.g., water limitation or high erosion risks sites [95].

4.6. Contribution to Natural Pest Control

Monocultures are notorious for their sensitivity and vulnerability to pests; entire crops can be lost to a single pest species during a single event. AFS has often been touted as a land-use system that can contribute to natural pest control, the increase in structural diversity can augment the functional biodiversity of the site, thus benefiting the natural antagonists of crop pests [161,162]. Recent research and meta-analyses have shown that trees in agricultural lands were likely to be providing refuge to insectivorous vertebrates and ground dwelling natural predators [162,163] although this is most likely pest species-dependent while also being dependent on crop and tree species combinations [161]. Meanwhile, it is also reported that the presence of trees does not necessarily increase the resilience of AFS against antagonists alone, but in combination with microclimatic conditions that influence pest performance, crop growth and soil conditions [163]. Further research and empirical study is needed to increase the understanding of the relationships between tree cover, food webs and natural pest suppression [161,162] with the development and testing of crop-pest modelling tools in multiple AFS systems of varying complexity.

4.7. Buffering and Prevention within Integrated Fire Management Planning

An increase in temperature, coupled with likely more erratic patterns of rainfall and windspeed are predicted for large parts of southern Africa. Many southern African landscapes have a pronounced dry season, and in these high radiation drylands, vegetation often synthesises reduced compounds (e.g., oils and lipids) that renders it more fire-prone. Southern Africa also has an increasing population, sporadic outbreaks of political instability and intensified land-use patterns, and these facts, combined with more erratic climatic patterns, are likely to increase the incidence and size of wildfire events. Reduction of fuel loads in strategic places and its fragmentation at the landscape level constitute probably the most powerful approaches to reduce the vulnerability of these landscapes under threat [164,165]. While AFS may lend itself to appropriate fuel management strategies, it remains essential that these systems are incorporated in landscape-level strategies for integrated fire management. AFS are seldom designed with the primary aim to combat wildfires. While it is true that specific AFS can be used to contribute to the strategic reduction or fragmentation of burnable fuel loads at the landscape level, some systems may increase fuel accumulation and thus make landscapes more vulnerable to wildfire. Ultimately, efficacy of AFS to contribute to fire safety will greatly depend on appropriate designs being implemented in specific locations and its integration into the landscape-level fire management strategy.

4.8. Increased Potential for Carbon Sequestration

AFS present the ideal opportunity for increased C sequestration within biomass and soils [9,18] as woody perennials can capture atmospheric CO_2 and store C above- and belowground. In general terms within the composition of woody plants, C constitutes approximately 50% of dry weights of specific plant parts (stem, branches, roots, etc.), and circa 30% of a plant's foliage. Growth rates vary along the lifespan of woody plants, and define the potential C sequestration rates, together with tree age, growing conditions (environment) and management practices applied. Furthermore, the woody biomass differs by its specific mass (wood density), within and between perennial species, affecting the total C stored.

The inclusion of trees within tree-less agricultural landscapes provides an extra-annual storage of C that would not be realised with annual cropping alone, alongside the dynamic incorporation of biomass within the soil matrix which increases C stored in the soil. At longer temporal scales, AFS aims at hosting mature trees, with a perennial character, with reduced wood harvesting interventions (i.e., pruning for fodder or fuelwood), or treatments aiming for the production of a higher-value product (i.e., pruning for knot free timber, for long-term C storage) which can achieve an increased C sink capacity, over other AFS and conventional monocropping systems.

Zomer et al. [54] assessed the contribution of AFS to global and national C budgets between 2000 and 2010, and found a minimum of 10% tree cover (in 2010) on 43% of all agricultural lands, an increase of 2% since 2000. Globally, biomass C increased from 20.4 to 21.4 t C ha^{-1} on agricultural lands: 75% contributed by the tree component. Nevertheless, with a total agricultural area of over 1.5 million km^2, eastern and southern Africa displayed minimal changes concerning average biomass C (14.6 t C ha^{-1}).

