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Review

Contributions of agroforestry to ecosystem services in the miombo eco-region of eastern and southern Africa

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The miombo, the most extensive tropical woodland formation of Africa with particular ecological and economic importance, is threatened by deforestation, land degradation and loss of biodiversity. Over the past two decades, agroforestry has been studied as one of the integrated natural resource management interventions for addressing various environmental and social problems. This has helped to establish a solid knowledge-base on the functions and capabilities of agroforestry. However, little attempt has been made to synthesize and publicize the knowledge on ecosystem services provided by the various agroforestry practices in southern Africa. This has led to lack of appreciation of the environmental benefits of the practices, and hence less attention being paid to accelerating their adoption and institutionalization in national agricultural and natural resource programmes. The objective of this review was to summarize the state of current knowledge on ecosystem services of agroforestry. From the studies reviewed, it is concluded that agroforestry practices provide (1) provisioning services such as food, source of energy and fodder, (2) regulatory services including microclimate modification, erosion control, mitigation of desertification, carbon sequestration and pest control, and (3) supporting services namely, soil fertility improvement, biodiversity conservation and pollination in the miombo eco-region. The paper also outlines challenges to wider adoption of agroforestry and makes recommendations for future research, development and policy to capitalize on ecosystem services.

Key words: Biodiversity, carbon sequestration, deforestation, fire, soil erosion.

INTRODUCTION

The miombo, the most extensive tropical woodland formation of Africa with particular ecological and economic importance (Kanschik and Becker, 2001), is threatened by desertification processes, deforestation, degradation of land and water resources and loss of biodiversity (Chidumayo, 1987a, b; Desanker, 1996; Desanker et al., 1997; FAO, 2004). The miombo covers some 2.7 million km^2 extending across much of central, eastern and southern Africa including Angola, Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe (Campbell et al., 1996; Lawton, 1978; Kanschik and Becker, 2001). The woodland is adjacent to arid areas and deserts, and serves as a barrier to spreading desertification. This ecosystem directly supports the livelihoods of over 39 million people, including the lowest *per capita* income and highest population growth rates in the world. A further 15 million people living in towns and cities throughout the region also depend on food, fibre, fuelwood and charcoal produced in miombo (Desanker et al., 1997). Deforestation through conversion to farmland, slash and burn agriculture, charcoal burning, bush fires and harvesting of wood (for tobacco curing, smoking fish, timber, poles, etc.) is playing a key role in the modification and transformation of the miombo woodlands landscape (Chidumayo, 1987a, b; Chilufya and Tengnäs, 1996).

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Table 1. Basic data on the extent of land degradation, deforestation and threat to biodiversity in the project countries and the world.

Land degradation #	Malawi	Mozamb	Tanzania	Zambia	Zimbabwe	World	References
% land degraded	61	NA	88	82	91	70	ISRIC/UNEP 1990
Light degradation	3	NA	31	21	53	NA	ISRIC/UNEP 1990
Moderate degradation	58	NA	31	44	39	NA	ISRIC/UNEP 1990
Severe degradation	0	NA	25	17	0	NA	ISRIC/UNEP 1990
Deforestation							
Change in forest area							
% annual change	-2.4	-0.2	-0.2	-2.4	-1.5	-0.22	FAO, 2000
% change in 1990-2000							
Total forest	-22	-2	-2	-21	-14	-2%	WRI, 2003
Natural forest	-23	-2	NA	-21	-15	-4%	WRI, 2003
Plantation forest	2	2	NA	3	2	3%	WRI, 2003
Threat to biodiversity							
Threatened forest trees*	6	10	191	11	4	3443	FAO, 2000
Higher plants*	14	46	239	8	17	NA	IUCN, 2005
Mammals*	7	12	34	11	8	NA	IUCN, 2005
Birds*	13	23	37	12	10	NA	IUCN, 2005
Reptiles*	0	5	5	0	0	NA	IUCN, 2005
Amphibians*	5	3	40	1	6	NA	IUCN, 2005
Fish*	0	21	28	0	0	NA	IUCN, 2005
CO_2 emission							
Total (mt), 1998	7.5×10^5	1.3×10^6	2.2×10^6	1.6×10^6	1.4×10^7	2.4×10^{10}	CDIAC, 2001
% change since 1990	25	34	-2	NA	NA	8	CDIAC, 2001
Per capita, 1998	0.1	0.1	0.1	0.2	1.2	4.1	CDIAC, 2001

NA = data not available; [#]Percentage of the total land area in 2003; *Number of threatened species by 2004

Land degradation threatens not only the future of smallholder agriculture in the miombo but also, economic growth prospects of nations. Some 61 - 91% of the land in the miombo eco-region experiences low to severe land degradation (Table 1). In addition to erosion, conversion of forests has adverse effect on soil organic carbon which include decline in soil structure, soil compaction, reduction in activity and diversity of soil fauna and nutrient depletion (Lal, 2004). Recent evidence demonstrates that deforestation not only influences the soil biological pools and fluxes, but also can modify the association of biological properties of the soils (Nourbakhsh, 2007).

Biodiversity is also under threat as species-rich miombo woodlands have been converted to relatively species-poor farmlands and plantations. The negative effect of deforestation on species richness and diversity in the miombo has been demonstrated by scientific studies (Chidumayo 1987a). Fire and human-created gaps inside forest-reserve also offer opportunities for establishment of invasive species, which are a threat to biodiversity. A severe late fire may destroy the over-storey entirely and the resultant “fire hole” may be rapidly colonized by undesirable thicket shrubs and scramblers (Piearce, 1986). According to the Global Forest Resources Assessment (FAO, 2000), some 4 - 191 forest tree species are endangered in the miombo eco-region. A number of other plant and animal species are also threatened (Table 1). The Figures could be much higher as the full extent of the region's species diversity is unknown, and the consequences of biodiversity loss are tremendous. Recently the miombo has been identified as one of the world’s biodiversity hotspots that need a global conservation strategy (Mittermeier et al., 2003).

