Carbon Footprints

Review

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Agroforestry systems for mitigating climate change and reducing Carbon Footprints of land-use systems in Southern Africa

Paxie W. Chirwa[1], **Misheck Musokwa**[2], **Saul E. Mwale**[3], **Ferdinand Handavu**[4], **George Nyamadzawo**[5]

[1]Department of Plant and Soil Sciences, University of Pretoria, Pretoria 0022, South Africa.
[2]Programme Coordinator - Climate Resilience, Southern African Confederation of Agricultural Unions, Centurion 0046, South Africa.
[3]Biological Sciences Department, Mzuzu University, Luwinga, Mzuzu 105203, Malawi.
[4]Department of Geography, Environment and Climate Change, Mukuba University, Kitwe 20382, Zambia.
[5]Agribusiness and Climate Resilience Expert, Devpact Consultants, Harare 7784, Zimbabwe.

Correspondence to: Prof. Paxie W. Chirwa, Department of Plant and Soil Sciences, University of Pretoria, Pretoria 0022, South Africa. E-mail: paxie.chirwa@up.ac.za

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Abstract

Farming systems in Southern Africa are mostly maize mixed cropping, with some tree and/or root crop-based systems. Agroforestry systems (AFS), in particular, represent a model for ecological sustainability, with the potential of sequestering carbon (C) within soils and biomass. This review reveals that rotational woodlots sequester more C than other AFS types in the region. Additionally, C levels above and below ground range from 0.29 to 15.21 Mg ha^{-1} yr^{-1} and 30 to 300 Mg C ha^{-1} in the first 100 cm soil depth, respectively. To measure C below- and aboveground biomass in different AFS, variable - and not easily adoptable - methodologies are being used in Southern Africa, which limits the standardization of C stock accounting. Since the magnitude of C sequestered in AFS is dependent on the species used, AF and farm management, and environmental conditions, we recommend the adoption of rigorous and replicable methodologies to account for C stocks in different AFS over time in Southern Africa.

Keywords: Aboveground carbon, agroforestry systems, sequestration, soil organic carbon

INTRODUCTION

Anthropogenic global warming is a current phenomenon that has aroused interest in several land-use systems that may help to avert or stabilize atmospheric CO_2 concentrations[1]. Reducing atmospheric CO_2 concentrations can be achieved by minimizing emissions or increasing C sequestration[2]. Forests have been a focus of emissions reduction strategies as they account for 45% of terrestrial C stocks[3,4]. Moreover, it is notable that trees in other land-use systems, including farmland, have considerable potential for C emission/sequestration owing to their spatial extent. More than 45% of farmland globally has up to 10% tree cover[5]. According to Nair[6] and Nair and Nair[7], biomass C stocks in farmland usually range from 3 to 18 t C ha^{-1}. Previous studies have focused on the C contributions of forests. However, current evidence supports the importance of both trees outside forests and agroforestry (AF) for C sequestration[8]. Important practices that could contribute to C sequestration include afforestation and reforestation programs in different formations[9-13]. Since smallholder farmers in developing nations, such as those in Southern Africa, are the main practitioners of AF, there is the potential to mainstream different agroforestry systems (AFS) into C financing mechanisms. This possibility is especially relevant to the Clean Development Mechanism (CDM) of the United Nations Framework Convention on Climate Change (UNFCCC). The role of AF in C sequestration is also recognized by the Intergovernmental Panel on Climate Change (IPCC)[14]. In fact, some studies have suggested that AFS sequester more C than pastures or field crops[15-18]. This suggestion is premised on the hypothesis that the incorporation of trees in agricultural landscapes results in greater net C sequestration both above and below ground[12,13,19]. In addition, AFS remain in place for longer than annual crops, thus contributing to greater C sequestration.

Agroforestry has been described as a dynamic, ecologically based, natural resources management system. These systems can diversify and sustain production, resulting in increased social, economic, and environmental benefits for land users at all levels[13,18,20], via the incorporation of trees in farms and agricultural landscapes.

In this review, we examine the current evidence for the capacity of AF C pools to mitigate climate change in Southern Africa. We explore the extent to which AFS could enhance soil organic C (SOC) storage and contribute to climate change mitigation. Additionally, we highlight the different measurements that are employed to account for above- and belowground C in different AFS. The information presented in this review can help inform the emerging role of AFS in Southern Africa and the potential to sequester C.

