Carbon Sequestration Potential of Agroforestry Systems in Africa

Eike Luedeling, Gudeta Sileshi, Tracy Beedy, and Johannes Dietz

Abstract Agroforestry can raise carbon (C) stocks of agricultural systems, and such increases can potentially be sold as CO_2 emission offsets. We assembled information on the biophysical, technical, economic, and practical potential of agroforestry to sequester C for the West African Sahel, East Africa, and Southern Africa. Agroforestry systems (AFS) such as parklands, live fences, and homegardens had substantial C stocks, but only accumulated 0.2–0.8 Mg C ha^{-1} $year^{-1}$. Rotational woodlots (2.2–5.8 Mg C ha^{-1} $year^{-1}$) and possibly improved fallows in Southern Africa sequestered C relatively faster, but only during the fallow phases. Data on soil C are scarce because most studies only compared soil C under different land uses, which provides limited (and sometimes unreliable) information on sequestration rates. Comparing results from different studies is difficult, because no standard protocols exist. Few studies have evaluated the economic potential of agroforestry to sequester C. However, at prices of $10 per Mg CO_2-eq or less, the value of stored C in most systems would be less than $30 ha^{-1} $year^{-1}$, which is a small fraction of annual farm revenue and it needs to cover all transaction measurement reporting and verification costs. Practical constraints to C sequestration (CS) such as land tenure, policy issues, and the opportunity costs incurred by possibly foregoing more profitable land management options have not been fully explored for Africa. For evaluating the challenges and opportunities involved in CS by smallholder farmers, comprehensive studies are needed that explore all C and non-C costs and benefits of agroforestry activities.

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Introduction: Carbon Sequestration Potential

Most agroforestry systems (AFS) have higher carbon (C) stocks than agricultural monocultures, and expansion of agroforestry practices could raise the C stocks of Africa's terrestrial systems (Albrecht and Kandji 2003). On a global level, Dixon et al. (1993) estimated a sequestration potential by forestry and agroforestry practices of about 1 Pg of C per year, corresponding to about 3.7 Pg CO_2, or roughly one-eighth of annual global emissions. This chapter explores the C sequestration (CS) capacity of African AFS, with particular emphasis on the West African Sahel, East Africa, and Southern Africa. This discussion requires at first a clarification of the term 'carbon sequestration potential', which can be and has been interpreted in different ways.

Referring to soil organic C, Ingram and Fernandes (2001) distinguished between 'potential' CS, which is determined by soil characteristics, 'attainable' CS, which accounts for limiting factors, such as net primary productivity and climate, and 'actual' CS, which is defined by reducing factors, such as removal of crop residue, tillage etc. Along the same lines, Cannell (2003) offered a terminology to differentiate between different assessments of the capacity of land management regimes to sequester C, using the terms 'theoretical potential capacity', 'realistic potential capacity', and 'conservative, achievable capacity'.

In agricultural contexts, studies on the CS potential of agroforestry are often conducted with a view to creating opportunities for smallholder farmers to benefit from international C payment schemes. We therefore use a modification of these two terminologies to guide the content of this chapter. Making decisions about the feasibility of CS activities requires an interdisciplinary approach, exploring the biophysical, technical, economic, and practical potential of land management options to sequester C. Figure 1 outlines these concepts and lists the most important constraints that are considered in quantifying the four types of potential.

1. Studies on the biophysical capacity deal with the general geographic setting of a region and use environmental and/or climatic parameters to estimate the additional amount of C that could be stored in terrestrial systems. This is often based on assessments of C stocks in natural vs. actual vegetation, as well as on the potentially available land area.
2. The technical potential explores the management options that are available, or innovative new options, and their effects on system C stocks. Studies on the technical capacity may include assessments of available technical skills and the availability of necessary inputs.
3. The economic potential to sequester C includes both above steps, but considers potential economic constraints, such as the profitability of a system, as well as estimates of opportunity costs or marginal abatement costs.

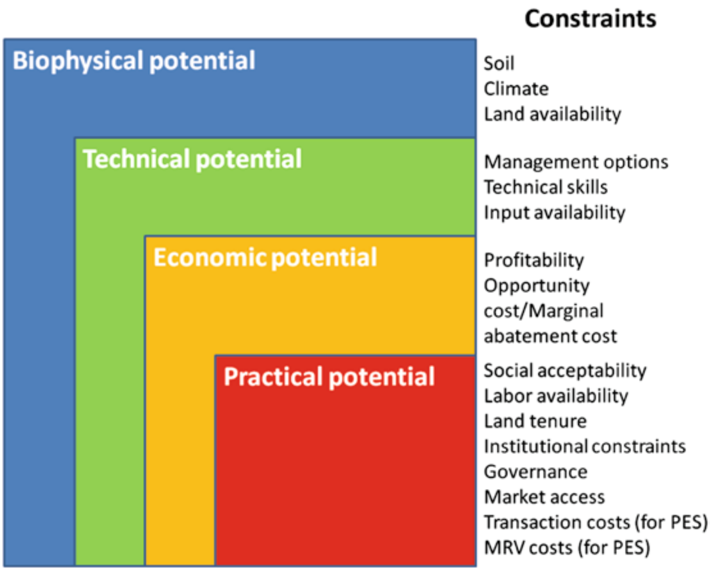

Fig. 1 Schematic illustration of the different types of carbon sequestration potentials, and the constraints that are encountered in their quantification

4. Finally, the practical potential considers additional constraints to system adoption. Examples of these are the social acceptability of the proposed land management option, labor availability, land tenure questions, institutional and governance constraints, as well as market access. For carbon sales and other payment for ecosystem services (PES) schemes, transaction costs, and costs incurred in measurement, reporting, and verification (MRV) can also be important constraints that determine the practical potential.

A thorough assessment of the potential of AFS to sequester C should comprise all four components, but many studies miss one or more of these, limiting the conclusions that can be drawn. For example, a high biophysical capacity to sequester C does not automatically mean that smallholder farmers can benefit from such a scheme, and it is clearly insufficient for guiding development efforts. On the other hand, assessments of the practical capacity are typically very limited in their geographic scope and cannot be used to justify international C payment schemes. A distinction between studies that focus on the different types of potential is therefore imperative for assessing the state of research, and for identifying current knowledge gaps.

In addition to different meanings of the word ‘potential’, the term ‘sequestration’ can also be interpreted in a number of ways. For climate change mitigation purposes, the most effective form of sequestration is the incorporation of C in long-lived C pools in the soil, in permanent biomass, or in long-lived wood products. Carbon sequestered into such pools is more or less permanently removed from the atmosphere. In most cases, however, these C pools are limited in their capacity, restricting CS activities – and potential C payments – to a limited time frame. Establishing trees as permanent structures on agricultural fields is an example of relatively permanent sequestration of C from the atmosphere. Other agroforestry systems may have substantial C accumulation rates, but require most of it to be released again after a few years. In improved fallows or rotational woodlots, especially when trees are grown as fuelwood, net C accumulation in the system is low, or even negative, in spite of fast tree growth. Rather than focusing only on C accumulation rates, it therefore makes more sense to examine net C increase rates, averaged over several rotation cycles or, for systems that reach C saturation, to specify the time frame, over which certain C accumulation rates can be sustained. This review attempts to be as specific as possible about the time frames, but not all studies provide enough information on this.