Another global concern is the amount of green house gas emission due to conversion of the miombo woodland. Although per capita CO_2 emission levels are lower than the world average, there has been an increase in emissions over the 1990 baseline (Table 1). According to the Intergovernmental Panel on Climate Change (IPCC) reports (2000), land-use changes have been releasing 1.6 - 1.7 Gt carbon annually, which is about a third of the emissions from fossil fuels and cement production. Estimated woody biomass fuel consumption alone amounts to about 48 Tg annually, releasing almost 22 Tg carbon (Desanker et al., 1997). Other natural and anthropogenic processes, such as wildland burning, clearance of land for cultivation, slash-and-burn agriculture and the cultivation of wetlands, also contribute unquantified amounts of trace gases to the atmosphere, as well as altering the nature of the land cover and hydrological processes in the miombo (Desanker et al. 1997).

If agricultural productivity is to be sustained and the miombo woodland conserved, alternative land use strategies are urgently needed. Agroforestry is often as a land use management system that offers solutions to land and forest degradation and to the loss of biodiversity in the tropics (Oke and Odebiyi, 2007). Over the past two decades, agroforestry has been promoted as one of the alternative land use approaches for meeting the conflicting goals of agricultural production and environmental stewardship in southern Africa. Much of the current endeavour in agroforestry development in the miombo has focused on increasing crop yields to meet the needs for human subsistence (Akinnifesi et al., 2006a; Mafongoya et al., 2006). This pressing objective has tended to create management aimed at only maximizing the primary concern of “soil fertility improvement”.

Little attempt has been made to review and synthesize knowledge on the functions, processes and capabilities of agroforestry practices being promoted in southern Africa. This has led to little appreciation of the environmental benefits of agroforestry, and hence less attention being paid to accelerating its adoption in policy making process in the region. This highlights the urgent need for synthesis of the current state of knowledge. We believe such syntheses will aid formulation of evidence-based practical guidelines and policies for the promotion of agroforestry in southern Africa. Therefore, the objective of this review is to avail the state of current knowledge to a wider audience. The review will focus on Malawi, Mozambique, Tanzania, Zambia and Zimbabwe, which are covered by the miombo eco-region and where agroforestry research has been going on for the last two decades. Here, agroforestry is broadly defined as the set of land use practices involving deliberate combination of trees (including shrubs, palms and bamboos) and agricultural crops and/or animals on the same land management unit in some form of spatial arrangement or temporal sequence such that there are significant ecological and economic interactions between tree and agricultural components (Sinclair, 1999). In this definition agroforests, which are complex agroforestry systems looking like and functioning as natural forest ecosystems, but are integrated into agricultural management systems are included (Oke an Odebiyi, 2007). This broader definition is preferred because farmers and forest dwellers, where agroforestry has developed as a significant land use, have tended to practice agroforestry by either integrating many tree species in various productive niches on their farms or by managing biodiverse forest resources.

How Can Agroforestry Contribute To Ecosystem Services?

Humans have always depended on nature for environmental assets like clean water, nutrient cycling and soil formation (Tallis and Kareiva, 2005). These have been called by different names through human history, but are presently gaining global attention as ‘ecosystem services’, defined as the set of diverse ecological functions that are essential to human welfare (Daily, 1997). These services can provide significant, measurable benefits to humanity, potentially providing an economic argument for ecosystem conservation (Kremen et al., 2002). Ecosystems services are becoming so degraded that many regions in the world risk ecological collapse (Tallis and Kareiva, 2005). Yet, their ecological and economic importance is poorly understood (Daily, 1997; Kremen et al., 2002). Generally, ecosystem services are grouped into four categories: (1) provisioning services (2) regulating services, (3) supporting services and (4) cultural services (Tallis and Kareiva, 2005). The discussion below is structured in the context of this classification.

Provisioning Services

Provisioning services are the products obtained from ecosystems, including genetic resources, food, energy, fibre and fresh water.

Food and medicinal products

Non-timber forest products such as fruits, medicinal products, mushrooms, honey, caterpillars, flying termites and bush meat from the miombo woodlands are central to the livelihoods of both rural and urban dwellers (Akinnifesi et al., 2006; Makonda and Gillah, 2007). Indigenous miombo fruits form a staple food during the hunger periods in the agricultural cycle and periods of famine (Akinnifesi et al., 2006; Mangu, 1999). It is argued that without this valuable contribution many children who are most vulnerable and the chief consumers of fruits would be affected by dietary deficiencies (Makombe, 1993). Fruits are used as food, beverages, and sources of essential oils for cooking (Akinnifesi et al., 2006).

Efforts are being made to domesticate, improve and introduce miombo trees into agroforestry systems in southern Africa (Akinnifesi et al., 2006). The achievements of this effort have been recently documented by Akinnifesi et al. (2006). Currently over 6000 farmers are involved in on-farm testing of indigenous fruit trees in the field and homesteads. More than 12,000 farmers were trained in nursery establishment and at least 5000 individual farmers are managing their own nurseries in Malawi, Mozambique, Tanzania, Zambia and Zimbabwe. Adoption by farmers, improved utilization and commercialization of tree products is considered as an incentive for conservation, and as a deterrent to destructive extraction from the miombo.