Aboveground C accumulation has been suggested to range from 0.29 to 15.21 Mg C ha^{-1} yr^{-1} within AFS [166]. Luedeling et al. [30] compiled C sequestration rates of AFS located in Mozambique, Zambia and Tanzania (on sites with mean annual rainfall ranges from 500 to 1200 mm) and found values ranging from 0.22 to 5.8 Mg C ha^{-1} yr^{-1}; rotational woodlots stored more C than other AFS in the studied regions. Ma et al. [167] in a global meta-analysis of C storage within AFS reported an average of 46.1 Mg Ha^{-1} more C than tree-less land-use systems with systems consisting of multiple tree species storing a higher C in their collective biomass.

Luedeling et al. [30] assembled information on the biophysical, technical, economic and practical potential of AFS to sequester C in Africa. For southern Africa, west African Sahel, and east Africa, they concluded that the existing data contributes for the assessment of the biophysical and technical capacity of agroecosystems to sequester additional C. Nevertheless, important aspects of C sequestration were not yet adequately investigated (i.e., soil C levels before and after AFS practices), and estimates of the associated economic potential were only available for few locations. In addition to present and future C storage potential, previous land use (e.g., clearance of forest for cropland or AFS) must be acknowledged and C losses accounted for (cf. [142]). Equally, the quantity of C conserved through the protection of existing forests, by the inclusion of trees in tree-less landscapes and reduction of pressure to forest resources, as opposed to the clearance of forests, can also be credited to the adoption of AFS [9].

Woodlots of drought-tolerant eucalyptus (*Eucalyptus* spp.) showed that high growth rates can be achieved also in harsh environments, as, for example, along the South African west coast, which receives an annual precipitation ranging from 230 to 420 mm [168]. Here, annual volume increments of 7 and 16 m^3 ha^{-1} are reported coupled with high basic wood densities that ranged between 550 and 860 kg m^{-3}, depending on the species [169,170]. Biomass production in such systems can be considered high [171], as is C sequestration. Calculations based on the results of such findings above show that around 1.9–6.8 C Mg ha^{-1} are incrementally sequestered each year in the eucalyptus stem wood alone during the lifetime of the plantation. Several studies have also shown that poles and valuable timber for several purposes can be produced from woodlots [169,170], which might leverage the C sequestration additionally through long term C capture and storage in products and substitution effects.

C storage projects are promoting advanced and sustainable AFS practices for recovering and/or establishing forests, planting trees within farmlands, and have potential to stimulate adoption of young farmers, due to the expected fast and long-term financial return [172,173]. The Gorongosa carbon sequestration project in Mozambique included the planting of tree species such as mango (*Mangifera indica* L.) and cashew (*Anacardium occidentale* L.) orchards to generate food and revenue; woodlots with siris (*Albizia lebbeck* (l.) Benth.), and African mahogany (*Khaya nyasica* (Welw.) C.DC.) to support charcoal production and timber requirements, intercropping with Faidherbia, soil fertilisation and thus raising crop yields [173]. In Mozambique, the rural annual consumption of hard fuel equals approximately 60–70% of the national sum, which in turn represents annual consumption per household of 0.9–1.0 $m^{3,}$ with potential to escalate due to demographic growth [174].

Charcoal production utilising non-sustainable hard fuel supplies is prevalent in many rural areas and city suburbs in southern Africa due to lack of implementation of appropriate fuelwood approach. The inclusion of an AFS management system can provide a substitution effect [175]. A multipurpose AFS practice can be included within existing land-use systems by including fast growing fuelwood trees and through the use of improved kilns and cooking stoves. In this way, it can positively provide a reduction in required cooking energy, pressure on natural forests and an improvement of farm sustainability with extra income source to rural households through the trading of charcoal and fire wood [175–177]. While AFS may already significantly contribute to global C budgets, rigorous and consistent procedures to measure the extent of C sequestration in AFS are required because of the integrated nature of AFS and the lack of specific data for areas under this land-use type [53]. AFS research must be addressed by including an accurate description of methods and procedures applied, such as sampling schemes, analytical details and computational methods, rather than only results.