Carbon Sequestration by Agroforestry Systems in Africa

From a biophysical point of view, Africa's agricultural systems clearly have potential for sequestering additional C. Across different eco-zones, Dixon et al. (1994) estimated a C storage potential of agroforestry and integrated land use approaches of between 12 and 228 Mg C ha^{-1} over a 50 year rotation, corresponding to 0.2–4.6 Mg C ha^{-1} year^{-1}. They provide two values for Africa, 0.6 Mg C ha^{-1} year^{-1} for establishing agroforestry in the tropical highlands of Congo (presumably Brazzaville), which could be realized at a cost of $69 per Mg C, and a sequestration rate of 1.1 Mg C ha^{-1} year^{-1} for a fuelwood system in the Democratic Republic of the Congo (DRC), at a cost of $4 to 12 per Mg C. Cost estimates here include only costs for establishing and maintaining land management systems, neglecting all other expenses. Especially in the latter system, however, net time-averaged sequestration rates appear to be much lower, because the fuelwood that is produced in the system is burnt after harvest, releasing most of the stored C.

Jarecki and Lal (2003) reviewed various studies on the potential of agroforestry systems to store C, listing a range of 0.25–1.58 Mg C ha^{-1} year^{-1} in the soil and 0.98–6.7 Mg C ha^{-1} year^{-1} in aboveground biomass. Their review does not include explicit estimates for Africa, but mentions a potential of 6.2 Mg C ha^{-1} year^{-1} in aboveground storage for new forests in tropical regions and 0.25–0.50 Mg C ha^{-1} year^{-1} in soil and 2–4 Mg C ha^{-1} year^{-1} aboveground for tree plantations in degraded tropical areas.

More detailed reviews collate information from case studies on the CS potential of AFS. Kuersten and Burschel (1993) provide estimates of the amounts of C sequestered by fuelwood production in AFS of 0.5–2.0 Mg C ha^{-1} year^{-1} for shade trees in coffee (*Coffea* spp.) and cacao (*Theobroma cacao* L.), 2.0–3.6 Mg C ha^{-1} year^{-1} for fuelwood plantations, 0.3–2.0 Mg C ha^{-1} year^{-1} for secondary forests, 0.1 Mg C ha^{-1} year^{-1} for trees in corrals and annual crops, and 1.4 Mg C ha^{-1} year^{-1} for living fences. Nair et al. (2009) estimated potential sequestration rates of 5.9 Mg C ha^{-1} year^{-1} for cacao agroforests of Cameroon, 6.3 Mg C ha^{-1} year^{-1} for

Table 1 Carbon sequestration rates reported for agroforestry systems across the West African Sahel, East Africa, and Southern Africa

Activity	Duration (years)	C sequestration rate (Mg C ha^{-1} $year^{-1}$)	Reference
West African Sahel			
Faidherbia albida plantation in Senegal	50	0.22	Tschakert (2004b)
Optimal agricultural intensification, incl. *Leucaena* prunings in Senegal	50	0.27	Tschakert (2004b)
Restoring degraded grassland to woody grassland in Senegal	20	0.77	Woomer et al. (2004b)
Establishment of new parklands in the Sahel	50	0.4	Data from Takimoto et al. (2008b), Tschakert et al. (2004), Woomer et al. (2004b)
East Africa			
Tree planting to restore highly degraded land	25	0.4–0.8	Batjes (2004a)
Intensification of windrows and tree biomass	20	0.8	Henry et al. (2009)
Conversion of cropland to homegardens	20	0.5–0.6	Henry et al. (2009)
Southern Africa			
Regrowth of woodland on abandoned farms in Mozambique	25	0.7	Walker and Desanker (2004)
Coppiced Miombo woodland in Zambia	16	0.5	Stromgaard (1985)
Coppiced Miombo woodland in Zambia	35	0.9	Chidumayo (1997)
Faidherbia albida plantation in Tanzania	6	1.2	Okorio and Maghembe (1994)
F. albida converted to 50 trees/ha	6	0.22	Okorio and Maghembe (1994)
Rotational woodlots in Tanzania	5	2.6–5.8	Nyadzi et al. (2003)
Rotational woodlots in Tanzania (wood C)	5	2.3–5.1	Kimaro (2009)
Rotational woodlots in Zambia	2	2.15–4.75	Kaonga and Bayliss-Smith (2009)

shaded coffee in Togo and between 0.3 and 1.1 Mg C ha^{-1} $year^{-1}$ for agroforestry in the Sahel. The review papers mentioned above do not provide information on the time-frames, over which the stated sequestration rates can be sustained.

The wide range of estimates in the case studies collected in these reviews may be caused by summarizing studies of different types of potential and by consideration of different C pools. Most reviews do not explicitly state the nature of the studies that are listed, and many are mixtures between different types of potential. We therefore focus on three African regions to provide a more comprehensive overview of existing studies. Biophysical and technical potentials are explored for each region separately. Carbon sequestration rates determined for selected tree-based systems across all three regions are shown in Table 1. Due to the scarcity of studies on the economic and practical potentials, we discuss these for all regions together.

West African Sahel

General Setting

The West African Sahel is the transition zone between the Sahara Desert in the North and the Sudan savanna zone in the South, comprising parts of Senegal, Mauritania, Mali, Burkina Faso, Niger, and Nigeria. It is characterized by mean annual rainfall of between 200 and 600 mm, falling during one summer rainy season, which lasts between 2 and 5 months. Annual rainfall amounts are highly variable between years and on inter-decadal scales, leading to recurrent droughts (Hulme 2001). Livelihood strategies in the Sahel therefore revolve around exploitation of the scarce rainfall, with agricultural systems focused on rainfed production of annual crops, such as maize (*Zea mays* L.), millets, peanut (*Arachis hypogaea* L.), and cowpea (*Vigna unguiculata* (L.) Walp.) or on extensive livestock production in nomadic systems. Agroforestry has a long history in this region, and traditional alongside modern improved systems are in existence. Traditional agroforestry parkland systems dominate the landscape in many parts of the Sahel (Boffa 1999), and novel practices such as live fences and fodder banks are being promoted.

Compared to the global average or even other parts of Africa, C storage potential in Sahelian agroecosystems is relatively low, due to harsh environmental conditions, with high temperatures and low precipitation restricting net primary productivity and thus the supply of C that can be sequestered (Batjes 2001). Hanan et al. (1998) measured an increment in biomass of about 5 Mg ha^{-1} $year^{-1}$ (corresponding to about 2.5 Mg C ha^{-1} $year^{-1}$ at 50% C in biomass) in a Sahelian fallow savanna in Niger. While raising C uptake rates may be possible, many land management options tend to decrease C stocks. In particular when the soil is tilled, soil organic matter is quickly decomposed, lowering C stocks substantially below those of natural systems (Batjes 2001; Tieszen et al. 2004).