Over 80% of the rural community in southern Africa also depends on medicinal plants for most of their health needs. The bark extract of fruit trees such as *Sclerocarya birrea* are used for the treatment of diseases such as malaria, dysentery, diarrhoea and rheumatism (Hall et al., 2002). The damage caused by destructive bark harvesting of medicinal plants in miombo woodlands is also huge (Makonda and Gillah, 2007). Because of destructive harvesting and economic pressures, species such as

Prunus africana is now threatened (Cunningham et al., 2002). As the rate of growth for most of the medicinal species are slow, the World Agroforestry Centre (ICRAF) is promoting a deliberate domestication strategy in southern Africa.

The miombo is also a source of other food such as honey and edible caterpillars. Several different types of caterpillars are of increasing socio-economic importance among local people in the miombo (Chidumayo and Mbata, 2002). Mbata et al. (2002) have identified *Gynanisa maja* and *Gonimbrasia zambesina* as the most important commercial species of edible caterpillars in the miombo woodlands of northern Zambia. However, populations of the caterpillars are becoming extinct locally due to unsustainable harvesting of the caterpillars as well as the host plants. The method of harvesting edible caterpillars has in turn contributed to deforestation in the miombo (Holden, 1991). Some of the tree species (e.g. *Anisophyllea boehmii*, *Parinari curatellifolia*, *Sclerocarya birrea*, *Syzygium guineense*, *Uapaca kirkiana*) on which edible caterpillars breed are among the priority indigenous fruit trees selected for domestication in southern Africa. This offers opportunities for integration of edible caterpillars into agroforestry systems (Holden 1991).

Energy

Over 90% of the people in the miombo depend on fuel wood for their energy needs (Chilufya and Tengnäs, 1996). The demand for fuel wood and charcoal continue to rise while growth of trees and shrubs in the miombo occur at a slower rate. Agro-processing operations such as tobacco curing require large quantities of fuel wood. For example, 9 - 37 and 19 - 33 m^3 of wood per ton of tobacco is required for flue and fire-cured tobacco (Geist, 2000). To meet the wood demand of tobacco curing, 140,000 ha of miombo woodlands are annually cleared (Chenje and Johnson 1994). This accounts for 4 - 26% of the deforestation in the miombo eco-region (Geist, 1999a).

Agroforestry practices can provide significant amounts of fuel wood. For example fuelwood production in the *Chagga* home gardens of Tanzania is estimated at 1.5-3 m^3 ha^{-1} $year^{-1}$). Assuming a minimum consumption of 1 m^3 per adult $year^{-1}$ and if each family requires 4-6 m^3 $year^{-1}$, a home garden supplies 25 - 33% of the household fuelwood requirements (Fernandes et al., 1984). Studies have also shown that trees grown in contour strips, rotational woodlots and fallows can produce large quantities of fuel wood (Table 2). For example, *Grevillea robusta* trees planted on contours on an average farm size of 1.64 ha in parts of Tanzania could meet the entire annual household demand for fuel wood (Mwihomeke and Chamshama, 2004). Fuel wood production in rotational woodlots has been studied widely especially in Tanzania (Kimaro et al., 2007; Nyadzi et al., 2003; Otsyina, 1999). After five years rotation, *Acacia crassicarpa* produced about 51 t ha^{-1}) at low nutrient costs (Kimaro et al., 2007). According to Kimaro, on a semi-arid site (Morogoro) in Tanzania, wood productivity in tree fallows averaged three times higher than that produced by typical miombo woodlands. Therefore, adoption of agroforestry practices can significantly reduce deforestation of the miombo by providing fuel wood (Ramadhani et al., 2002).

Per capita firewood consumption for an average family of six dependent on the miombo source is 10 kg per week (Biran et al., 2004). Based on this estimate, wood yields of rotational woodlot systems utilizing species such as *A. crassicarpa* would be sufficient to meet the household fuelwood demands for 7 – 16 years (Kimaro et al., 2007). Such high wood yields exemplify the significance and potential of agroforestry systems in meeting local firewood demands, as well as conserving natural forests that currently serve as the main local source of fuelwood in the region (Kimaro et al., 2007). In the growth and development strategies of countries such as Malawi, production of cash crops like tobacco will continue to be the core sectors of the economy. Agroforestry plantations are probably the only option to meet a major share of the wood demand. Biofuel production from species such as *Jatropha curcas* can also be integrated with agroforestry practices including contour planting, live fences and hedges.

Fodder

The majority of the smallholder farmers in the miombo eco-region keep livestock under rangeland conditions. However, farmers face fodder shortage especially during the dry season when most pastures have dried up. An agroforestry practice called fodder bank, which involves planting fodder trees and shrubs has been instituted in Tanzania, Malawi and Zimbabwe particularly under the smallholder dairy sector. The trees and shrubs are grown largely along boundaries, pathways and across contours to curb soil erosion. The fodder can be used for controlled browsing or feeding to animals in an enclosure in a cut-and carry fashion.

The fodder shrubs are harvested periodically during the growing season and used either as a supplement or a substitute to the more expensive dairy concentrate. Work conducted in East Africa shows that 500 shrubs of species such as *Calliandra calothyrsus* are sufficient to feed one dairy cow for one year when used as a substitute to dairy concentrate (Franzel and Wambugu, 2007). Feeding the shrub forages has also resulted in significantly higher milk quality and cow condition. The fodder shrubs have real potential to alleviate livestock feed shortages, reverse the negative effects of over-grazing and improve on livelihoods of smallholder farmers. Over 200,000 farmers in East and southern Africa have established fodder banks (Chakeredza et al., 2007; Franzel and Wambugu, 2007).

