Soil organic carbon sequestration in agroforestry systems. A review

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REVIEW ARTICLE

Soil organic carbon sequestration in agroforestry systems. A review

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Abstract The increase in atmospheric carbon dioxide (CO_2) concentrations due to emissions from fossil fuel combustion is contributing to recent climate change which is among the major challenges facing the world. Agroforestry systems can contribute to slowing down those increases and, thus, contribute to climate change mitigation. Agroforestry refers to the production of crop, livestock, and tree biomass on the same area of land. The soil organic carbon (SOC) pool, in particular, is the only terrestrial pool storing some carbon (C) for millennia which can be deliberately enhanced by agroforestry practices. Up to 2.2 Pg C (1 Pg=10^{15} g) may be sequestered above- and belowground over 50 years in agroforestry systems, but estimations on global land area occupied by agroforestry systems are particularly uncertain. Global areas under tree intercropping, multistrata systems, protective systems, silvopasture, and tree woodlots are estimated at 700, 100, 300, 450, and 50 Mha, respectively. The SOC storage in agroforestry systems is also uncertain and may amount up to 300 Mg C ha^{-1} to 1 m depth. Here, we review and synthesize the current knowledge about SOC sequestration processes and their management in agroforestry systems. The main points are that (1) useful C sequestration in agroforestry systems for climate change mitigation must slow or even reverse the increase in atmospheric concentration of CO_2 by storing some SOC for millennia, (2) soil disturbance must be minimized and tree species with a high root biomass-to-aboveground biomass ratio and/or nitrogen-fixing trees planted when SOC sequestration is among the objectives for establishing the agroforestry system, (3) sequestration rates and the processes contributing to the stabilization of SOC in agroforestry soils need additional data and research, (4) retrospective studies are often missing for rigorous determination of SOC and accurate evaluation of effects of different agroforestry practices on SOC sequestration in soil profiles, and (5) the long-term SOC storage is finite as it depends on the availability of binding sites, i.e., the soil's mineral composition and depth. Based on this improved knowledge, site-specific SOC sequestering agroforestry practices can then be developed.

Keywords Agroforestry systems · Carbon sequestration · Soil organic carbon · Climate change mitigation · Root-derived carbon

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1 Introduction

Global anthropogenic emissions of carbon dioxide (CO_2) to the atmosphere increased to about 9.7 Pg carbon (C) (1 Pg=10^{15} g) in 2012 mainly due to an increase in fossil fuel combustion

(Peters et al. 2013). However, not all of emitted CO_2 accumulates in the atmosphere as land-based sinks take up significant amounts, i.e., about 28 % of anthropogenic CO_2 emissions were taken up on average between 2002 and 2011 (Peters et al. 2012). Managing more efficiently the carbon (C) flows in agricultural ecosystems can particularly reduce anthropogenic CO_2 emissions (Smith et al. 2008). Thus, reducing agriculture's C footprint is central to limiting climate change (Vermeulen et al. 2012). Some agroforestry systems, in particular, have received increased attention regarding their net C sequestration effect by their ability to capture atmospheric CO_2 and store C in plants and soil (Nair 2012a).

Agroforestry refers to the practice of purposeful growing of trees and crops and/or animals, in interacting combinations, for a variety of benefits and services such as increasing crop yields, reducing food insecurity, enhancing environmental services, and resilience of agroecosystems (Fig. 1; Ajayi et al. 2011). Both agriculture and forestry are combined into an integrated agroforestry system to achieve maximum benefits by a greater efficiency in resource such as nutrients, light and water capture, and utilization (Kohli et al. 2008). Agroforestry systems are recognized as an integrated approach for sustainable land use aside from their contribution to climate change adaptation and mitigation (Cubbage et al. 2013; Nair et al. 2009a; Schoeneberger et al. 2012). Globally, an estimated 700, 100, 300, 450, and 50 Mha of land are used for tree intercropping, multistrata systems, protective systems, silvopasture, and tree woodlots, respectively (Nair 2012b). Numerous and diverse agroforestry systems are especially practiced in the tropics because of favorable climatic conditions and various socioeconomic factors. Tropical and temperate agroforestry practices can be grouped under the subgroups (a) tree intercropping, (b) multistrata systems, (c) silvopasture, (d) protective systems, and (e) agroforestry tree woodlots (Nair and Nair 2014). The awareness of agroforestry's potential for climate change adaptation and mitigation in boreal and temperate systems is growing (Nair et al. 2008; Schoeneberger et al. 2012).