Projected climate change in the Sahel may exert additional pressure on system C stocks. While future projections for this region disagree substantially, the majority of projections indicate a drier and hotter climate (Tieszen et al. 2004), which will likely reduce equilibrium C levels, even in the absence of cultivation (Batjes 2001). Lufafa et al. (2008) estimated soil organic carbon (SOC) losses between 21% and 23% in Senegal's Peanut Basin for two climate change scenarios. Adverse impacts on crop yields are also likely (Liu et al. 2004; Tieszen et al. 2004). Woomer et al. (2004a) reported that net losses in C stocks in response to climate change have already occurred in various ecozones of Senegal. On a related note, Gijsbers et al. (1994) and Maranz (2009) reported that existing agroforestry parklands are degrading, which may be attributable to a decline in environmental suitability due to recent climate change (Maranz 2009). Agroforestry and other land management practices may have potential to counteract current trends towards lower C stocks (Batjes 2001; Woomer et al. 2004b). The recent, farmer-driven regeneration or establishment of parklands in parts of Niger (Reij et al. 2009) and the introduction of irrigated AFS along the Senegal River (Venema et al. 1997) are promising steps in this direction.

Biophysical Potential to Sequester Carbon

General estimates of C stocks in the Sahelian ecosystems are difficult, because of the strong dependence of C stocks on environmental conditions. In particular, the soil type is a primary determinant of system C stocks. Batjes (2001) reported large differences in C stock between soil types, even under the same land use. In Senegal, the top meter of a rice (*Oryza sativa* L.) field on a Gleyic Cambisol (US Taxonomy: Tropepts, Inceptisols) may store 34 Mg C ha^{-1}, whereas the same land use of a Dystric Gleysol (Aquepts, Inceptisols) may have 65 Mg C ha^{-1}. Combined with short grassland, soil C stocks in the top meter of a rice field on a Dystric Fluvisol (Entisols) may even reach 301 Mg C ha^{-1}.

It has been argued that not all C in an ecosystem can be considered sequestered, because of widely variable turnover rates among different C pools. Batjes (2001) distinguished seven different soil C pools, with turnover times ranging from 0.1 to 3,000 years. Simpler models distinguish only between stable and labile C pools (Traoré et al. 2008). The turnover time of aboveground C stocks also varies substantially, with annual crops being harvested every year, intensively used trees persisting for up to 10 years, and structural elements of traditional agroforestry and forestry systems remaining in place for many decades. Ideally, ecosystem scale and time-averaged C accounting, in particular when the focus is on climate change mitigation, would consider such differences in C pool stability.

Nevertheless, most studies to date have focused on quantifying total system C stocks, soil C stocks, and/or C stored in aboveground biomass. Figure 2 summarizes results from seven studies, investigating C stocks in a range of natural and agricultural ecosystems of the Sahel. Takimoto et al. (2008b; a in Fig. 2) investigated various agroforestry systems in Ségou, Mali, reporting C stocks (including the top 40 cm of the soil) of 70.8 Mg C ha^{-1} in parklands dominated by *Faidherbia albida* (Delile) A. Chev., which was almost twice as high as when the dominant species was *Vitellaria paradoxa* C.F. Gaertn. Carbon stocks in live fence systems and fodder banks were substantially lower (Takimoto et al. 2008b). Woomer et al. (2004a; b in Fig. 2) determined C stocks in 16 ecosystem types along a transect through Senegal, and reported C stocks from 11 to 112 Mg C ha^{-1}, with lowest values in degraded or cultivated land, followed by pastures, fallow plots, parkland, woodland, and forest. Liu et al. (2004; c in Fig. 2) measured C stocks in different ecosystem types in Senegal, and reported 31.8–52.1 Mg C ha^{-1} for cropland, parklands, and fallows with trees. Tschakert (2004a; d in Fig. 2) estimated total system C stocks of 28 Mg C ha^{-1} in the Old Peanut Basin in Senegal, with 11 Mg C ha^{-1} stored in the top 20 cm of the soil and 6.3 Mg C ha^{-1} in trees. She found that parklands on average contained 9.3 Mg C ha^{-1} more than cultivated land. Finally, Woomer et al. (2004b; e in Fig. 2), investigated C stocks across a range of grasslands and silvopastoral systems along a climate gradient covering the Sahelian transition in Senegal. With increasing aridity, they found that total system C declined from 31.9 Mg C ha^{-1} in shrubland with scattered trees to 19.4 Mg C ha^{-1} in grasslands with scattered shrubs and 12.0 Mg C ha^{-1} in degraded grasslands at the arid end of their transect. It should

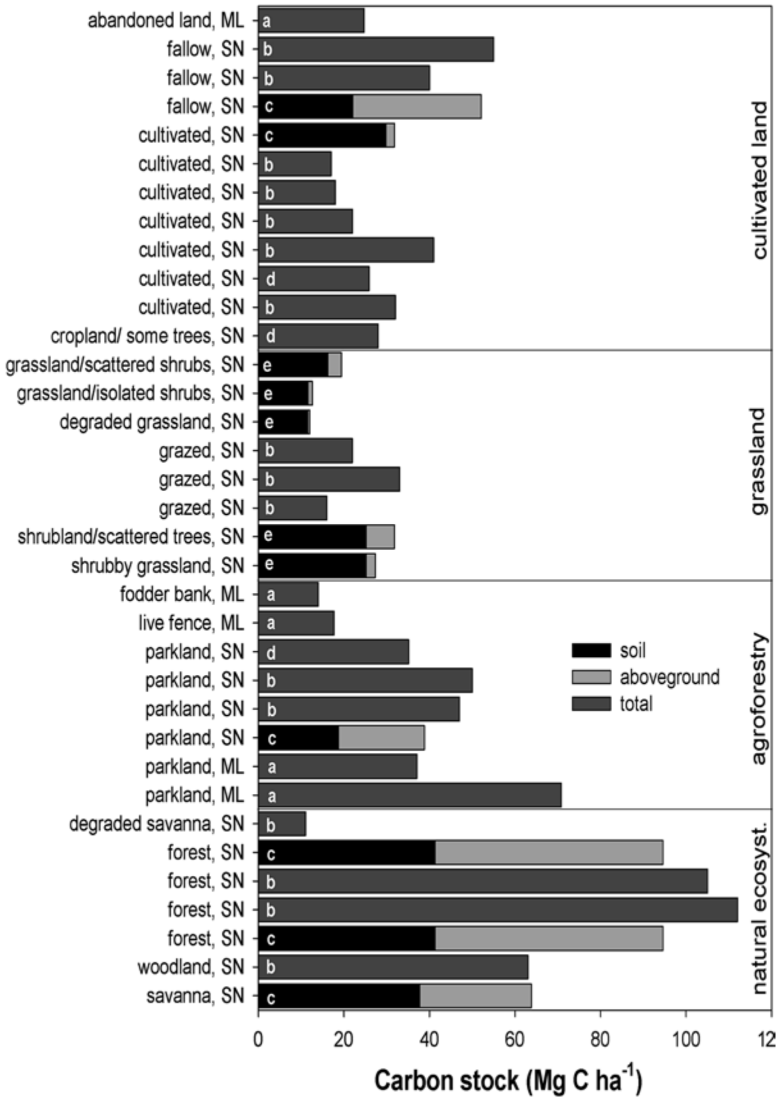

Fig. 2 Carbon stocks in natural and cultivated ecosystems of the Sahel. *ML* Mali, *SN* Senegal. Data sources: a=Takimoto et al. (2008b), b=Woomer et al. (2004a), c=Liu et al. (2004), d=Tschakert (2004a), e=Woomer et al. (2004b)

be noted that in all these studies, C stocks are a result not only of management, but also of site-specific pedological and climatic conditions. Conclusions about the effects of management on C stocks should thus be drawn with caution.