AGROECOSYSTEMS OF SOUTHERN AFRICA

Ecosystems in the Southern Africa sub-region have been influenced by both natural and anthropogenic factors, such as fire, cultivation practices, and charcoal production. These factors have had an influence on both biodiversity and primary production and, in turn, C status. The degradation of agroecosystems in the sub-region is associated with a loss of nutrients, fauna, flora, and productive ecosystems. Agricultural land constitutes more of the land surface of Southern Africa than any other land-use type. These areas host a vast diversity of life, ranging from pests and associated organisms in cultivated lands to natural vegetation containing rare and endemic species that require protection.

Agricultural systems in Southern Africa are largely subsistence farming on diminishing plots of land with declining soil fertility. These farming systems have been inadequate to cope with the population growth explosion experienced in the region. Traditional systems include the tree legume-based system of

Faidherbia albida parklands, in which farmers have retained a low density of trees, or two-tiered systems in the tropics, especially in semi-arid areas, to improve the yield of understorey crops[21-23]. Other systems include *dambo* ecosystems, which are seasonally wet agricultural lands where dry season cropping (*dimbas*) is practiced, especially vegetables[22,24]. In animal-dominated landscapes, transhumance grazing systems are prevalent. For example, transhumance grazing is still practised in flood plains in some parts of Zambia and Zimbabwe[25,26]. In the last three decades, improved AF technologies have been promoted with varying success. Most of these have shown positive results with respect to soil C and general soil health.

It has been argued that, despite a lack of investment in African farming, there have been changes in agricultural production. There has been a shift from diversified cropping systems-associated with healthy soils with respect to nutrients, including SOC - towards ecologically simpler cereal-based systems, characterized by inorganic fertilizer inputs (with a high C footprint), which have contributed to poor diet and crop diversity[22].

The general agroecosystem/farming system in Tanzania, Zambia, and Malawi is maize mixed farming, but Tanzania and Zambia also have forest-based and root crop farming[27]. Forest-based farming is characteristically found in humid forests in the region, and farmers practice shifting cultivation by clearing a new plot in the forest every 3-5 years, with a fallow period of ~7-20 years. This system is the basis of the Chitemene system in Zambia and the Machambas that are used to cultivate crops such as cassava, maize, beans, and potatoes in the Niassa Province of Mozambique[27-29].

Rice-tree crop farming is prevalent in some parts of Madagascar. Banana and coffee are major crops and are complemented by rice, maize, cassava, and legumes. Root crop farming is also practiced in southern Madagascar and is dominant in some parts of Mozambique, especially cassava (*Manihot esculenta*), which is grown in typical home gardens in the Indian Ocean coastline provinces, such as Inhambane in Mozambique.

In South Africa, agroecosystems are both large commercial farms and smallholdings in semi-arid and dry sub-humid zones. These systems comprise scattered smallholdings in former homelands and large commercial farms, both with mixed cereal-livestock systems. Commercial farms are generally associated with a high C footprint as a result of the high mechanisation and inorganic fertilizer inputs. Also predominant in the commercial sector are private nature reserves, which contribute to *in situ* biodiversity conservation and potentially high above- (AGB) and belowground biomass (BGB) and C.

CARBON CAPTURE IN AGROFORESTRY SYSTEMS

AFS sequester more C than other agricultural systems[30] [Table 1]. However, below- and aboveground vegetation C sequestration is highly variable[13] as the amounts of biomass and SOC addition vary with tree species, soil type, rainfall, and environmental conditions. Overall, C sequestration in AFS is a function of the availability of resources with higher vegetation C sequestration rates in fertile humid areas than in water-limited and degraded sites. Larger SOC pools in AFS are a result of the quantity and quality of biomass C that is incorporated into the soil, which stabilizes and builds soil organic matter (SOM)[31,32]. Plant species and litter quality influence decomposition rates in AFS[33]. High lignin and tannin contents lower the rate of decomposition[34,35]. Additionally, the C/N ratio of the decomposing material affects the soil C inputs[36]. AF practises, known as “climate-smart”, contribute to increased SOC pools[37,38]. In Southern Africa, these include *Faidherbia* parklands, improved fallows, and conservation agriculture with trees[21]. AFS also improve the physical condition of soil as a result of better soil aggregation, lower bulk density, lower resistance to penetration[39], improved soil porosity and reduced surface sealing, and increased hydraulic

Table 1. Potential annual harvestable fuelwood produced from fertilizer trees planted in contour strips, woodlots, or rotational fallows