Fig. 1 Agroforestry system in Burkina Faso, West Africa: sorghum (*Sorghum bicolor* (L.) Moench) grown under *Faidherbia albida* and *Borassus akeassii* (photo credit Marco Schmidt; licensed under the Creative Commons Attribution-Share Alike 2.5 Generic license)

Growing agroforestry biomass for biopower and biofuels and thereby replacing fossil fuel has also the potential to reduce increases in atmospheric CO_2 (Jose and Bardhan 2012). Thus, agroforestry has been recognized as having the greatest potential for C sequestration of all the land uses analyzed in the Land-Use, Land-Use Change and Forestry report of the IPCC (2000). Agroforestry was also included in global programs such as Reducing Emissions from Deforestation and Forest Degradation including the role of conservation, sustainable management of forests, and enhancement of forest C stocks (REDD+) related to climate change adaptation and mitigation (Nair and Garrity 2012). Further, implementation of some agroforestry systems has been recommended to reduce soil erosion and improve water quality (WBCSD 2010). Agroforestry is a key approach in the integration of climate change adaptation and mitigation objectives, often generating significant co-benefits for local ecosystems and biodiversity, and should be promoted in the voluntary and compliance C markets (Matocha et al. 2012; Stavi and Lal 2013). While providing project financing and a source income to resource-poor farmers and smallholders, agroforestry practices can make a significant contribution to climate change mitigation by C sequestration in vegetation and soil (FAO 2009). However, designing co-benefit smallholder agroforestry projects for climate and development is challenging (Anderson and Zerriffi 2012). In conclusion, land-based C sinks including those in agricultural ecosystems take up about one third of anthropogenic CO_2 emissions. Some practices of agroforestry, i.e., the purposeful growing of trees and crops and/or animals in interacting combinations, have received increased attention for their capability to store C in plants and soil.

The article discusses briefly the meaning of C sequestration for climate change mitigation, the importance of agroforestry trees for soil organic carbon (SOC) sequestration, and compares evidence for C sequestration among different agroforestry systems. It concludes with a discussion of soil and land use management practices having potential to enhance SOC sequestration in agroforestry systems.

2 Carbon sequestration

The potential of agroforestry systems for C sequestration depends on the biologically mediated uptake and conversion of CO_2 into inert, long-lived, C-containing materials, a process which is called biosequestration (U.S. DOE 2008).

Biosequestration temporarily removes C from active cycling. More generally, C sequestration can be defined as the uptake of C-containing substances and, in particular, CO_2 into another reservoir with a longer residence time (IPCC 2007). However, it has become customary for the term C sequestration to imply a contribution to climate change mitigation (Powlson et al. 2011). For this reason, C sequestration in an agroforestry system must slow or even reverse the increase in atmospheric concentration of CO_2. Thus, movement of C from one reservoir in the system to another should be appropriately termed accumulation, whereas an additional transfer of C from the atmosphere into a reservoir of the agroforestry system should be termed sequestration as this process is a genuine contribution to climate change mitigation (Powlson et al. 2011). However, there is little consensus in the literature what the term C sequestration means (Krna and Rapson 2013). The reasons why a specific agroforestry practice contributes to C sequestration at a specific site whereas another practice does not are not well known (Jose and Bardhan 2012).

Some SOC in agroforestry systems may persist for millennia indicating that terrestrial sequestration for climate change mitigation occurs particularly by avoided net SOC losses and the slowly ongoing accumulation of the slowest SOC pool (Mbow et al. 2014; Schmidt et al. 2011; Wutzler and Reichstein 2007). However, there is lack of consensus over the period for which C has to be immobilized in soil before it is considered to be sequestered as a useful contribution to climate change mitigation (Krna and Rapson 2013; Mackey et al. 2013). For climate change mitigation, C may remain stored not just for 100 years, but probably for more than 10,000 years. Specifically, a “pulse” or unit of CO_2 emitted to the atmosphere is only fully removed from the atmosphere so that it no longer interacts with the climate system when it has completely dissolved in the deep ocean. This process requires the concurrent dissolution of carbonate from ocean sediments lasting about 5,000 to 10,000 years and enhanced weathering of silicate rocks lasting around 100,000 years (Mackey et al. 2013). Thus, SOC sequestration requires that C must persist for very long periods of time in soil by stabilization processes that reduce the probability and, therefore, rate of SOC decomposition. The aim of using agroforestry systems for climate change mitigation should be reducing SOC losses and enhancing SOC stabilization as the SOC pool contains organic matter (OM) with radiocarbon ages of 1,000 to more than 10,000 years especially in subsoil horizons (Schmidt et al. 2011). This article focuses on the relationship between agroforestry practices and SOC sequestration causing a net additional long-term removal of CO_2 from the atmosphere as this process is a genuine contribution to climate change mitigation (Stockmann et al. 2013). In conclusion, useful C sequestration in agroforestry systems for climate change mitigation must slow or even reverse the increase in atmospheric concentration of CO_2 by storing some SOC for more than 10,000 years.