Climates, ecosystem types, and environmental conditions among all these study sites were variable and so were the sampling protocols. For example, the depth to which soil was included was variable and aboveground biomass was determined using different allometric equations, which in some cases were transferred from a different environment due to the lack of site-specific equations. Nevertheless, the wide range of C stock estimates gives an impression of the variation encountered in the field and the difficulty of extrapolating results beyond the immediate sampling sites. It should also be noted that most estimates listed in this section are empirically derived and include the confounding effects of site-specific soil and climate conditions. For deriving the technical potential, different management systems should be compared under similar environmental conditions for a better indication of the effect of individual land use options.

Technical Potential to Sequester Carbon

A wide range of management options can have substantial impacts on C stocks in natural and agricultural ecosystems, when implemented over a sufficiently long time scale. Judging the effectiveness of such a management option for CS, and ultimately the potential of farmers to reap benefits from C payments, requires consideration of both the total effect they may have and the time needed to achieve this effect. Doraiswamy et al. (2007) modeled the effect of various management regimes on soil C stocks in agricultural systems in Mali. In this study, the effect of 25 years of continuous conventional agriculture was a net loss of between 0.5 and 0.7 Mg C ha^{-1}, across four different crops. The best management option in their study, ridge cultivation with incorporation of crop residue and increased fertilization produced net gains between 1.5 and 3.0 Mg C ha^{-1}. Since treatments had to be implemented for 25 years to obtain these results, the amount of C that could theoretically be marketed amounted to less than 0.15 Mg ha^{-1} $year^{-1}$ in all treatments (Doraiswamy et al. 2007).

Tschakert (2004b) used the CENTURY model to evaluate 25 management options on C stocks in the Old Peanut Basin in Senegal. During the first 25 years, net C changes amounted to between −3.2 Mg C ha^{-1} and +10.8 Mg C ha^{-1}. The highest gains were achieved by ‘optimal’ agricultural intensification (crop rotation, fallow, manure, *Leucaena* prunings, and increased fertilization), followed by plantation of *F. albida* at 250–300 trees per hectare (+5.8 Mg C ha^{-1}). Net C changes thus ranged between −0.13 and +0.43 Mg C ha^{-1} $year^{-1}$. During the second 25 year period of maintaining the same management options, C changes decreased substantially for all management options (−0.74 to +5.30 Mg C ha^{-1}). Over the entire simulation period, annual C gains were thus 0.22 Mg C ha^{-1} $year^{-1}$ for *F. albida* plantations and 0.27 Mg C ha^{-1} $year^{-1}$ for ‘optimal agricultural intensification’.

Woomer et al. (2004b) estimated that restoring degraded grasslands in Senegal to woody grasslands over a 20-year time frame may sequester up to 0.77 Mg C ha^{-1} $year^{-1}$. Establishing new parkland agroforestry systems may sequester about 20 Mg C ha^{-1} in addition to C stored in continuous cropland (averaging data from Takimoto et al. 2008b; Tschakert et al. 2004; Woomer et al. 2004b). Assuming 50 years to reach potential C stocks, the annual C stock increment could be fixed at about 0.4 Mg C ha^{-1} $year^{-1}$.

Takimoto et al. (2008a) concluded that further substantial increases in C stocks would not be feasible for existing parkland systems. In all these studies, none of the investigated management options, including agroforestry practices, sequestered more than 0.8 Mg C ha^{-1} $year^{-1}$ (Table 1).

East Africa

General Setting

The East African region extends across Kenya, Uganda, Rwanda, and northern Tanzania. It is comprised ecologically of a narrow coastal strip, arid deserts, semi-arid savannas, and the highlands region, which is densely populated and predominantly used for intensive agriculture. The savanna region is characterized by scarce and irregular rainfall and predominantly used as grazing land. Net primary productivity in this environment has been estimated at 6.2 Mg C ha^{-1} $year^{-1}$ (e.g. Nairobi National Park: Long et al. 1989), but net increases in C stocks are relatively low. Because establishing trees in this environment would require irrigation, agroforestry is not commonly practiced. In contrast, farmers in the East African Highlands practice a wide variety of AFS. Shade trees in coffee plantations, shelter belts (windbreaks) around homesteads and agricultural fields (Stigter et al. 2002), fruit trees, and woodlots on scarce fallow or infertile patches of land are common features of land use systems. Among the most intensively managed AFS in this region are the multi-story Chagga homegardens in northern Tanzania (Fernandes et al. 1985; Hemp 2006).

Biophysical Potential to Sequester Carbon

Because most pure cropping systems have negligible time-averaged C stock changes in aboveground vegetation, tree C stocks can be used to approximate aboveground C gains as a consequence of tree introduction. Studies on biomass in the highly heterogeneous agroforestry-dominated landscapes of the East African highlands are scarce. Glenday (2008) computed a C stock of 19 Mg C ha^{-1} in aboveground biomass for AFS around the Arabuke Sokoke forest on the Kenyan coast, a value that equals the one for woodlands in the same study. Tree planting has also been explored as an option for restoring highly degraded land, where it can sequester 0.4–0.8 Mg C ha^{-1} $year^{-1}$ (Batjes 2004a). For Kenya, Batjes (2004b) integrated CS estimates from various sources to arrive at potential C stock increases between 0 and 0.5 Mg C ha^{-1} $year^{-1}$, for seven agroclimatic zones in the country. For three different scenarios, in which he assumed that improved management practices are introduced on between 10% and 30% of current croplands and on 5–15% of current grasslands. For all of Kenya, he estimated a CS potential of between 5.8 and 9.7 Tg C over 25 years, or 0.23–0.39 Tg C $year^{-1}$.