Handavu et al. [178], reviewing concepts of C dynamics and assessment in the Miombo woodlands of southern Africa, drew awareness to the remaining challenge of quantifying forest C, highlighting knowledge gaps and methodological challenges. Considering the inherent spatial heterogeneity of the landscapes in the region, varying stand density, land-use and land-cover change story, the development of widely applicable biomass models will require detailed biomass assessments. Accurate assessment of C in living biomass and information on wood C content from a wide range of species are needed to inform the final C accounting, as trees in forests or AFS.

Assessment of aboveground C stock is directly derived from destructive measurements of tree aboveground biomass (AGB). The understanding of the role of forests in sequestering C is proved by various allometric equations developed for different forest types in southern Africa [179–182] and species-specific equations, even though many regions and vegetation types were never or have been rather poorly addressed [181,183]. Efforts in developing allometric equations specific to trees growing in AFS are largely missing.

For the estimation of tree AGB, a credible alternative to destructive approaches is the use of terrestrial laser scanners (TLS) in combination with Quantitative Structural Models (QSM; [184, 185]). Although this methodology has been often applied on forests in different countries [186–188], its application on trees growing in AFS [67,185,189] and its application in southern Africa are confined to few studies (e.g., [190]).

The soil C pool has been reported as being three times as large as the atmospheric C pool, and is of particular importance in the global C cycle [191–193]. Sequestration of CO_2 from the atmosphere into the SOM (of which soil SOC is a component) with only slow turnover is a promising strategy for climate change mitigation [103]. Adoption of AFS and implementation of key agroforestry practices are heralded as an accepted strategy for C capture and long-term C storage in soils [119,194,195]. Estimates of C storage potentials and C sequestration rates of soils vary widely and are frequently not based on analytical evidence [196]. As an example, an estimated 1.1 to 2.2 Pg of atmospheric C could be stored with a worldwide implementation of AFS in a 50-year period [197]. However, there is little data available on accurate C sequestration potentials of soils, showing it as depending on land management and site conditions [198].

Most existing models on SOM dynamics assume that C storage is linear to C input, namely quantity and quality of biomass. But C sequestration capacity is even more determined by physicochemical soil properties [115] and site-specific soil minerals and their binding places [117]. Due to stabilisation mechanisms within the soil, C is protected against decomposition [199]. Different SOM fractions are characterised by their stability against degradation processes [192]. Changes of land-use practices and associated changes in composition and amount of residue material affect not only quantity but also quality of sequestered C within the SOM fractions [200,201]. It has been suggested that AFS as land-use systems have the largest potential to increase the SOM pool in SSA [119]. But detecting these changes often takes decades due to relatively minor alterations at large background C stocks [202]. Thus, long-term observations to measure the effects of AFS over long periods of time and under different site conditions are of utmost importance. Nair et al. [166] proposed that, in general, belowground storage of C (up to 1 m in depth) within AFS could total 30 to 300 Mg C ha^{-1}. In southern Africa, very few long-term documented AFS experiments exist and results are difficult to reproduce [203]; existing data on sequestration rates in different African AFS varies considerably (e.g., [30]). In SSA, tree intercropping systems have the highest potential to sequester C (1.5 to 3.0 Mg C ha^{-1} yr^{-1}), followed by silvopastoral systems (1.0 to 2–5 Mg C ha^{-1} yr^{-1}) and protective systems like shelter belts (0.4 to 1.0 Mg C ha^{-1} yr^{-1}). All estimates are highly variable, depending on agroecological distribution [2]; nevertheless, a conversion of cropland to AFS has the potential to increase SOC [167]. More research is needed in order to get consistent and reliable data [53]. Apart from fixing C, SOM is a key element for physical and chemical soil fertility in providing more stable soil structure and improved nutrient status [204], thereby decreasing susceptibility to erosion, improving water storage capacity and increasing soil fertility [205], while also improving adaptation of such systems to erratic and altered rainfall patterns [206].