3 Importance of trees for soil organic carbon sequestration in agroforestry systems

Previous terrestrial C sequestration efforts have largely focused on adaptive management of existing forests and conservation tillage of croplands (Perry et al. 2008). However, tree-based farm practices such as agroforestry systems are a viable C sequestering option. Agroforestry systems have, in particular, a higher potential to sequester atmospheric CO_2 than the croplands, pastures, or natural grasslands, i.e., treeless land uses they replace, but effects on SOC vary greatly depending on biophysical and socioeconomic characteristics of the system parameters (Nair et al. 2009a; Nair and Nair 2014). The incorporation of trees, in particular, improves soil properties and can result in greater net C sequestration (Young 1997).

3.1 Effects of trees on soil organic carbon

Trees have extensive root systems which can grow deep into the mineral soil. The root-derived C inputs are critical sources for the SOC pool in deeper soil horizons (Kell 2012). Specifically, root-derived C is more likely to be stabilized in the soil by physicochemical interactions with soil particles than shoot-derived C (Rasse et al. 2005). For example, the relative root contribution of European beech (*Fagus sylvatica* L.) to SOC was 1.55 times than that of shoots (Scheu and Schauermann 1994). Similarly, in croplands, total root-derived C contributed between 1.5 times to more than 3 times more C to SOC than shoot-derived C (Johnson et al. 2006). Thus, agroforestry systems store more C in deeper soil layers near trees than away from trees (Nair et al. 2010). However, quantitative information about belowground C inputs in agroforestry systems is scanty (Schroth and Zech 1995).

Aside from deep soil C inputs, another reason for the promotion of SOC sequestration in agroforestry systems is that tree roots have the potential to recover nutrients from below the crop rooting zone. The resulting enhanced tree and crop plant growth by subsequent increase in nitrogen (N) nutrition may result in an increase in SOC sequestration (van Noordwijk et al. 1996). Similar, mixed plantings with N-fixing trees may cause higher biomass production and, thus, SOC sequestration and pools particularly in deeper soil horizons as N may promote humification rather than decay, but SOC and N interactions are not entirely understood (Gärdenäs et al. 2011; Nair et al. 2009a). Also, changes in microbial decomposer community composition under N-fixing trees may result in greater retention of relatively stable SOC (Resh et al. 2002). N-fixing trees in mixtures with non-N-fixing trees may develop deeper root profiles due to niche partitioning (da Silva et al. 2009). Mixed tree plantings in agroforestry systems may enhance SOC sequestration as increases in tree species diversity may potentially result in increases in fine root productivity (Meinen et al. 2009; Schroth 1999). Further, higher species richness and tree density can result in higher SOC contents in agroforestry systems (Saha et al. 2009). In addition to fixing N, fertilizer trees may recycle the soil's phosphorus, calcium, magnesium, and potassium (Ajayi et al. 2011). However, interspecific root competition may affect SOC sequestration (Schroth 1999). For example, the roots of wheat (*Triticum aestivum* Linn.) intercropped with jujube (*Ziziphus jujuba* Mill.) trees had more shallow distribution in the soil profile and smaller root length densities than mono-cropped wheat (Zhang et al. 2013). In addition, the roots of intercropped jujube trees occupied a comparatively smaller soil space than sole-cropped trees. Decreased soil exploration and apparent root competition led to decreases in yield and biomass (Zhang et al. 2013). This may result in decreased soil C inputs but few experimental studies have quantified patterns of root distribution and their impacts on interspecific interactions in agroforestry systems (Schroth 1999).