Technical Potential to Sequester Carbon

Putting the biophysical capacity of C sequestration into a realistic perspective, Henry et al. (2009) estimated current C stocks of 9–11 Mg C ha^{-1} on average for the agroforestry landscapes of Western Kenya. These stocks could be raised by about 16 Mg C ha^{-1} over 20 years or 0.8 Mg C ha^{-1} year^{-1}, on average across seven land use types including the introduction and intensification of hedgerows. In their detailed study, Henry et al. (2009) distinguished between several spatially explicit land use types and assessed their potential of tree intensification. Assuming across the board a 20 year time frame for such transitions, they showed that windrows are currently almost at their maximum capacities, while woodlots have the potential to sequester 1.4–3.2 Mg C ha^{-1} year^{-1} and homegardens 0.20–0.25 Mg C ha^{-1} year^{-1}, if more trees were introduced. Conversion from food crops to homegardens would result in an aboveground biomass increase of 0.5–0.6 Mg C ha^{-1} year^{-1}.

Southern Africa

Agro-Environmental Setting

In Southern Africa, agroforestry research over the past two decades has mainly focused on Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe. Within these countries, efforts have concentrated on the upland plateau zone, which lies between 600 and 1,200 m above sea level. Mean annual rainfall ranges from 500 to 1,200 mm, mainly falling during a single rainy season between December and April, followed by a dry season of 7–8 months duration. Rainfall is greatly variable both within the rainy season and between years, in particular in the drier parts of the region.

The dominant vegetation type is Miombo woodland, the world's largest savanna region covering some 2.7 million km^2 (Campbell et al. 1996; Kanschik and Becker 2001; Lawton 1978). It is comprised of slow growing mainly deciduous trees that form a 15 to 20-m high light-but-closed canopy above a forest floor covered by grasses (Lawton 1978). The traditional land use in this region is slash and burn shifting cultivation, with cropping periods of 3–5 years followed by bush fallow phases of 10–20 years (Nhantumbo et al. 2009). In densely populated areas, shortening fallow periods have led to decreases in soil fertility (Chidumayo 1987; Matthews et al. 1992) and to expansion of farming activities to marginal lands (Abbot and Homewood 1999). Agricultural systems consist mainly of continuous maize-mixed cropping and extensive production of cattle and goats (Chakeredza et al. 2007).

Farmers in Southern Africa use a wide range of AFS, including both traditional and improved practices (Akinnifesi et al. 2008; Campbell et al. 1991; Sinclair 1999). Improved practices that are developed and promoted by researchers and development agencies include various options of fertilizer (Akinnifesi et al. 2008), fruit, fodder (Chakeredza et al. 2007) and fuelwood trees. Traditional agroforestry practices include intensive intercropping in highly diversified, multi-story homegardens, as well as various other systems that integrate trees with food or cash crops.

In some systems, trees are recruited from the natural tree population, and cropping systems resemble the parklands of the West African Sahel. Such systems are common in Malawi, Tanzania, Zambia, and Zimbabwe (Boffa 1999; Campbell et al. 1991). They include the *Faidherbia*/coffee system in Tanzania, and the *Faidherbia*/maize system in riparian settings in Malawi, Zambia, and Zimbabwe (Akinnifesi et al. 2008; Campbell et al. 1991). In other settings, trees are deliberately planted along farm and field boundaries, on soil conservation structures and as terrace risers. Many farmers practice relay fallow intercropping, in which fast growing nitrogen-fixing trees or shrubs (e.g. *Sesbania* spp., *Tephrosia* spp. or *Cajanus cajan* (L.) Millsp. and *Crotalaria* spp.) are planted into a field when annual crops have already been well established (Akinnifesi et al. 2008). Such improved fallows can also take the shape of rotational woodlots (Akinnifesi et al. 2008; Sileshi et al. 2008), in which leguminous trees are grown for about 5 years, then harvested and replaced by food crops (Nyadzi et al. 2003). Another common form of agroforestry is permanent tree-cereal intercropping. Trees in such systems are typically leguminous coppicing species, which are cut regularly. Leaves and twigs are incorporated into the soil to increase soil fertility (Sileshi et al. 2008). The best known manifestation of such a system is the intercropping of *Gliricidia sepium* (Jack.) Kunth. ex Walp. with maize in Malawi and Zambia (Akinnifesi et al. 2008; Sileshi and Mafongoya 2006). In Southern Africa, agroforestry trees provide a range of products and ecosystem services, such as soil fertility, fuelwood, poles, fruits, or shade.

Biophysical Capacity to Sequester Carbon

Carbon stocks of natural and agricultural ecosystems are generally lower than potential stocks, due to a range of human activities, such as C-depleting farming practices (e.g. ridging of soils, burning of crop residues, and inadequate fertilizer use), charcoal production, bush fires (Eriksen 2007) and wood harvesting (Abbot and Homewood 1999; Chidumayo 1987, 1997). In particular in comparison with undisturbed Miombo woodland, C stocks in agricultural systems are low (Walker and Desanker 2004; Williams et al. 2008). Conversion of Miombo woodland to agriculture in Mozambique reduced stem wood C stocks by 19.0 Mg C ha^{-1} and total C stocks by 23% (Williams et al. 2008). In Malawi, such conversion reduced C stocks in the top 150 cm of soil from 82.5 Mg C ha^{-1} to 49.0 Mg C ha^{-1} in fallow land and to 52.2 Mg C ha^{-1} in agricultural soil (Walker and Desanker 2004). Following clearing, Solomon et al. (2000) reported a 56% reduction of soil C content in the cultivated fields in a semiarid area in Tanzania. Reintroducing trees into the landscape can restore some of the lost C. In Mozambique, Williams et al. (2008) showed that on farmland that had been abandoned for more than 20 years, stem C stocks were at 15.7 Mg C ha^{-1} almost as high as in protected woodland (19.0 Mg C ha^{-1}). During 2–25 years of re-growth, wood C stocks accumulated at 0.7 Mg C ha^{-1} $year^{-1}$

in Mozambique (Walker and Desanker 2004). Similarly, mean annual increment was 0.5 Mg C ha^{-1} year^{-1} in 16-year old coppiced Miombo woodland in northern Zambia (Stromgaard 1985) and 0.9 Mg C ha^{-1} year^{-1} over 35 years (Chidumayo 1997). According to Williams et al. (2008) soil C stocks in the top 0.3 m on abandoned land had a narrower range (21–74 Mg C ha^{-1}) than stocks in the Miombo woodland soils (18–140 Mg C ha^{-1}) and with a median C stock of 44.9 Mg C ha^{-1} had reached 78% of median C stocks in Miombo soils (57.9 Mg C ha^{-1}) (Williams et al. 2008). Agroforestry practices are designed to raise system C levels without requiring abandonment of crop production.

Technical Capacity to Sequester Carbon

Although the C sequestration potential of parkland systems in Southern Africa has not yet been studied extensively, these systems are believed to store substantial amounts of C. *Faidherbia albida* at Morogoro, Tanzania accumulated 1.2 Mg C ha^{-1} year^{-1} during 6 years after planting at 6 m spacing (Okorio and Maghembe 1994). If calculated at 50 trees ha^{-1} density, which is more realistic for an agroforestry setting, this C accumulation would amount to an annual rate of 0.22 Mg C ha^{-1}.