4.9. Enhanced Provisioning Capacity

The human population in southern Africa is inextricably linked to available woodland resources due to the provisioning services that include food safety net, health and energy. Traditional AFS are shown to fulfil this role better than normal agricultural systems. AFS has the potential to provide multiple NWFP as a form of semi-wild or cultivated produce aside from the crop actively promoted [18,207]. NWFP derived from the woodlands and forests of southern Africa play an important role in the livelihood of people by providing a range of products for subsistence consumption and trade. These include medicinal plants, exudates, forage, bee products, edible plants, woodcrafts, mushrooms and bush meat [138,158]. Climate variability, poverty and other factors have increased the reliance on NWFP for a large number of people. In the developing world, an estimated 80% of the population use traditional medicines for their primary healthcare needs [208]. The availability of NWFP serves as an important gap-filler or safety-net when food stocks are low [106,207], as a means of dietary supplementation [209,210] and also as a source of income [32]. Miombo species whose fruits are widely marketed throughout the ecoregion include *Uapaca kirkiana* Müll. Arg., *Azanza garckeana* (F.Hoffm.) Exell & Hillc., *Sclerocarya birrea* (A.Rich.) Hochst. and *Strychnos cocculoides* Baker [211]. Harvesting Miombo indigenous fruits from the wild and semi-domesticated trees growing on-farm can substantially boost rural income and create employment [9,32]; however, additional research efforts should be devoted to the beneficial substitution effects of food production within AFS vs. wild-collected NWFP.

4.10. Improved Rural Livelihoods via Policy and Institutional Instruments

The past four decades have witnessed concerted global efforts to promote AFS as part of the solutions for landscape management, secure food production and improving the livelihoods of mostly rural populations [212]. Despite the scientifically attested potential of AFS [23], the economic and political contexts of many SSA countries render targeted policy approaches even more difficult. Barriers to successful AFS at a local level are not only imposed by climatic and ecological conditions, yet also depend on a continued, often state-supported, focus on monoculture food production, industrial agricultural crops and mechanised farming. In some regions, the administrative barriers for establishing AFS are significant, especially when linked to complex land ownership arrangements and land tenure issues.

Largely, the development of AFS is constrained by legal, policy and institutional arrangements. AFS receives limited policy and institutional support as it is rarely formally recognised as a priority in national development plans, policies and land management strategies [55]. Additionally, AFS as a concept lacks an institutional home and exists within a number of policy fields. These sectors do not necessarily share a common agenda with sometimes contradictory strategies, hence the prominence of incoherent and conflicting policy regimes, which have an impact on AFS implementation [15,16,18]. To stress the importance of policies and institutions, Place and Dewees [213] assert that policies play a crucial role in either incentivising or and disincentivising farmers to invest in AFS. The existence of supportive policy and institutional arrangements is critical for the removal of barriers to necessitate upscaling, adoption and implementation of AFS innovations. Clear policies by the government are a necessary pre-condition for AFS to be adopted with the consequent benefits to individual farmers and rural communities [214]. According to Fones-Sundell and Teklehaimanot [215], policies can only be established if the government recognises AFS as an important land-use practice. Only then can incentives be made for adoption of such a longer-term investment over and above the annual returns received for agricultural cropping.

Ndlovu and Borrass [216] note that "the reframing of AFS in influential global political discourses is influencing a change in advancing AFS programmes from a policy and institutional perspective in different national contexts". AFS is discussed in global political processes such as the United Nations Framework Convention on Climate Change (UNFCCC) [13] and the SDGs [3,17,217]. In the SADC region, there are examples of countries which have included AFS in different sectoral programmes. For instance, South Africa adopted an AFS strategy which stresses the importance of creating and enabling an institutional and governmental framework for AFS. Zimbabwe's draft forest policy emphasises the importance of AFS, whilst in Malawi, the agricultural policy and National Land Resources Management Strategy discusses AFS at length and hosts a dedicated department for the implementation of AFS. Malawi, Zambia, Eswatini, Zimbabwe have co-opted AFS as part of the strategies to achieve their nationally determined contributions under the auspices of the UNFCCC [216].