Table 2. Potential annual harvestable fuel produced by trees planted in contour strips (CS), woodlots (WL), coppicing fallows (CF) and non-coppicing fallows (NCF).

Agroforestry practice	Country	Site	Tree species	Age (years)	Quantity (t ha^{-1} Yr^{-1})	References
CS	Tanzania	Lushoto	*Calliandra*	4.5	3.2	Mwihomeke & Chamshama (2004)
		Lushoto	*Casuarina*	4.5	1.8	Mwihomeke & Chamshama (2004)
		Lushoto	*Croton*	4.5	1.5	Mwihomeke & Chamshama (2004)
		Lushoto	*Grevillea*	4.5	2.7	Mwihomeke & Chamshama (2004)
WL	Tanzania	Mganga	*A. crassicarpa*	5	22.4	Otsyina (1999)
		Kiwango	*A. crassicarpa*	4	24	Otsyina (1999)
		Dotto	*A. crassicarpa*	4	19.5	Otsyina (1999)
		Sanania	*A. crassicarpa*	4	21.0	Otsyina (1999)
		Shinyanga	*A. nilotica*	7	1.2	Nyadzi et al. (2003)
		Shinyanga	*A. polycantha*	7	10.1	Nyadzi et al. (2003)
		Shinyanga	*Leucaena*	7	12.7	Nyadzi et al. (2003)
		Morogoro	*A. crassicarpa*	5	51.0	Kimaro et al. (2007)
		Morogoro	*A. mangium*	5	40	Kimaro et al. (2007)
		Morogoro	*A. polycantha*	5	39	Kimaro et al. (2007)
		Morogoro	*A. nilotica*	5	27	Kimaro et al. (2007)
		Morogoro	*Gliricidia*	5	30	Kimaro et al. (2007)
CF	Zambia	Chipata	*Senna*	3	10.7	Ngugi (2002)
		Chipata	*Leucaena*	3	9.7	Ngugi (2002)
		Chipata	*Sesbania*	3	8.0	Ngugi (2002)
		Chipata	*Gliricidia*	3	7.0	Ngugi (2002)
NCF	Zambia	Chipata	*Sesbania*	1-3	7.3	Kwesiga and Coe, 1994

Regulating Services

Regulating services are the benefits obtained from processes, including the regulation of climate, control of flood and some human diseases.

Microclimate modification

Trees and shrubs in agroforestry systems can contribute to better microclimate by providing shade and windbreak. The trees bring about a whole complex of environmental changes, affecting not just available light but also air temperature, humidity, soil temperature, soil moisture content, wind movement, pest and disease complexes (Sileshi et al., 2007a). These factors impact plants, and the effect can be beneficial to a wide array of crops. There is increasing evidence demonstrating the enrichment of natural shade agroforestry with planted legumenose trees is a promising management option to improve yields of crops and keep complex agroforestry systems with their high functional biodiversity (Bos et al., 2007; Rice and Greenberg, 2000).

Farmers in the miombo have traditionally managed and exploited the shady environment under trees. The cultivation of crops under canopies of trees in parklands, homegardens and agroforests are the most notable of traditional agroforestry practices in southern Africa. Specific examples of parklands include the coffee / *Faidherbia albida* system in Tanzania, and the *F. albida* / maize system in southern and central Malawi (Saka et al., 1994). The tree litter and canopy have been documented to influence the microclimate in terms of improved rainfall infiltration, soil structure and microfau-na, reduced evapotranspiration and temperature extremes, and increased relative humidity (Saka et al., 1994). In agroforests and homegardens, crops such as coffee are grown under a canopy of shade trees that may be remnants of the original forest or have been deliberately planted. A typical example of this is the agroforestry sys-tem of the Chagga homegardens in Tanzania (Hemp 2006). The homegardens maintain not only a high biodi-versity, they are an old and very sustainable way of land use that meets several different demands. The high demand for wood, introduction of coffee varieties that are sun-tolerant and low coffee prices on the world market endanger the Chagga homegardens.

Erosion control and soil conservation

Miombo woodlands are being converted to farmland at an annual rate of 2.4% in countries such as Malawi and Zambia and between 2 to 22% of the natural forest area has been lost during 1990-2000 (Table 1). Rooted in colonial interventions, the agricultural economies based on export crops were increasingly drawn into the world market. Tobacco became an important crop in the miombo, and its increased production led to accelerated conversion of woodland areas to crop land and increased wood demand for curing (Chenje and Johnson 1994; Geist, 1999b).

Conversion of woodlands to crop land has led to soil erosion, continuous loss of nutrients and degradation of 15% of the region's land. The severity of recent floods is an indicator that water regulating ecosystem services are stressed. According to a recent analysis, with each 10% decrease in natural forest area in the countries included in the analysis (some from the miombo-ecoregion), flood frequency increased by 4 - 28% (Bradshaw et al., 2007). The annual net nutrient depletion exceeds 30 kg nitrogen and 20 kg potassium ha^{-1} of arable land (Stoorvogel and Smaling, 1990). Malawi alone loses between US$350 million worth of nitrogen and phosphorus through erosion each year, which translates to a gross annual loss of income of US$6.6-19.0 million. This is equivalent to 3% of the agricultural GDP of Malawi (Bojo, 1996). One of the main conceptual foundations of tropical agroforestry is that trees control soil erosion and improve the soil beneath them. Researchers have developed various agroforestry practices including contour planting, contour hedges and woodlots for soil and water conservation. For example *Leucaena* contour hedges have effectively controlled soil erosion on steep slopes in Malawi (Banda et al., 1994).