Nyadzi et al. (2003) compared the performance of different tree species in rotational woodlots in Tabora and Shinyanga in Tanzania reporting biomass accumulation in the wood between 9.6 and 40.9 Mg biomass ha^{-1} over 5 years, corresponding to mean C accumulation rates between 2.6 and 5.8 Mg C ha^{-1} year^{-1} (assuming 50% C in biomass). In Tanzania, C sequestered in wood ranged from 11.6 Mg C ha^{-1} in *Acacia nilotica* (L) Del. and *A. auriculiformis* A. Cunn. ex Benth. to 25.5 Mg C ha^{-1} in *A. crassicarpa* A. Cunn. ex Benth. after 5 years (Kimaro 2009). The resulting stocks were comparable with wood C (19 Mg C ha^{-1}) reported from protected Miombo forests in Mozambique (Williams et al. 2008). Wood C accumulation rates ranged between 2.3 Mg C ha^{-1} year^{-1} under *A. nilotica* and 5.1 Mg C ha^{-1} year^{-1} under *A. crassicarpa* (Kimaro 2009). These figures are higher than the 1.5–3.5 Mg C ha^{-1} year^{-1} estimated for smallholder AFS in the tropics (Montagnini and Nair 2004), but these rates are of course only reached during the woodlot fallow phases. Soil organic C stocks (within 0–30 cm depth) under 5 year old rotational woodlots (15.8–25.6 Mg C ha^{-1}) in Morogoro were higher than in soils that had been continuously cropped for the same time period (13 Mg ha^{-1}) and fallowed Miombo soils (9–15 Mg C ha^{-1}: Kimaro 2009). However, because initial C stocks were not measured in this study, inferring sequestration rates is not possible.

Kaonga and Bayliss-Smith (2009) compared woodlots of eight different agroforestry species in eastern Zambia, and reported that 4.3–9.5 Mg C ha^{-1} were stored in aboveground biomass after 2 years. Rotational woodlots satisfy household and regional fuelwood demand (Nyadzi et al. 2003) and may thus reduce pressure on adjacent woodland, opening potential opportunities for payments for avoided deforestration and forest degradation. Improved fallows can also store substantial amounts of C in plants and soil (Albrecht and Kandji 2003). In eastern Zambia, Kaonga and Coleman (2008) estimated the annual aboveground plant C input at 2.8 Mg C ha^{-1} $year^{-1}$ for *Tephrosia vogelii* Hook.f., 2.7 Mg C ha^{-1} $year^{-1}$ for *Sesbania sesban* (L.) Merr. and 2.5 Mg C ha^{-1} $year^{-1}$ for *C. cajan*, which was comparable with 2.7 Mg C ha^{-1} $year^{-1}$ recorded for fully fertilized maize. Estimated total SOC stocks under these species were higher at 27.3–31.2 Mg C ha^{-1} (Table 1; Kaonga and Coleman 2008) than under fully fertilized maize (26.2 Mg C ha^{-1}) and unfertilized maize (22.2 Mg C ha^{-1}).

Makumba et al. (2007) compared C sequestration in two fields of *Gliricidia*-maize intercropping conducted for 7 and 10 years with continuous cropping of sole maize. Carbon stocks in the top 200 cm of the soil were about twice as high in the intercropping system as in sole maize. In addition, tree stumps and structural roots stored a total of 17 Mg ha^{-1} of C after 7 years of intercropping (Makumba et al. 2007).

Economic Potential of Carbon Sequestration in Africa

Little work has been done on the economic potential of CS activities. However, rough estimates of the economic benefits that farmers may be able to derive from different kinds of C-sequestering agroforestry practices can be calculated based on a few relatively straightforward factors. The value of C that is sequestered annually depends on the C accumulation rate and the sale price of the C (Fig. 3). Since C prices vary widely among sequestration schemes and future C prices are uncertain, it seems sensible to calculate benefits for a range of values.

While the C value can relatively easily be computed, other economic factors are more site-specific and difficult to estimate. Costs of participating in C markets must be subtracted from the total C value. These costs include expenses for MRV of sequestered C, the cost of registering the C project, and possibly additional transaction costs incurred by C marketing. An economic budget must also include the costs of planting or protecting trees or changing management practices in other ways. Added benefits from higher system C, such as higher crop yield potential due to higher soil organic matter contents, should also be taken into account. Finally, total profit from the C sequestration activity, including the value of all goods that are produced should be compared with profits that could be derived from other activities. Where these opportunity costs, the income foregone by choosing the high C management option, are higher than the profit from the high-CS system, adopting this system may not ultimately benefit farmers.

Most factors are difficult to estimate and require site-specific research, modeling and a range of assumptions. It is, however, relatively easy to estimate C values by multiplying sequestration rates by assumed C prices (while correcting for the fact that C prices are commonly given per Mg CO_2-eq, while sequestration rates are often in Mg C). Figure 4 shows C value estimates for typical AFS in Africa. Carbon accumulation rates are taken from the case studies mentioned above, and contours

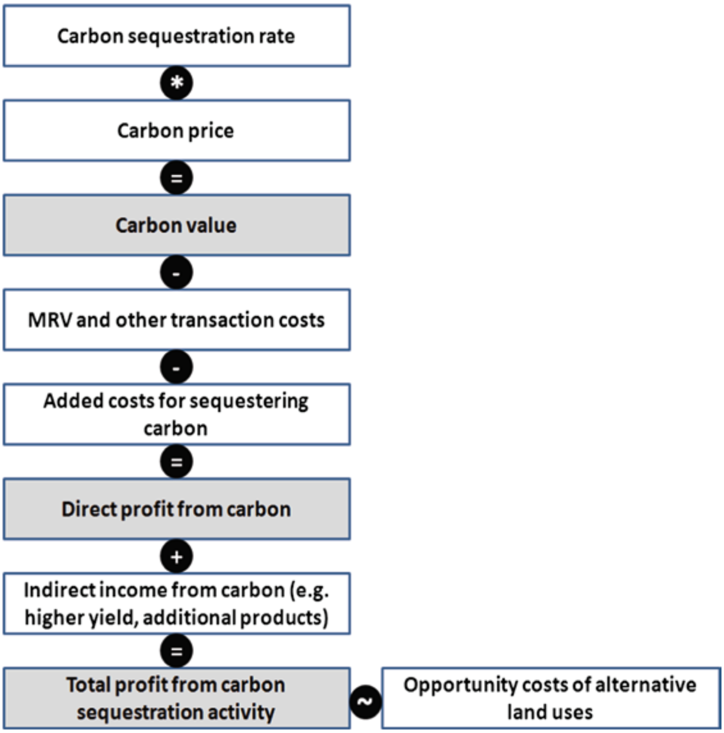

Fig. 3 Factors determining the economic potential of agroforestry systems to sequester carbon

in the figure show C values, as a function of C price (given on the y-axis). For most agroforestry options, C accumulation rates are relatively low, resulting in low C values, in particular at low assumed C prices. Common estimates of C prices in the literature range around 10 USD per Mg CO_2-eq or less, which would translate into C values of less than 30 USD ha^{-1} year^{-1} for typical AFS. The only AFS that were reported to accumulate C at a relatively fast rate were improved fallows and rotational woodlots. At a C price of 10 USD per Mg CO_2-eq, sequestration rates would translate into C values of up to 200 USD ha^{-1} year^{-1}. These values, however, are only produced during the fallow phases of the AFS, after which trees and shrubs are harvested and incorporated into the soil, processed into wood products, or used as fuelwood. Net C accumulation rates, and thus the amount of C that is credibly and permanently (or at least for a long time) sequestered from the atmosphere is thus substantially lower than biomass C buildup suggests. Nyamadzawo et al. (2008) tracked the effects of improved fallow practices on soil C stocks (0–20 cm depth) over two fallow/cropping cycles (2 years improved fallow/3 years cultivation), finding consistently higher soil organic matter contents under rotation than in continuous maize. However, after two full rotations, the improved fallow system had only