5. Future Prospects

As shown, AFS can be an effective means to mitigate and adapt agricultural systems to climate change as well as providing enhancement to food security and local employment [15,23]. Such systems are a far more stable and long-term solution to meet environmental and socio-economic needs in southern Africa in lieu of monocropping, livestock rearing or other less sustainable activities. Following the conceptual idea of plant community mixtures proposed by Harper [218], thereafter adopted and refined describing forest stand mixtures by Bauhus et al. [219], Figure 3 depicts land-use system replacement series applied to a conceptual and vastly simplified two-component AFS. Within such a conceptual example, the density of the AFS tree component is the same as in the monoculture cropping system and always summing to 100%. The following figure describes four scenarios (a–d) where one system component is gradually replaced by the other towards either full forest cover or pure agricultural cropping. In the given example, it is assumed that the agricultural crop is more productive than the tree culture.

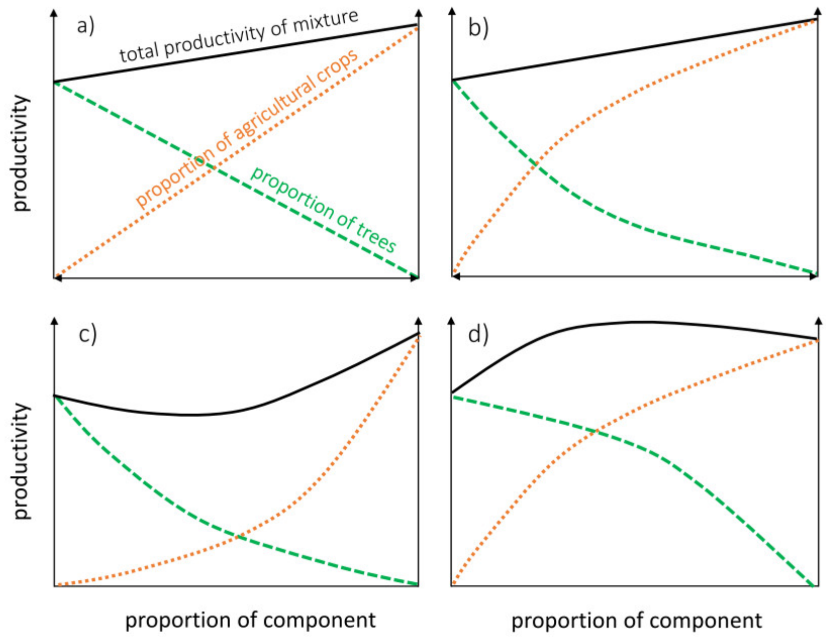

Figure 3. Different effects of mixing agricultural crops and trees in agroforestry systems on the total productivity of the land-use system (solid line) and the individual productivities of the participating agricultural crops and the trees (dotted/orange and dashed/green lines, respectively). The figure shows four scenarios (a–d) where one system component is gradually replaced by the other towards full forest cover or pure agricultural cropping; full analysis is given in the text. (After [218]).

Four simplified AFS scenarios (independent of external variables such as climate and site characteristics) can be described combining trees with crops within AFS, following a modified description originally presented by Bauhus et al. [219]:

(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), cf. [220]).

Such a simplistic view, however, does not reflect the complexities of the interactions that occur within AFS. Figure 4 demonstrates the yield potentials and yield gaps between agricultural production systems and AFS after the work of Ittersum and Rabbinge [221]. This conceptional description highlights actual, achievable and experimental yields in comparison with a potential which is limited by growth-defining factors which include temperature, CO_2, available solar radiation, plant physiology and plant phenology. Such a potential is modified by growth-limiting factors such as water and nutrients, growth-reducing factors such as biotic (e.g., weeds, diseases, pests) and abiotic (e.g., drought, storm) influences, and also highlights a so-called experimental yield gap which accounts for yield differences between field trials and practice, an important aspect to consider in order to bridge the science-praxis knowledge gap.