Among the reasons for the positive effects of trees on SOC sequestration are that trees modify the quality and quantity of belowground litter C inputs and modify microclimatic conditions such as soil moisture and temperature regimes (Laganière et al. 2010). Root litter usually decomposes more slowly than leaf litter of the same species (Cusack et al. 2009). Further, hydraulic lift of soil water by roots of a single tree may enhance soil water uptake by neighboring trees and other plants in the agroforestry system which may affect SOC sequestration due to an increase in productivity and accelerated decomposition (Kizito et al. 2006; Liste and White 2008). Trees may have a higher potential for SOC sequestration than crop and pasture plant species as trees may be associated with higher proportions of stabilized SOC in deeper mineral soil horizons (Nepstad et al. 1994; Jobbágy and Jackson 2000). Trees contribute to more C in the relatively stable silt- + clay-sized, i.e., lower than 53 μm diameter, fractions in deeper soil profiles than any other agroforestry species (Nair et al. 2009b). Further, in surface soil horizons of intensively managed agricultural landscapes, trees potentially reduce SOC losses by reducing soil erosion (Lal 2005). The changes in soil microbial communities and activities and biodiversity under trees may also enhance SOC sequestration. For example, the addition of a single tree species to moorland resulted in changes in belowground soil microbial communities and in nutrient cycling (Mitchell et al. 2010). However, field studies on the mechanisms and processes associated with C dynamics and storage in tree-based systems such as agroforestry systems are scanty.

The integration of trees into agricultural production systems may create positive interactions such as enhanced productivity, cycling of nutrients, soil fertility, and macroclimate (Nair et al. 2010). However, there are also many possible negative interactions. For example, pests aside from drought, bush fires, or other biotic or abiotic factors may contribute to poor tree performance in agroforestry systems in Africa (Sileshi et al. 2007). Further, understory species may be negatively affected by the tree presence, and trees and crops may compete for water (Burgess et al. 2004). The competitive relationship of tree and understory depends, in particular, on edapho-climatic conditions (Mosquera-Losada et al. 2010; Rigueiro-Rodríguez et al. 2009). Allelopathic and disease vectors are other possible negative interactions in agroforestry systems. Allelochemicals are present in many types of plants and are released into the soil by a variety of mechanisms (Jose et al. 2004). Mulching with plant residues, in particular, may result in the liberation of allelochemicals into the soil (John et al. 2006). Allelochemicals affect germination, growth, development, distribution, and reproduction of a number of plant species (Inderjit and Malik 2002). Most of the tropical agroforestry species compared by Rizvi et al. (1999) have negative allelopathic effects on food and fodder crops. Allelochemicals may also contribute to pest management as trees live long and produce a large amount of leaves and litter. Thus, species mixtures with no or positive allelopathic effects on the companion crops must be created in agroforestry systems (Rizvi et al. 1999). Less well studied are allelopathic effects of temperate agroforestry species (Jose et al. 2004). However, allelopathic investigations in agroforestry systems are often lacking conclusive field verification. For example, separating allelopathic effects of trees from root competition is challenging (John et al. 2006).

3.2 Afforestation effects on soil organic carbon

Studies about afforestation, i.e., the introduction of trees on previously treeless cropland, pasture, or natural grassland, may provide some insight on the potential effects of agroforestry trees on SOC sequestration. Observations about the effects of afforestation on SOC have been synthesized and reviewed by Post and Kwon (2000), Guo and Gifford (2002), Paul et al. (2002), and Li et al. (2012). In temperate regions, afforestation of former cropland caused a long-lasting SOC sink but the majority of afforested grasslands lost SOC (Poeplau et al. 2011). The SOC changes below 25 cm soil depth followed the trend of changes in 0–25 cm but were smaller. Afforestation impacts on subsoil SOC were also detected in tropical regions (Don et al. 2011). Specifically, in the tropics, SOC increased for both afforested croplands in 0–44 cm depth and for grasslands in 0–35 cm depth. According to a recent meta-analysis, SOC in 0–10, 10–20, 20–40, 40–60, and 60–80 cm were not significantly reduced with afforestation of grassland, but the conversion of cropland to forests, i.e., trees or shrubs, increased SOC significantly for each soil depth layer up to 60 cm depth (Shi et al. 2013). However, Laganière et al. (2010) showed that conclusions based on the observations of SOC changes by afforestation may be limited by inappropriate experimental design, sampling methods, and/or soil analysis techniques.