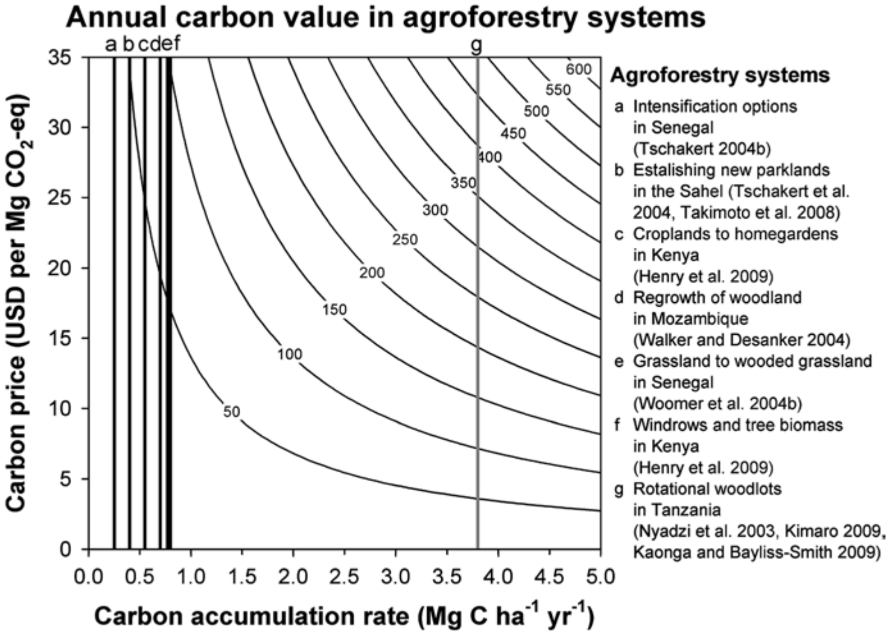

Fig. 4 Potential carbon values (in USD) produced annually by agroforestry systems in Africa, assuming that carbon is sold at international markets. *Black bars* (bars a–f) indicate permanent agroforestry systems, whereas the *grey bar* (bar g) signifies rotation woodlots that are only present for part of the cropping cycle. All bars are *straight lines*, assuming constant CS rates in each AFS, and carbon values for each AFS depend primarily on the carbon price. For example, at a price of 10 USD per Mg CO_2-eq, conversion of croplands to homegardens in Kenya, which can store 0.55 Mg C ha^{-1} $year^{-1}$ (*bar c*), would produce a carbon value of 20 USD $year^{-1}$; at 30 USD per Mg CO_2-eq the value would be 61 USD $year^{-1}$

between 2.2 and 6.6 Mg C ha^{-1} more than the continuous maize system, corresponding to a time-averaged advantage compared to continuous maize of between 0.2 and 0.7 Mg C ha^{-1} $year^{-1}$. Because soils under continuous maize cultivation (the control in this study) likely experienced further depletion of soil C during the study period, the net sequestration rate of improved fallows is even lower. Such considerations will also apply to C dynamics of rotational woodlots. Carbon sequestration rates by such systems depend on processes during the tree and the cultivation phases, as well as the use of the trees. Where trees are processed into long-lived wood products, substantial amounts of C may be sequestered, but when woody biomass is predominantly used as fuelwood, sequestration rates are likely low. Few studies contain sufficient data for calculating time-averaged net CS rates, but we find it unlikely that such rates exceed 1 Mg C ha^{-1} $year^{-1}$, especially for fuelwood systems. It is also worth noting that C finance projects normally only pay for C sequestered *in situ*, and that all C that is removed from the field is considered emitted, even if the wood is preserved elsewhere.

While complete budgets cannot be derived from our back-of-the-envelope calculations, low C values for many AFS indicate that they may not be profitable, unless substantial additional benefits can be produced by the system. Due to transaction and MRV costs, profits from C sales may be quite a bit lower than the net C value produced. Of course, many AFS deliver added benefits, such as yield increases and additional marketable products, and more economic analysis should focus on the importance of C credits in whole farm budgets.

A few studies have explored the economics of CS by African agroforestry in more detail. Henry et al. (2009) found that in East Africa, afforestation is likely among the fastest ways to increase aboveground C stocks, whereas inducing smallholder farmers, with average land holdings of about 1 ha, to plant additional trees without adversely affecting food production is 'a real challenge'. They demonstrate that at the current market price for C and considering average farm sizes in their study area, 140–300 farms (or 170 to >400 ha depending on intensification scenarios) would have to collaborate in C marketing, in order to compensate for the minimum transaction costs incurred by marketing C in Clean Development Mechanism Afforestation/Reforestation (CDM A/R) projects (Henry et al. 2009).

Some site-specific modeling efforts have been undertaken to evaluate the suitability of C sequestration as an income option for farmers in the West African Sahel. Doraiswamy et al. (2007) assumed a carbon price of \$10 per Mg of sequestered C (not CO_2-eq, which is more commonly used), which resulted in annual returns from C sales of between \$0.84 and \$1.46 ha^{-1}. This was between 0.2% and 0.8% of net annual revenue of the modeled farm. In the case of the most economically successful farming option, even a C price 20 times higher than \$10 per Mg C would bring the proportion of farm revenues from C sales to only 4.3%. All these figures assume that no transaction, measurement, reporting, or verification costs are incurred. Tschakert (2004a) also reports low C revenues, amounting to between <\$2 and <\$7 per hectare and year, or between 1% and 4.5% of revenue per hectare (at \$15 per Mg C; once again not CO_2-eq). At a higher C price of \$25 per Mg C, C income would constitute between 1.6% and 7.2% of farm revenue, again without including the costs of C marketing. Assuming a C price of \$42 per Mg C, Takimoto et al. (2008a) calculated that selling C credits would raise the net present value of live fences by \$14 (from \$96 to \$110) and that of fodder banks by \$16.5 (from \$159 to \$175). Carbon revenues would thus amount to between 9 and 13% of net present value. This estimate assumes an accounting method that is favorable to farmers (C revenues drop to 0.2–0.3% of net present value, if the alternative 'tonne-year accounting' is chosen) and that all costs of C marketing are external to landowners.