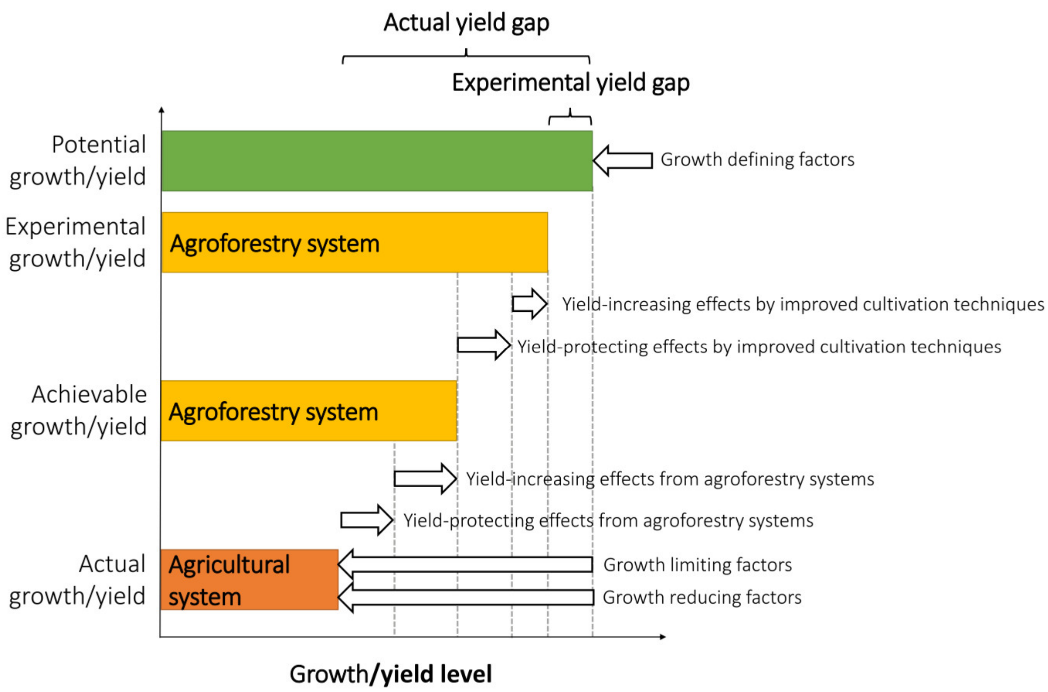

Figure 4. Yield potentials and yield gaps and relationships among yield levels and growth-defining, growth-limiting and growth-reducing factors, and yield-increasing and yield-protecting measures (after [221]).

It is at the praxis level, i.e., AFS "in the wild", that such conceptual models must be tested and modified to provide elevated productivity over simple agricultural production methods accounting for species mixture (Figure 3) and for limiting or reducing factors that prevent the full potential of AFS being realised (Figure 4). 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 a real and serious growth reduction factor. Increased frequency and severity of extreme weather events can also affect the viability of crops, can bring disruption and loss of profitability widening the gap between actual, achievable and potential yield (Figure 4). 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.

The use of trees as rows, clumps, windbreaks or as woodlots within the farmed landscape can alter the microclimate through shade and wind reduction. In addition, advantages against wind and water erosion with water retention within the fields have been frequently suggested, thus providing a more suitable and stable environment for cropping activities and ecosystem service provision [23]. Such characteristically diverse functions of AFS can also increase the resistance and resilience of farmed landscapes (cf. [1,21]); increasing crop yield due to provision of better soil nutrition, plant pollination, pest control and risk reduction can be achieved with an appropriate tree crop combination (Figure 3).