Laganière et al. (2010) compared afforestation effects on SOC pools by meta-analysis of observations from studies designed specifically to test afforestation. Afforestation resulted in an increase in SOC pools by 26 % for croplands, but changes for pastures and natural grasslands were not significantly different from zero. Soil sampling was probably done too early as it may take much longer until a new SOC equilibrium in the soil profile is reached after plantation establishment. For example, it takes more than 100 years after plantation establishment to create a significant increase in SOC pool in the boreal zone (Ritter 2007). Also, tree root systems are generally deeper than the sampling depths for the studies compared by Laganière et al. (2010). Thus, whole profile studies after long periods of time are needed to accurately determine SOC pool changes following afforestation (Shi et al. 2013).

Some effects of tree species on SOC pools were also reported by Laganière et al. (2010). However, effects of planting conifer trees other than *Pinus* spp. on SOC pools may be negligible. The planting of N-fixing trees for afforestation can increase the SOC pool as indicated by the more than 30 % increase in SOC pools when N fixers are present in forest stands (Johnson and Curtis 2001; Resh et al. 2002). However, the long-term tree productivity in plantations and, thus, C inputs to soils may be reduced as trees take up considerable amounts of nutrients from the soil which may be partially removed by repeatedly harvesting tree biomass (Berthrong et al. 2009).

In conclusion, major factors contributing to restoring SOC pools after afforestation on agricultural soils are previous land use, tree species, soil clay content, preplanting disturbance, and, to a lesser extent, climate zone (Laganière et al. 2010). In particular, the positive impact of afforestation on SOC pools is more pronounced in croplands relative to pastures or natural grasslands. Broadleaf tree species have a greater capacity to enhance SOC pool, most probably due to their higher root biomass-to-aboveground biomass ratio than conifer trees. Also, soils containing more than 33 % of clay have a greater capacity to enhance SOC than those containing less than 33 % (Laganière et al. 2010). Yet, it may take several decades after afforestation until effects on SOC pools can be observed in deeper soil horizons (Shi et al. 2013). Recommendations for agroforestry systems are that soil disturbance must be minimized during tree establishment and tree species with a high root biomass-to-aboveground biomass ratio and/or N-fixing trees should be planted when SOC sequestration is among the objectives for establishing the agroforest. Furthermore, sustainable practices for harvesting tree biomass must be used to maintain long-term soil fertility and productivity.

4 Carbon sequestration in agroforestry systems

Carbon sequestration in agroforestry systems occurs in aboveground biomass, i.e., stem, branch, and foliage, and in belowground biomass, i.e., roots, and in soil. Especially, the large volume of aboveground biomass and deep root systems of trees in agroforestry systems have received increased attention for climate change adaption and mitigation (Nair 2012a). Further, between 30 and 300 Mg C ha^{-1} may be stored in agroforestry soils up to 1-m depth (Nair et al. 2010). Global estimates for the C sequestration potential of agroforestry systems over a 50-year period range between 1.1 and 2.2 Pg C year^{-1} but, in particular, estimates of land area are highly uncertain (Dixon 1995). Further, the above- and belowground vegetation C sequestration potential is highly variable (Nair et al. 2009a). In general, agroforestry systems on fertile humid sites have higher vegetation C sequestration rates than those on arid, semiarid, and degraded sites, and tropical agroforestry systems have higher vegetation C sequestration rates than temperate agroforestry systems.

Higher SOC pools in agroforestry systems can be particularly achieved by increasing the amount of biomass C returned to the soil and by strengthening soil organic matter (SOM) stabilization and/or by decreasing the rate of biomass decomposition and SOM destabilization (Lal 2005; Sollins et al. 2007). Compared to monocultures, agroforestry systems are more efficient in capturing the resources available at the site for biomass growth and the increased growth may result in higher C inputs to the soil. Also, direct C inputs to the soil can potentially be increased by some agroforestry practices. These include (a) returning prunings of woody species to the soil as mulch and allowing abundant tree litter to decompose on site, (b) allowing livestock to graze and add dung to the soil, (c) allowing woody species to grow and add surface and belowground litter during crop fallow phases, (d) integrating trees and their litter input in animal production systems, (e) allowing litter inputs to the soil from shade-tolerant species growing under trees, and (f) benefiting from the soil C inputs of agricultural crops grown during early stages of the establishment of forestry plantations. Whether mechanisms of SOM stabilization and destabilization can potentially be affected by agroforestry practices is less well known, although practices that promote the depth transfer of SOM may result in higher profile SOC pools as decomposition is slower and the proportion of stabilized SOM is higher in deeper soil layers (Lorenz and Lal 2005). Otherwise, the rate of biomass decomposition can potentially be directly reduced by manipulating litter chemical and physical properties through selection of species mixtures in agroforestry systems. For example, lower decomposition rates are observed when litter is more recalcitrant, i.e., when it contains larger proportions of biopolymers of higher molecular weight and irregular structure that are less accessible to enzymes and also more hydrophobic (Preston et al. 2009a). Higher molecular weight structures include condensed tannins, cutin, lignin, or modified lignin (Preston et al. 2009b). However, lignin is generally not preserved with decomposition or lost only slightly more slowly than other components. Only wood decomposition by brown-rot fungi causes large relative increases in lignin concentrations (Preston et al. 2009b). Aside from the amount of recalcitrant material, decomposability of soil C inputs may also be related to their C/N ratio and N content (Horwath 2007). However, the formation and stabilization of SOC may be more controlled by the quantity of litter input and its interaction with the soil matrix than by litter quality (Gentile et al. 2011).