Tree species	Age (years)	Quantity (Mg ha^{-1} yr^{-1})	C/Factor	C (Mg ha^{-1} yr^{-1})	Sufficient for N families of 6	Country
Calliandra	4.5	3.2	**0.5**	1.60	1.1	Tanzania
Casuarina	4.5	1.8	**0.5**	0.90	0.6	
Acacia crassicarpa	5	22.4	**0.5**	11.20	7.7	
A. crassicarpa	4	22	**0.5**	11.00	8.2	
Vachellia nilotica	7	1.2	**0.5**	0.60	0.4	Tanzania
Senegalia (Acacia) polycantha	7	10.1	**0.5**	5.05	3.5	
Leucaena	7	12.7	**0.5**	6.35	4.4	
Acacia crassicarpa	5	51.0	**0.5**	25.50	17.5	Tanzania
A. mangium	5	40.0	**0.5**	20.00	13.7	
Senegalia (Acacia) polycantha	5	39.0	**0.5**	19.50	13.4	
Vachellia nilotica	5	27.0	**0.5**	13.50	9.3	
Gliricidia	5	30.0	**0.5**	15.00	10.3	
Leucaena	3	9.7	**0.5**	4.85	3.3	Zambia
Sesbania	3	8.0	**0.5**	4.00	2.7	
Gliricidia	3	7.0	**0.5**	3.50	2.4	
Sesbania	1-3	7.3	**0.5**	3.65	2.5	

Source: Modified from Sileshi *et al.*[30]

conductivity[40], infiltration rates[38,39,41], and water holding capacity.

While C sequestration depends on the type of AFS, there is a paucity of published information[21]. Gama-Rodrigues *et al.* reported SOC pools of 302 Mg C ha^{-1} in 0-100 cm depth soil in a 30-year-old cacao AFS in Brazil[42]. In fact, AFS are reported to have higher SOC than other land-use systems, apart from forests, and can be classified in the order forests > AFS > tree plantations > arable crops[13].

ABOVEGROUND BIOMASS SEQUESTRATION

In Southern Africa, multiple tree species have been shown to sequester a substantial amount of C through biomass accumulation[30] [Table 1]. In fact, some studies showed that improved fallows, especially those with exotic multipurpose species, sequester more carbon (2.0-6.0 Mg C ha^{-1} yr^{-1}) than coppiced miombo woodlands (a dominant vegetation type in Southern Africa; < 1.0 Mg C ha^{-1} yr^{-1}) [Table 2]. These rates depended on the species used, site characteristics, planting densities, and the formation or agroforestry technology used. For example, where improved fallows with *Sesbania* tree species are used in Eastern Zambia, AFS can sequester C at rates of 26-120 Mg C ha^{-1}[43]. In Zimbabwe, Nyamadzawo *et al.* reported C accumulation of 26.3 and 25.4 Mg ha^{-1} in leaves and twigs in a two-year improved fallow with *Acacia angustissima* and *Sesbania sesban*[44]. In another fallow variant, where rotational woodlots were used in tobacco growing areas in Tanzania, five-year rotational woodlots sequestered 11.6 to 25.5 Mg C ha^{-1}[45].

In Malawi, a modified system that used permanent stands of *Gliricidia sepium* as fertilizer trees in a mixed intercropping formation sequestered between 123 and 149 Mg C ha^{-1} in the soil[46] [Table 3]. This rate is relatively higher than that recorded for a six-year stand of *Faidherbia albida* in Tanzania (9.4 Mg C ha^{-1})[47]. One explanation for this difference is that rotational fallows predominantly use fast-growing exotic species,

Table 2. SOC fixed in different improved fallow systems from selected countries in Southern Africa

Location	Fallow species	SOC stocks (Mg ha^{-1})	Source
Zambia	Copping fallows	32.2-37.8	[43]
Zambia	Non-coppicing fallows	29.5-30.1	[43]
Zimbabwe	Acacia angustissima	26.3	[44]
Zimbabwe	Sesbania sesban	25.4	[44]
Morogoro, Tanzania	Acacia crassicarpa	15.8	[45]
Tanzania	Acacia mangium	25.6	[45]
Tanzania	Acacia polyacantha	21.6	[45]
Tanzania	Gliricidia sepium	18.8	[45]
Tanzania	Acacia nolotica	22.7	[45]

SOC: Soil organic C.