Nevertheless, AFS can (and must) be complementary to other existing land uses. It would be hard to introduce a competing land-use system to local stakeholders who are already accustomed to a certain lifestyle and source of income; likewise, it must be compatible and complimentary with the natural ecosystem it is placed within. Proposed approaches such as "analog forestry" may also find suitable application in the region [222]. The African Union has recently called for increases in farmer-managed natural regeneration of trees within farmland [223], and capacity building with the education of farmers about the benefits of incorporating trees and AFS without significantly interrupting the existing systems in place is an important implementation tool [222]. Key to the long-term success of AFS is a well-established and functional information infrastructure, as well as long-term monitoring programs to provide "on-the-ground" experience or "bottom-up" participation as a means of increasing resilient cropping potential supporting rural livelihoods, increasing food security and intensifying resilience against climate change threats [1,17,18]. Walker et al. [224] suggest that a successful adoption of sustainable AFS should be led by social and traditional knowledge, as most AFS practices are related and stem from traditional cultivation systems. The implementation of such AFS initiatives allows rural communities to access extension services with ultimate technological approaches as improved genetic material, advanced techniques on plant propagation, promote market-oriented production, facilitate access to the international carbon market, promote community associativism and the provision of equipment, or simply provide access to seed and basic knowledge to equip farmers with the know-how and perspective needed to grow and manage trees. Nevertheless, experiences show that long-term adoption of sustainable practices has the potential to fail if it is not attractive and the benefits are not immediately visible, in particular for younger farmers. The same is true if new ideas do not align with traditional viewpoints, farmers' needs and agro-ecological specificities [175,224]. Likewise, the issue of land tenure and land ownership often influences the adoption of agroforestry practices, those with customary rights are less likely to implement and invest in some form of sustainable agricultural practice [225] such as AFS when they do not have long-term land tenure security.

Lack of multi-sectorial partnerships and empowering of local NGOs is perceived as one of the weaknesses within AFS research, dissemination and sustainability. Despite the increasing engagement of scientific literature with AFS, research on the topic remains very much applied at a praxis level. It does not aim at a fully developed, coherent theoretical interest in policies and institutions. While natural scientists and practitioners laud the concept and attach substantial potential to it [23], the social, political, and institutional dimensions remain very much understudied [18]. This does not prevent scientific articles from presenting social scientific claims, nor does it deter the definition of institutional prerequisites for implementation or adoption of AFS. This finding indicates a gap in the scientific literature with regard to a thorough and comprehensive analysis of aspects of policy and institutions. The absence of policies targeting AFS, and thus the persisting absence of institutionalisation of AFS practices as the overwhelming problem, requires contextualisation. Focus on AFS from large international organisations presenting a unified approach, such as that heralded by the recently formed CIFOR-ICRAF merger, has the potential to bring about transformative multidisciplinary strategies that function on multiple levels [29].

While AFS research and development have made great strides in the last three decades in southern African countries, many gaps remain (Table 1). Efforts should be directed towards tackling individual issues and local differences on the composition and management of particular AFS that are suited to individual circumstances. Innovation should be sought to alleviate known pressures on natural ecosystems such as the provision of fuelwood or charcoal [226]. AFS should not be viewed as a one-size-fits-all standardised solution (cf. Figure 3), but rather a recipe with many ingredients that can be individually applied to bake the cake that is appropriate for the occasion. The foreseen scaling-up of AFS in the southern African region for enhanced agricultural productivity, profitability and sustainability improving livelihoods of rural people across the region is already a reality. The diffusion and adaptation of AFS technologies has occurred, through farmer-to-farmer networks, and through NGO-led projects that spotlight alternative technologies and provide support for farmer learning in the region. We echo and confirm the conclusion of Kwesiga et al. [28] who optimistically assert that AFS has the potential to achieve the compound goals of poverty alleviation and increased food security while facilitating global environmental protection in the face of the diverse challenges troubling the southern African region. AFS remains an appropriate and sustainable response in our toolbox for an increased resilience against a changing climate in southern Africa for the benefit of livelihoods and environmental values.