Agroforesty systems can also be managed for increasing SOC pools by avoiding burning and conserving soil by minimizing soil disturbance due to reduction or cessation of tillage operations and by erosion control (Soto-Pinto et al. 2010). The inclusion of trees in perennial crops for alley cropping or hedgerow intercropping can serve as erosion control measures (Albrecht and Kandji 2003). Erosional SOC losses can directly be reduced by practices which never leave the soil un-vegetated such as improved fallows and Taungya. Shelterbets, windbreaks, and riparian buffer strips are other agroforestry practices with a potential to reduce SOC losses caused by erosion. Further, the occlusion of C in soil macroaggregates is proposed as a major mechanism of C protection in cacao (*Theobroma cacao*) agroforest soils in Brazil (Gama-Rodrigues et al. 2010). The low level of soil disturbance in these agroforestry systems may, thus, promote SOC stabilization.

The C sequestration in soils varies widely depending on the agroforestry system but the number of published studies is small (Nair et al. 2009a). For example, SOC pools ranged from 1.25 Mg C ha^{-1} in the top 40 cm of a 13-year-old alley cropping system in Southern Canada to 173 Mg C ha^{-1} in the top 100 cm of 10- to 16-year-old silvopastoral systems at the Atlantic Coast of Costa Rica (Amézquita et al. 2005; Oelbermann et al. 2006). Very high SOC pools of 302 Mg C ha^{-1} to 100 cm depth have been reported for 30-year-old cacao agroforestry systems in Brazil (Gama-Rodrigues et al. 2010). Compared to other land use practices with the exception of forests, agroforestry systems have higher SOC contents and can be ranked in the order forests higher than agroforestry systems higher than tree plantations higher than arable crops (Nair et al. 2009a). However, agroforestry systems may not be superior to traditional systems in avoiding SOC loss during initial phases after converting forest for agricultural land use, but the agroforestry system offers a greater potential to improve soil fertility and biological health.

Ideally, SOC sequestration in agroforestry systems should be reported as rates, i.e., mass SOC per units of area and time. However, SOC sequestration data are mostly reported as stocks or pools (Nair et al. 2009a). Data on SOC sequestration rates for some agroforestry systems are presented in Table 1.

Although tropical agroforestry systems may have higher SOC sequestration rates, temperate systems may be more effective in soil stabilization of the residue C inputs from tree prunings, litterfall, and crop residues (Oelbermann et al. 2006). SOC sequestration in agroforestry systems may be strengthened when the proportion of the stabilized SOC fraction in deeper soil horizons increases (Shi et al. 2013). This trend may be the result of major C inputs from the decomposition of dead tree roots, root exudates, and associated microorganisms (Lorenz and Lal 2005; Haile et al. 2008). For example, the introduction of slash pine (*Pinus elliottii* Englem) in bahiagrass (*Paspalum notatum* Flueggé) pasture resulted in SOC increases deeper in the soil profile to 125 cm depth and in increases in relatively stable SOC, i.e., C associated with silt + clay in deeper soil horizons (Haile et al. 2010). Similarly, the SOC content associated with silt + clay to 1 m depth followed a trend of increasing amount with increasing tree density in tropical home gardens in Kerala, India (Saha et al. 2010).

In conclusion, available results indicate that agroforestry systems store higher amounts of C above- and belowground than the single-species cropping and grazing systems they replace. Thus, agroforestry systems sequester C by an additional net up take of atmospheric CO_2 compared to systems replaced but data on the SOC sequestration rates are scanty.