These figures indicate that payments for CS by agroforestry are unlikely to generate substantial income to smallholder farmers in most cases, unless C payments are combined with payments for other environmental services provided by agroforestry. Carbon prices will also influence the attractiveness of sequestration projects. A macro-economic simulation by Diagana et al. (2007) confirms this impression, finding that the amount of C likely to be sequestered in the Nioro region of Senegal's Peanut Basin ranges between 200 Gg C at a C price of \$0 and 1.3 Tg C at \$200 per Mg C. Future C prices are difficult to predict, but if an efficient global market develops, with abundant participation by small- and large-holder farmers around the world, C prices will likely drop to close to the costs of C sequestration paid by the most efficient sequestration efforts. Carbon is most easily sequestered in ecological zones that are much more productive than the Sahel, e.g. in the humid tropics. It is thus difficult to imagine that at world market prices, C sequestration projects by Sahelian farmers will be competitive. In all studies that we reviewed, C incomes were very low, even when (probably unrealistically) assuming that no costs were incurred by C sales. It is also troubling that, according to the 'additionality' criterion in the Clean Development Mechanism, the most C intensive forms of land use in the region, such as Sahelian parklands, would be excluded because they allow for only little additional C sequestration. From the smallholder perspective, it should also be considered that C sales do not necessarily present a 'win-win' situation, because on Sahelian farms, most resources, including trees, are intensively used. Depending on the opportunity costs of potential income options that are restricted under C sequestration contracts, net benefits compared to a situation without a formal C contract could thus easily turn negative, because farming in the Sahel is often opportunistic and requires farmers to adapt to variable circumstances (Tschakert 2004a).

Practical Potential to Sequester Carbon in Africa

In most situations the practical potential to sequester C is even lower than economic calculations suggest, due to a number of constraints that are often overlooked. Acceptance of new land management options by farmers, for example, has been shown to depend on a variety of factors in addition to the economic bottom line (Ajayi 2007). Even farmers who decide to test a new AFS may choose not to adopt it because of poor tree performance in initial trials, caused by pests, drought, bush fires or other biotic or abiotic factors (Sileshi et al. 2007). Damage of young trees by livestock can also limit adoption rates (Ajayi and Kwesiga 2003).

Commonly encountered constraints to the adoption of tree-based systems also include land tenure, cultural norms, and household power structures in many regions (Chidumayo 2002; German et al. 2009; Mwase et al. 2007; Aquino et al. 2011). For example, land tenure insecurity may result in degradation of open access land and unwillingness of people to plant trees (German et al. 2009; Mwase et al. 2007). Many traditional land use systems include customary land resources, which are exploitable by the entire community through grazing, hunting, settlement areas, crop fields, and graveyards. In Malawi, customary land covers 3.1 million ha and half of the forested area is on customary land, and about two-thirds of the customary land is disturbed (Mwase et al. 2007). The incentive for individuals to plant trees on common land is low, and the distribution of potential benefits from C sales would be complicated. Land tenure has been identified as one of the central impediments to making the CDM work for smallholder farmers (Unruh 2008; Aquino et al. 2011). Moreover, a deficit of information on management options or appropriate inputs may constrain the CS potential. The reasons for this are weak extension capacity, scarcity or lack of appropriate planting material (quality seed, seedling, etc.), and lack of knowledge and skills in tree management in agroforestry.

Even though CS is often mentioned as a means to fight poverty, the poorest households in resource-constrained settings are likely to benefit least from C sales. Studies by Tschakert (2004a, b, 2007) in Senegal indicate that due to the initial investments necessary for implementation of CS activities, poor farmers may not be able to participate in C markets, and if they do, their incomes will be lower than those of rich farmers. Dixon et al. (1994) estimate the costs of establishing productive tree plantings at between \$500 and \$3,000 per hectare, in various parts of the world. Even at the low end of this range, establishment costs would thus probably be too high for most Sahelian farmers. A pro-poor focus rather than a purely market-based approach is thus needed, if smallholder projects are really to help the poor. Such an approach is more likely to be endorsed by a development agency rather than by a more profit-oriented organization, taking away from the idea of C economics more or less automatically leading to enhanced livelihoods of smallholder farmers (Tschakert 2004b). Unfortunately, such socioeconomic considerations have been absent from most CS studies. In the context of relatively food insecure farmers, for whom risk management is of crucial importance, socioeconomic aspects must be considered when planning and studying CS options and potentials. Tschakert and Tappan (2004) therefore called for a farmer-centered approach to CS that includes not only effects of C storage on climate, but also the impacts of the necessary activities on farmers' livelihoods.

The most striking knowledge gap among all CS studies is the lack of efforts to estimate the transaction costs for implementing C projects, as well as the costs of measurement, reporting and verification of the sequestered C. Institutional and governance constraints, land tenure, and market access are also typically neglected. This is understandable, because most of these factors are difficult to study empirically and many cannot reliably be projected. However, analyzing plausible policy scenarios and including estimates of MRV costs into economic analyses would provide insights that are necessary for making justifiable recommendations about the implementation of C schemes. Moreover, the trade-offs incurred by retaining trees for C sequestration vs. using them as fuel, fodder and fertilizer have not been explored adequately.

Conclusions

For many parts of Africa, some data exist for the biophysical and technical potential of agroecosystems to sequester additional C, but important aspects of CS have not been adequately investigated. Many studies have delivered good estimates of aboveground C accumulation in AFS, but numbers for the soil are scarcer and less reliable. While some studies have compared soil C stocks under agroforestry with stocks under different land use types, experimental studies that have compared soil C levels before and after agroforestry establishment are currently lacking.

Such studies, however, are needed to separate the likely build-up of soil C by agroforestry from the decreases effected by, say, continuous (year-after-year) maize cultivation. Estimates of the economic potential of agroforestry to sequester C are only available for very few locations. The few studies that have investigated this in the relatively unproductive ecosystems of the Sahel indicated limited opportunities for farmers to benefit from C markets.

Complete assessments of the practical potential to implement C schemes for smallholders are currently lacking. Without knowledge about the complete array of potentials, ex-ante assessments of the impact that C schemes would have on African livelihoods are currently data-limited. It is quite clear that large-scale implementation of agroforestry practices in Africa would benefit the global climate, but whether such a move would produce benefits for farmers is unclear. Given that in terms of productivity, the African drylands compare unfavorably with most other ecosystems of the world, the chance to generate substantial incomes from C sales is probably quite slim for farmers in such regions, in particular if C prices are determined by international supply and demand dynamics. Without more comprehensive studies that explore CS potentials at all levels, however, such considerations are highly speculative. Laying the groundwork for involving smallholder farmers in international C schemes will require comprehensive, interdisciplinary, and objective assessments of the potential constraints to adoption, as well as the whole array of impacts that C schemes may have on farmers and farming communities.

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