Table 3. Soil organic carbon sequestration in agroforestry systems in Southern Africa

Agroforestry system	Location	Age	Soil depth (cm)	Sequestration rate Mg C ha^{-1} $year^{-1}$	Reference
Gliricidia spp	Malawi		0-20	123-149	[46]
Faidherbia albida plantation	Tanzania	6		1.2	[47]
Tree fallows (*Sesbania sesban*)	Zimbabwe	2	200	25.4	[44]
Coppiced miombo	Zambia	16		0.5	[48]
Coppiced miombo	Zambia	35		0.9	[49]
Rotational woodlots	Tanzania	5		2.6-5.8	[50]
Rotational woodlots (wood C)	Tanzania	5		2.3-5.1	[45]
Rotational woodlots	Zambia	2		2.15-4.75	[51]
Conserved Forest-Nyasamba	Tanzania		0-10	48.84	[52]
			10-200	22.57	
			20-30	12.37	
			0-10	37.17	
Trees species	Tanzania-Bubinza			79.22tCO_2 e/year	[52]
	Tanzania-Nyasamba			57.37tCO_2 e/year	
Herbaceous	Tanzania-Bubinza			125.36tCO_2 e/year	
	Tanzania-Nyasamba			63.35tCO_2 e/year	

such as Australian acacias. In contrast, *Faidherbia* parklands are traditional agroforestry systems. *Faidherbia albida* is also drought tolerant, as evidenced by its wide distribution as far as the Sahel region of Africa. Hence, *F. albida* can be considered a keystone species for climate-smart agriculture in much of Africa[23,53].

In most systems, long-lived species sequester more C than short-term fallow systems or agroforestry technologies where fertilizer trees are used for biomass transfer, with the woody biomass used as fuel. In this case, one must provide proper C budgets to establish the net C in an ecosystem. In the miombo woodlands of Southern Africa, AGB, BGB, and C stocks were estimated at the stand level using allometric models. The best estimate of AGB was 222.2 Mg ha^{-1}, which translated to C stocks in AGB of 125.3 Mg C ha^{-1}[53,54]. Using a nonlinear seemingly unrelated regression, total tree biomass was estimated at 270.1 Mg ha^{-1} (95%Cl: 207.4-328.7 Mg ha^{-1}), with resulting C stocks estimated at 152.1 Mg ha^{-1} (95%Cl: 115.9-184.1 Mg ha^{-1}); in terms of the amount of CO_2 sequestered in tree biomass, this translates to 558.3 Mg CO_2 ha^{-1}. Earlier studies on AGB and/or C sequestration also produced variable values for unevenly aged mature woodlands of miombo and mopane woodlands, ranging from 1.5 to 90 Mg ha^{-1}[30,54].

BELOWGROUND (SOIL) C SEQUESTRATION

The main limiting factor to agricultural production in Southern Africa is low soil fertility. Hence, agroforestry with nitrogen-fixing multipurpose tree species has high potential in the region, where poor agricultural practices, such as slash-and-burn agriculture and charcoal production, are prevalent[55]. Agroforestry therefore has tremendous C sequestration potential and is an alternative to shifting cultivation or continuous monocropping, which has resulted in forest cover loss[56-58].

In terms of SOC, a positive effect has been shown by all the systems previously discussed [Tables 2 and 3]. The SOC under canopies of *Faidherbia* was shown to be higher (3%-30%) than that outside the canopy[59]. In both improved and rotational fallows in Zimbabwe and Tanzania, respectively, SOC was higher than that under continuous cropping with maize (1.7 times higher in the former and 15.8-25.6 Mg ha^{-1} *vs*. 13 Mg ha^{-1} in the latter)[44,45,50]. Other species have also been used in different agroforestry systems, including *Tephrosia*, *Sesbania*, and pigeon pea (*Cajanus cajan*), where SOC stocks were higher (27.3-31.2 Mg ha^{-1}) than those under fully fertilized monocropped maize (26.2 Mg ha^{-1}) and unfertilized monocropped maize (22.2 Mg ha^{-1}) in eastern Zambia[43]. Tree-based intercropping systems using *Gliricidia* also showed that soil C doubled after 7-10 years compared with that for monocropped maize. These results clearly show the positive effect of agroforestry systems and technologies on soil C enhancement.

MEASUREMENT OF C SEQUESTRATION IN AGROFORESTRY SYSTEMS

AGB and BGB are critical constituents of terrestrial ecosystem C stocks in agroforestry C cycles. The amount of biomass, as well as C stocks distributed in different tree components (trunk, branches, twigs, leaves, and roots), are dependent on several critical factors, such as tree species, floristic composition and growth characteristics within a climatic zone, tree size and density, and geographic location[60,61]. Therefore, accurate measurement of the size and dynamics of C stocks requires that these factors are taken into consideration as essential inputs to the formulation of climate change mitigation and adaptation policies. IPCC[62] noted that to enhance strategic C management in AFS, the collection of reliable biomass data is required for successful screening of tree species potential. However, a major challenge in the measurement and monitoring of the C sequestration potential of agroforestry systems is accurate, replicable methods for measuring AGB, which stores a substantial amount of the C assimilated by these systems[63,64].