5 Enhancing soil organic carbon sequestration in agroforestry soils

The management of integrated tree, livestock, and crop production systems may alter rate and magnitude of C sequestration, but rigorous datasets are required to identify the underlying mechanisms for improved agroforestry practices aimed at SOC sequestration (Nair et al. 2010). For example, net increases in the SOC pool may be managed through selection of agroforestry systems and soil management practices that affect the amount and quality of C inputs especially belowground by tree and non-tree components (Nair et al. 2009a). Litter fall and in turn SOC sequestration may be affected by stand-density management as, for example, higher stocking levels of trees enhance the vegetation C pool (Nair et al. 2010). In contrast, thinning and pruning of trees may reduce SOC sequestration by reducing litter fall and accelerating decomposition due to changes in understory light, air/soil temperature, and soil moisture regimes. However, processes leading to SOC stabilization and sequestration are not completely understood. Monitoring and predicting changes

Table 1 Soil organic carbon sequestration rates (in megagrams of C per hectare per year) in some agroforestry systems

Agroforestry system/species	Location	Age (years)	Soil depth (cm)	Sequestration rate (Mg C ha^{-1} $year^{-1}$)	Reference
Alley cropping system: hybrid poplar (*Populus deltoides* × *nigra* DN-177) + wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), and maize (*Zea mays* L.) rotation	Southern Canada	13	0–20 0–40	0.30 0.39	Oelbermann et al. (2006)
Intercropping system: Norway spruce (*Picea abies* L.) + barley (*Hordeum vulgare* L. cv. OAC Kippen)	Southern Canada	13	0–20	0	Calculated from Peichl et al. (2006)
Intercropping system: hybrid poplar + barley	Southern Canada	13	0–20	1.04	Calculated from Peichl et al. (2006)
Alley cropping system: *Erythrina poeppigiana* (Walp.) O.F. Cook + maize and bean (*Phaseolus vulgaris* L.)	Costa Rica	19	0–20	1.79	Oelbermann et al. (2006)
			0–40	2.34	Oelbermann et al. (2006)
Multistrata agroforest: cacao (*Theobroma cacao* L.) + *Erythrina poeppigiana* (Walp.) O.F. Cook	Costa Rica	10	0–45	4.16	Calculated from Beer et al. (1990)
Multistrata agroforest: cacao + *Cordia alliodora* (Ruiz & Pav.) Oken	Costa Rica	10	0–45	1.55	Calculated from Beer et al. (1990)
Multistrata agroforest: cacao + canopy trees	Ghana, West Africa	15	0–15	−0.39[a]	Calculated from Isaac et al. (2005)
		25	0–15	0.06	Calculated from Isaac et al. (2005)

[a] Soil organic carbon loss

in the SOC pool can be challenging given the slow rate at which changes occur (Jandl et al. 2014). The full impact of agroforestry management, for example, can often take decades to become apparent. Thus, a long-term monitoring approach coupled to a modeling approach is required. Soil C models of different complexity are available. However, the fact that long-term agroforestry system experiments are rarely replicated may limit the confidence in SOC model predictions (Jandl et al. 2014).

5.1 Soil organic carbon stabilization

The SOC sequestration depends primarily on the soil C input and soil stabilization processes. Plant root and rhizosphere inputs, in particular, make a large contribution to SOC (Schmidt et al. 2011). However, the link between plant litter quality and SOC is not well understood (Torn et al. 2009). Accumulation of SOC is mainly the result of partial degradation, microbial products, and fire residues rather than humic substances. Physical disconnection, e.g., from enzymes, decomposers, electron acceptors, and sorption/desorption, i.e., organomineral associations, and freezing/thawing govern SOC cycling and these processes are shaped by environmental conditions (Schmidt et al. 2011).

Some surface residue C may be incorporated into the mineral soil by physical mixing and solubilisation, transport, and subsequent adsorption (Lorenz and Lal 2005). Plant roots, i.e., litter and rhizodeposition, are the primary vector for most C entering the SOC pool (Rasse et al. 2005). Thus, the depth distribution of organic residues residing inside and outside of soil aggregates, i.e., the light fraction organic C, matches the depth distribution of roots (Schrumpf et al. 2013). The relative importance of root litter and rhizodeposition versus other incorporation processes for profile SOC distribution and dynamics depend on climate, soil, and vegetation types (Rumpel and Kögel-Knabner 2011). However, inventory data on root biomass are uncertain due to spatial and temporal heterogeneity, uneven sampling, and methodological differences among studies. The fine root turnover transfers a large fraction of net primary production into soil but published estimates on fine root turnover time differ more than fivefold which may also be the result in differences in methods (Guo et al. 2008). Thus, estimates of the belowground C inputs from plant root litter to SOC are uncertain (Denef and Six 2006).