Mitigating desertification

Desertification has emerged as an environmental crisis of global proportions, currently affecting an estimated 100 to 200 million people, and threatening the lives and livelyhoods of a much larger number. As a result of desertification, persistent reductions in the capacity of ecosystems to provide services such as food, water and other necessities, are leading to a major decline in the well-being of people living in drylands. There is also mounting evidence that desertification leads to adverse impacts on adjacent non-drylands, which may include downstream flooding, impairment of global carbon sequestration capacity, and climate change.

The role of agroforestry in combating desertification has been widely recognized. In arid and semi-arid areas, expansion of forested areas can be viewed as a desertification-reduction activity (IPCC, 2000). Therefore, agroforestry has become one of the activities of the thematic programme network (TPN) in Asia, Africa and Latin America established in the framework of the UNCCD implementation (UNCCD, 2007). In Senegal, two successive phases of the IFAD-initiated agroforestry project to combat desertification have helped improve soil fertility, access to water and regeneration of tree cover. In the Miombo eco-region, little effort has been made to incorporate agroforestry in desertification-reduction activities.

Carbon sequestration

Land use change has a significant impact on below ground carbon (C) stocks in the miombo (Walker and Desanker, 2004). Conversion of woodland to agricultural land depletes terrestrial C stocks by drastically reducing the vegetation C and soil organic carbon (SOC) pools. Introduction of trees in agroforestry arrangements has the potential to increase soil organic matter (SOM) and store significant amounts of C in woody biomass (Unruh et al., 1993; Figure 1). For smallholder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 t C ha^{-1} y^{-1} (Montagnini and Nair, 2004). For example in Zambia, two to 12 year old trees in *Leucaena* spp woodlots stored up to 74 t ha^{-1} in aboveground biomass and 140 t ha^{-1} in the soil (Kaonga, 2005). Coppicing fallows of *Gliricidia sepium*, *Senna siamea*, *Acacia* and *Leucaena* spp. store more C than the short duration fallows of *Tephrosia*, *Sesbania* and pigeon pea (Figure 1). Even simple systems, such as the gliricidia-maize intercropping practiced in Malawi, recycle substantial amounts of above ground C stocks to the soil via the organic materials (Figure 1). Although the average C stocks per unit area of agroforestry systems practiced in southern Africa are lower than what is reported in temperate areas, net organic C intakes of improved fall-ows (1.4 – 4.3 t ha^{-1} yr^{-1}) and woodlots (3.5 – 8.0 t ha^{-1} yr^{-1}) were comparable to those of planted and natural sub-humid ecosystems (Kaonga, 2005).

The analysis of C stocks from various parts of the world shows that 1100 – 2200 Tg C could be removed from the atmosphere over the next 50 years if agroforestry systems are implemented on a global scale (Albrecht and Kandji, 2003). Based on assessments of national and global terrestrial C sinks, Kursten and Burschel (1993) identified two primary mitigatory effects of agroforestry on CO_2 emissions. The first direct near-term effect is C storage in trees and soils through accumulation in live tree biomass (3 - 60 t ha^{-1}), wood products (1 - 100 t ha^{-1}), and SOM (10 - 50 t ha^{-1}), and through protection of existing forests (up to 1000 t ha^{-1}). Secondly, agroforestry has potential to offset greenhouse gas emissions through energy and material substitution, and reduction of fertilizer C foot print. About 5 - 360 t ha^{-1} of greenhouse gas emissions are offset through energy substitution, up to 100 t ha^{-1} through material substitution and 1 - 5 t ha^{-1} through reduction of fertilizer inputs. In addition, agroforestry can enhance C sequestration by decreasing pressure on natural forests, which are a terrestrial C sink.

The total carbon emission from global deforestation which is currently estimated at the rate of 17 million ha y^{-1} is 1600 Tg. Assuming that one hectare of agroforestry could save 5 hectares from deforestation and that agro-