Table 1. Identified knowledge gaps and potential solutions within the study of southern African AFS.

Knowledge Gaps Relevant for AFS in Southern Africa	Possible Solutions
Ecosystem Services, Provisioning, Carbon Accounting and Integrated Fire Management	
Interplay between biodiversity types and land-use strategy	Examination with appropriate methodology, e.g., ecosystem-based management approach.
Threats presented by non-native trees	Ecology and distribution of non-native trees. Case studies.
AFS influence on pest populations	Observational and experimental exploration of bottom-up and top-down influence of AFS on pest populations, relationships between tree cover, food webs and pest suppression.
Crop-pest modelling tools do not account for AFS' complexity	Data collection on both focused AFS and broad indications for common applications.
Benefits of AFS produced NWFP vs. wild harvesting	Case study and experimental explorations of impacts of sustainable wild harvesting and AFS substitution.
Extent of carbon sequestration potential in AFS	Landscape level estimations of AFS utilisation, species mixture and applied management, coupled with biomass studies and modelling activities.
Allometric functions relevant for trees utilised in AFS	Sampling and development of allometric functions for appropriate species.
Minimal data available for carbon storage potential dependent on land management and site conditions	Plot and landscape level modelling, use of LiDAR technology. Empirical studies. Biomass modelling. Long-term observations of carbon dynamics.
Low levels of information on fuels and fire behaviour in AFS	Dedicated studies on fuel types and fuel loading and its dynamics over time in AFS.
Tree-Crop-Site Interactions	
Shelterbelt/tree spatial arrangements within AFS, crop selection and combinations	Measurement of existing systems, modelling and extrapolation (e.g., wind loading of trees; cf. [227]).
Competition vs. facilitation (e.g., light and water)	Modelling utilising empirical shading measurements and tree parameters in relation to ecophysiological shade tolerance (i.e., tree-crop water use, 3D-based approach; [67]).
Shading effects and benefits provided by AFS	Observational and experimental research into combinations and suitability of crops for usage in AFS.
Effects of nitrogen-fixing species	Experimental methodology, ecophysiological measurements. Cultivation of different tree species under different climatic and site conditions [3].
Low data availability on water retention studies and plant-plant soil water flow	Detailed throughflow measurements in combination with plant-plant water transfer (e.g., [85]) with soil/structure type referencing.
Evaluation of species combination, soils and management practices for different regions	Disentangling the various influences (case studies in different systems with clear designs regarding species combination, soils and management practices).
Low data availability on erosion control and soil conservation in AFS	Experimental quantification of erosion and deposition in relation to land use, soil types, terrain and climate. Research on aggregate formation [53] to assess site-specific erosion risk.
Political, Social and Economic Issues	
Lack of institutional home, mis-aligned policy agendas	Closer cooperation and communication between government, research and NGOs.
Impact of AFS on rural livelihoods	Further scrutiny of impact of AFS on the improvement of food security, employment and resilience issues

Author Contributions: Conceptualization: J.P.S. Writing—Original draft preparation: J.P.S., R.B.R., L.B., P.W.C., C.J.C., R.F., S.K.H., S.H., F.K., F.L., R.M., M.M., C.M., N.P.N., T.S., B.d.T., M.V. Writing—Review and editing: J.P.S., R.B.R., L.B., P.W.C., C.J.C., R.F., S.K.H., S.H., F.K., F.L., R.M., M.M., C.M., N.P.N., T.S., B.d.T., M.V., H.-P.K. Project administration: J.P.S., H.-P.K. Funding acquisition: J.P.S., C.M., H.-P.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry of Education and Research (BMBF), grant number 01LL1803. The article processing charge was funded by the Baden-Württemberg Ministry of Science, Research and Art and the University of Freiburg in the funding programme Open Access Publishing.

Acknowledgments: We recognise and appreciate the fruitful discussions and mutual learning with colleagues of the project consortia reflected in this piece. Furthermore, we thank the anonymous reviewers whose comments helped improve and clarify this manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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