Two methods are employed in AGB assessments: destructive (direct measurement) and non-destructive. Non-destructive biomass assessments use previously developed allometric equations selected from the literature. Although approximation of tree biomass by direct measurements of the actual weight of each tree constituent is the most accurate method, entire-tree harvesting is destructive, time-consuming, and costly[65]. However, sound statistical formulations, especially for AFS that have not been exhaustively explored, require destructively acquired data. The process entails totalling the quantity of harvested constituent tree parts (trunk, branches, and leaves)[53,66] and standing biomass. Prior to undertaking destructive sampling, all trees are identified to species level, and the diameter at breast height and tree height is measured (in m). Sub-samples, in the form of disks, are taken from the middle of the trunk, branches, and leaves, and the total wet weight of biomass is measured in the laboratory. Prior to oven drying, the irregular sample discs are first submerged in water for 48 h to reach saturation point and their volume is determined using the water displacement method. Oven drying of samples is conducted at 105 °C (stem and branch discs) and 60.5 °C (twigs and leaves) for 48 h and samples are subsequently weighed to obtain the dry weight. Oven-dried sample components (stem, branches, twigs, and leaves) are then ground into powder for analysis of C fractions.

BGB and the C stocks of root systems of AFS are constituents of the C pool that demand greater attention. For example, Nair *et al*. noted that the ability of roots to store large quantities of C in the soil makes them an essential component of soil C stocks[13]. However, BGB and C stocks are poorly estimated for many forest formations; hence, their potential to mitigate the effects of climate change remains a major knowledge gap[67]. However, understanding root biomass dynamics, root profiles and architecture, and rooting depth is important for improving our understanding of the allocation and storage of C in AFS. It is worth noting that sampling depths vary from one study to another; hence, standardization is required to enable comparison of the contributions of root biomass to C sequestration along soil profiles. For determination of BGB, the entire root system of sampled trees is dug up and tracked outward from the stump to make sure that no detected roots are improperly assigned[53,68].

Apart from root biomass and C, SOC is also determined separately as total soil C. The soil C pool is reportedly three times greater than the atmospheric C pool and is of particular significance in the global C cycle[69]. Various methods of measuring SOC exist, which creates high variability in the results[70,71]. Available methods include loss-on-ignition, the Walkley-Black method, and dry oxidation[72]. Studies in parts of the miombo woodlands in Southern Africa and other tropical forests used the following depths: 0, 5, 15, 25, and 50 cm[73]; 0-10, 0-20, and 0-30 cm[74]; 0-10, 10-20, and 20-30 cm[75]; 0-20 and 20-50 cm[76,77]; 0-10, 10-20, 20-45, and 45-60 cm[78]; and 0-10, 10-20, 20-40, 60-100, and 100-150 cm[79]. Results to date show that most soil C sequestration studies of AFS have focused on changes in the topsoil layer (0-20 cm) where the largest C pools are detected. This focus, however, ignores the important role of tree roots in sequestering C in the deeper soil layers, where substantial quantities of C are supplied through root exudes and root turnover[13,80]. These variations in sampling techniques require standardization to allow for comparability of SOC sequestration along the soil profile, rather than in the surface layer only.

CONCLUSION

This review sought to highlight different land-use systems in Southern Africa and use available literature to establish the extent of C sequestration, accumulation, and measurement of C stocks in AGB and BGB in different AFS. The dominant farming system in the region is subsistence with declining soil fertility. Traditional tree legume-based systems, e.g., *Faidherbia albida* parklands, especially those in semi-arid areas, have been shown to improve the yield of understorey crops. The predominant farming systems in the region are maize mixed farming with some forest-based and root crop farming. Forest-based farming is characteristically found in humid forests in the region, where farmers practice shifting cultivation. Rotational woodlots have the potential to accumulate greater C stocks than other AFS types. C storage accumulation was greater in BGB than in AGB in the studied AFS in Southern Africa. In addition, it has been shown that C storage potential is a function of the species used, the quality of the biomass, and site characteristics. However, methodological challenges in C stocks accounting and the potential for climate change mitigation within diverse AFS types need to be addressed in the future.

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Authors' contributions

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