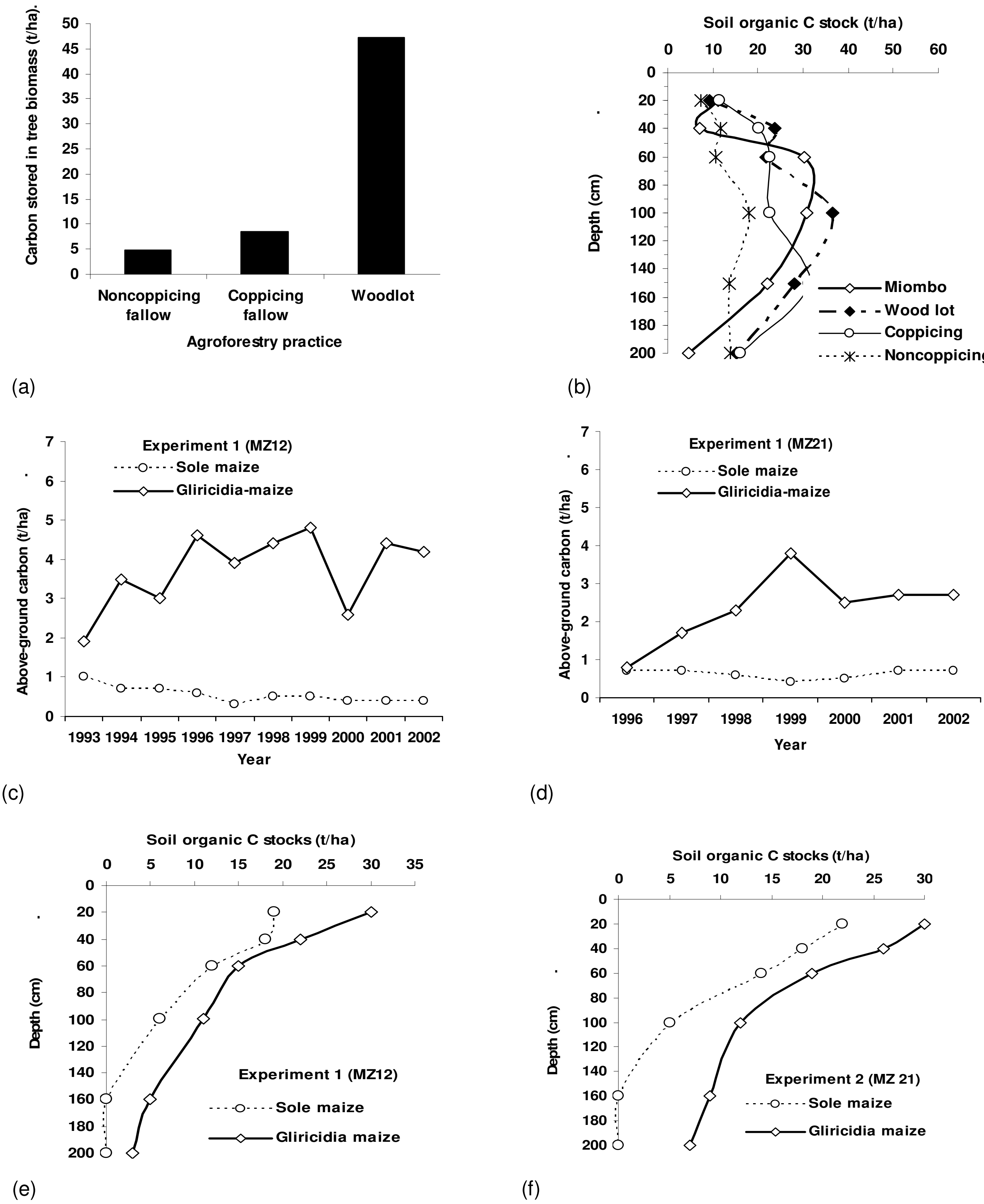

Figure 1. (a) Carbon storage in tree biomass and (b) stocks in the soil depths under woodlots, Miombo woodland, and coppicing and noncoppicing fallows at Msekera, Zambia (Source: Kaonga, 2003); (c & d) organic carbon recycled via the organic materials and (e & f) organic carbon in the soil profile in gliricidia-maize intercropping and sole maize in two experiments at Makoka, Malawi (Source: Makumba, 2003). Woodlots were 12 year old trees of *Leucaeana* species; coppicing fallows were two to 7 year old *Gliricidia*, *Leucaena* spp., *Senna*, *calliandra*; noncoppicing fallows were two-year-old *Sesbania sesban*, *Tephrosia* spp. and pigeon pea (Source: Kaonga, 2003).

forestry systems could be established on up to 2 million hectares annually, a significant portion of C emissions caused by deforestation could be reduced (Palm et al. 1999). There is a growing consensus among scientists that agroforestry is a viable option of enhancing the terrestrial C sink (Lal, 2004) and an environmentally-friendly facility under the Clean Development Mechanism (Antle et al., 2007; Wise and Cacho, 2005). Recent analyses conducted in Australia (Wise and Cacho, 2005) and Peru (Antle et al., 2007) have shown that agroforestry systems are profitable at certain levels of C prices. Little research has been conducted on this aspect in the Miombo eco-region.

Control of crop pests

In the miombo, reduction of agro-biodiversity and continuous monoculture of crops with minimal rotation has a tendency to deplete the soil and for crop pests to become endemic (Geist, 1999b). The shortening of fallow periods may increase the intensity of serious pests including witch weeds (*Striga* spp) (Sileshi et al., 2006). There is growing evidence showing that some agroforestry practices can drastically reduce serious pests of maize such as termites (Sileshi et al., 2005) and weeds (Sileshi et al., 2006) in southern Africa. Agroforestry increases plant diversity and structural complexity, with implications on pest population dynamics. It is an ecological maxim that diversity is closely related to stability because structural heterogeneity and genetic diversity regulate pest populations. However, simply increasing diversity will not necessarily increase the stability of all agro-ecosystems (Sileshi et al., 2007a). In a recent review, Sileshi et al. (2007a) provided specific examples and situations where agroforestry practices reduce pests in the miombo eco-region.

Supporting services

Supporting ecosystem services are those that are necessary for the production of all other ecosystem services. Some examples include biomass production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

Biomass production and soil fertility improvement

Trees planted in contour strips, improved fallows, rotational woodlots and intercrops with crops fix nitrogen and produce large amounts of biomass that improve soil quality. The repeated application of tree biomass to the soil increases soil organic matter that leads to important increases in soil water retention capacity providing good environment for soil microbes and plant nutrients during its decomposition. These services cannot be offered under conventional crop monocultures.

However, nutrient accumulation and export from the site are crucial considerations for sustained productivity of short-rotation high yield agroforestry systems where nutrient removal through frequent biomass harvests may exceed replenishment rates through natural processes such as mineral weathering, atmospheric inputs, and biological fixation (Kimaro et al., 2007). Some studies have considered these issues in the rotational woodlots, and encouraging results have been found. For example, after five years soil organic carbon and exchangeable cation levels in *Acacia polycantha* and *Acacia mangium* woodlots reached close to natural status of miombo woodlands. Initially deficient in soil N and P for maize culture, top soils after fallowing were replenished sufficiently in nutrients to support one cropping season of maize without fertilizer supplementation (Kimaro et al., 2007). These results reflect the high potential of the rotational woodlots to improve maize production after wood harvest.

Several tree-mediated processes determine the extent and rate of soil quality improvement, viz. (1) increased nitrogen (N) input through biological N fixation by legume trees (Mafongoya et al., 2004), (2) enhanced availability of nutrients resulting from production and decomposition of tree biomass (Akinnifesi et al., 2006; Mafongoya et al., 2006; Chirwa et al., 2006), (3) greater uptake and utilization of nutrients from deeper layers of soils by deep-rooted trees (Chirwa et al., 2006), (4) increased activity of soil biota (Sileshi and Mafongoya, 2006a &b), (5) improvement in water dynamics (Chirwa et al., 2007; Phiri et al., 2003). A recent synthesis (Sileshi et al., 2007b) shows that these improvements in soil quality in turn result in improved agricultural productivity and increased yields of staple crops such as maize.

Biodiversity conservation

The accelerated extinction of species may disrupt vital ecosystem processes and services (Sekerciolglu et al., 2004). Reductions in species abundance and richness are also likely to have far-reaching consequences, including the loss of agricultural pest control, and the spread of disease.

Agroforestry systems can be integrated into biodiversity corridors for a variety of uses, such as timber and non-timber forest products, thereby minimizing the exploitation of protected areas (Huang et al., 2002). In areas where the forest has been lost, indigenous fruit and timber trees are grown as companion species to provide environmental services. In southern Cameroon and eastern Brazil, cocoa agroforests have been credited with conserving the biodiversity of the humid forest zone, including birds, ants and other wildlife (Rice and Greenberg, 2000). In Tanzania efforts are being made to train farmers in agro forestry to protect nature reserves. Huang et al (2002) found a significant positive impact of agroforestry on the biodiversity conservation of nature reserves in Tanzania. A study in Zambia has also shown that agroforestry practices harbour more soil invertebrates than a monoculture maize (Sileshi and Mafongoya, 2006a,b). Agroforestry practices also harbours about the same diversity and abundance of soil invertebrates as the miombo woodland (Sileshi and Mafongoya, 2006a, b). This diversity can, in time, provide ecological resilience and contribute to the maintenance of beneficial ecological functions such as pest suppression. Even simple practices such as rotational fallows could suppress insect pests (Sileshi et al., 2005) and weeds (Sileshi et al., 2006).

Pollination

Evidence is mounting on the negative impact of agricultural practices on honey bees and other native bee communities that provide pollination services. The decline of pollination services with agricultural intensification resulted from significant reductions in both diversity and total abundance of native bees. Agricultural intensification may affect functionally important pollinator species disproportionately (Kremen et al., 2002). Restoring pollination services in areas of greatest agricultural intensity would require both reducing insecticide use and restoring native or surrogate vegetation to provide nesting habitat and floral resources for bees when they are not using crops. Currently, communities in the miombo practice traditional honey hunting, which is destructive to both bees and trees. The trees are usually felled in order to extract honey from their hollow trunks. Since cropping is not properly timed, bees are killed off by the excessive fire that is used to subdue them. Agroforestry can improve beekeeping (Chilufya and Tengnäs, 1996) because some trees used in agroforestry produce nectar and pollen and improved bee hives can be introduced in the fruit orchards, woodlots or fodder banks.

Cultural services

Cultural services are the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience, including knowledge systems, social relations, and aesthetic values. In southern Africa, trees play a crucial role in the cultural and spiritual lives of local communities. In some communities in Mozambique, the fruit tree *S. birrea* is considered as a sacred tree and it is never cut when clearing forests (Mangu, 1999). In the Manica Province, both *U. kirkiana* and *S. birrea* are known to be of great importance due to their cultural value. Agroforestry appropriately places the traditional values given by local communities to such trees in the context of conservation and production.

Challenges to Adoption

Despite the remarkable potentials of agroforestry, the level of institutionalization and farmer uptake has generally lagged behind the advances that have been made in scientific and technological development (Ajayi, 2007; Carr 2004). There are several challenges to adoption (Ajayi et al., 2007; Kwesiga et al., 2003). For example adoption of soil fertility management practices by farmers is affected by the biophysical characteristics of the technologies themselves, the individual and household conditions of farmers and, the policy institutional context within which the adoption of technologies take place.

Many smallholder farmers do not have the knowledge and skills to manage agroforestry. They also do not have access to the necessary resources such as seeds. The use of trees for soil fertility or other benefits involves quite new concepts and therefore farmers need some basic education (Carr, 2004). The limited capacity of extension workers in number, time available and knowledge on agroforestry makes it difficult for them to reach a large number of farmers. Lack of appropriate tree species and shortage of tree seeds is another challenge. Access to good quality seed is a persistent constraint to rural farmers (Kwesiga et al., 2003).

Although, the scientific community started promoting agroforestry in the 1980s, the number of National Agricultural Research Systems (NARS) involved in agroforestry research and development (R and D) is small. It is often the NARS which influence Rand D priorities in each country, and if they do not include agroforestry in their national programmes then funds will not be allocated for R and D. Past research and extension efforts have also been biased towards cultivation of exotic tree species and neglected indigenous species. This is probably because indigenous species have not been subjected to positive agricultural or forestry policy (Campbell, 1987).

The debate on the effect of reforestation on water availability and flood control has also contributed to some misconceptions about agroforestry and tree planting in general. For example, there has been gross simplification and generalization that trees consume too much water. This was essentially based on biased geographical data and monoculture plantation of exotic species (Nyberg, 2007). This has been further exaggerated in the popular press, with headlines like “Down with Trees” in the Economist (Anon, 2005). Similarly, some reports (FAO-CIFOR, 2005) argued that the evidence that trees reduce flooding is weak and retaining or regenerating forest areas is an economically dubious strategy from a flood-reduction perspective. However, a comprehensive global analysis (Bradshaw et al., 2007) provides strong evidence that forests do reduce the frequency and severity of floods in developing nations including those in the miombo-ecoregion.

Land tenure has long been considered a critical factor in the management of the miombo woodland as well as adoption and long-term maintenance of agroforestry practices. For example, land tenure and use history significantly influence the rate of woodland recovery and structure of the miombo (Chidumayo, 2002). Lack of secure land tenure and property rights to trees, high labour costs for tree management, poor institutionalization and policy constraints, inadequate funding for research and extension, and lack of economic incentives for environmental services also hinder progress (Ngugi, 2002; Mercer 2004). Adoption of agroforestry is also limited by national and international policies that promote crop monocultures and input subsidies.

Farmers who first tested may also choose not to adopt because the trees did not do well as a result of damage by bush fires (Ajayi and Kwesiga, 2003), pests or diseases (Sileshi et al., 2007c). In the miombo, forest fires are widespread and almost invariably started by people (Ajayi and Kwesiga, 2003; Eriksen, 2007). The prevalence of fire has over time created a degree of fire dependency for the growth, production, regeneration and coexistence of miombo species (Van Wilgen and Scholes, 1997) and as land management tool by people. It is generally agreed that frequent uncontrolled fires are harmful both to vegetation and soil (Chidumayo, 2002; White, 1993) and biodiversity (Sileshi and Mafongoya, 2006c). Much controversy still surrounds discussions on fire utilization and the sustainability of indigenous land management practices. This controversy has been shown to be a result of a discord between official fire policies and actual indigenous fire management practices (Eriksen, 2007).

Pests and diseases represent a major threat to tree planting in general and adoption of agroforestry in particular in the miombo eco-region (Sileshi et al., 2007a, c). Pests and diseases reduce biomass production and diminish the goods and services from trees. Exotic tree species used in agroforestry can also become invasive and affect ecosystem functions and biodiversity (Sileshi et al., 2007a). Some *Acacia*, *Prosopis*, *Casuarina* species, *Tithonia diversifolia* and *Leucaena leucocephala* have potentials to become invasive in southern Africa (Richardson, 1998). It must be noted here that not all alien species are invasive, and not all invasive species may be economically important. However, transformer species—a subset of invasive plants which change the character, condition, form or nature of a natural ecosystem over a substantial area—have profound effects on ecosystem functions and biodiversity (Richardson, 1998).

CONCLUSIONS AND RECOMMENDATIONS

From the work reviewed and discussion presented, it is concluded that when properly designed and strategically located, agroforestry practices can contribute to ecosystem services by mitigating land degradation, climate change and desertification, while adding structural and functional diversity to the agricultural landscapes in the miombo. Where agroforestry is applied to restore degraded lands, it also is likely to provide tree-based goods and services while keeping the land in agricultural production. Agroforestry can be considered an adaptive strategy in areas with increasing climate variability. Agro-forestry practices also serve as viable carbon sinks because they capture and store carbon in soils and biota, reduce deforestation, produce low-carbon biosolids that serve as substitutes for high-carbon fossil fuels, and they reduce carbon losses through erosion. Therefore, agroforestry has tremendous potential to help farmers and governments balance the conflicting goals of agricultural production with environmental stewardship in the miombo.

Agroforestry can also be used to link forest fragments and other critical habitat as part of a broad landscape management strategy that enables species to be conserved. This is common in much of temperate agroforestry, where the major interest is in the aggregated effect of trees at a landscape scale. For example, trees are used in integrated riparian management in the US to filter out nitrates and phosphates from water running into streams and in Australia to lower saline water tables to prevent salinization of agricultural land (Sinclair, 1999). Modest considerations, like mixing tree species, allowing for small clearings and water catchments in planting, and incorporating under storey vegetation can also greatly improve habitat for many animals and create micro-site conditions for plant species. To achieve this, farmers need to be trained and supplied with a range of tree species to suit the needs of different farmers and farm conditions. The participation of poor farmers in the emerging markets for carbon sequestration could potentially contribute to the goals of enhancing productivity and sustainability while reducing poverty. Recent analyses show that participation in carbon contracts could also increase adoption of terraces and agroforestry practices (Antle et al., 2007). Environmental programs similar to those adopted by the European Union that rewards farmers for covering their land by trees also need to be introduced in the miombo-ecoregion.

Combating desertification, conserving biodiversity, and mitigating climate change are linked in many ways. To create system sustainability requires that multiple concerns are addressed simultaneously, which will mean joint implementation of the UN Conventions to Combat Desertification, on Biological Diversity, and Climate Change. This requires an operational shift in thinking and strategy that recognizes the broader working nature of managed landscapes, along with new ways of valuing the productive and protective functions. Agroforestry offers a vital opportunity for the implementation of such a strategy. To bring about a shift in thinking, first national agricultural research organizations need to recognize the contribution of agroforestry to ecosystem services. Existing policies on tree and land tenure as well as fire management also need to be reviewed to make them more responsive to emerging challenges. Regulation of land use and land tenure is crucial to both the proper management of miombo woodland and adoption of agroforestry.

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