Rhizodeposition describes the release of organic C compounds by roots (Jones et al. 2009). Most isotopic labeling studies used to quantify the amount of C fixed by plant photosynthesis partitioned belowground have focused on young plants at a vegetative stage but partitioning is strongly affected by plant age. Further, almost half of the published data on rhizodeposition are for wheat (*Triticum* spp.) and ryegrass (*Lolium* spp.), and 76 % of the studies are related to only five crop/grassland species. Thus, the knowledge of C rhizodeposition and, in particular, those of mixed plant communities such as agroforestry systems is scanty. The rigorous quantification of C sequestration in agroforestry soils is particularly hampered by the fact that the amount of rhizodeposition by trees is virtually unknown (Jones et al. 2009).

Adsorption of dissolved organic carbon (DOC) in soil profiles is another direct belowground C input but represents only a small portion of profile SOC as the majority of DOC is ultimately returned to the atmosphere as CO_2 (Bolan et al. 2011). Throughfall, stemflow, recently deposited litter including crop residues, humus, and application of organic amendments such as manure and biosolids are important DOC sources in agroforestry systems. Retention of DOC in subsoils is related to the concentration of poorly crystalline iron and aluminum (hydr)oxides with a high specific surface area. Thus, DOC translocation contributes to the formation of mineral-bound SOC in the subsoil (Schrumpf et al. 2013). Some DOC may also leach from soils into adjacent aquatic ecosystems (Bolan et al. 2011). The C leaching losses may be particularly important for the C balance of agroforestry systems (Kindler et al. 2011).

The SOC stability is an ecosystem property as it depends on the biotic and abiotic environment (Schmidt et al. 2011). In contrast, the molecular structure of plant inputs and OM plays only a secondary role in determining SOC residence times over decades to millennia. However, microbially derived materials may play a crucial role in SOC stabilization (Kleber et al. 2011). The SOC turnover appears to be a function of microbial ecology and the resource availability within a given physical soil environment. Thus, processes which slow down mineralization are major centennial-scale stabilization mechanisms for SOC (Sanderman et al. 2010). The two important groups of processes for long-term stabilization of SOC are (a) processes which lead to physical protection, rendering OM spatially inaccessible to decomposers or their water-soluble degradative enzymes, and (b) organomineral complexes and organo-metal interactions, i.e., interactions of OM with minerals, metal ions, and other organic substances (von Lützow et al. 2006). Physical protection may retard decomposition for decades to centuries, whereas organomineral complexes or organo-metal interactions may be responsible for stabilization of most of the non-charred SOC for centuries to millennia (Kögel-Knabner et al. 2008). However, biochemical recalcitrance and physical protection may allow SOC to remain in the soil longer, giving time for organomineral complexes to form (Six et al. 2000). Thus, stabilization of SOC in agroforestry systems is a combination of these short- and long-term processes (Nair et al. 2010). Any disruption of the stabilization process may result in the decomposition of SOC even if its thousands of years old (Ewing et al. 2006). In summary, the persistence of SOC is largely due to complex interactions between SOC and its environment, such as the interdependence of compound chemistry, reactive mineral surfaces, climate, water availability, soil acidity, soil redox state, and the presence of potential degraders in the immediate microenvironment (Schmidt et al. 2011). The most important factor in SOC stabilization is probably the association with soil minerals, irrespective of vegetation, soil type, and land use. Unless other environmental constraints hamper decomposition, the SOC storage capacity will depend on the availability of binding sites, i.e., the soil's mineral composition and depth. Thus, the long-term SOC storage is finite (Schrumpf et al. 2013).

5.2 Reducing soil organic carbon loss

The biomass C input to the soil in agroforestry systems can be increased and its decomposition rate decreased by adoptions of conservation-effective measures that reduce losses of nutrients and water, increase biomass production, and protect SOC against losses through enhancing biological, chemical, and physical stabilization mechanisms (Lal and Follett 2009). Thus, a decrease in cultivation intensity may result in an increase in SOC levels in agroforestry systems (Nair et al. 2010). Similar to other agricultural systems, adding amendments such as fertilizers and composts, supplying water through irrigation, and incorporating organic residues into soil may enhance SOC sequestration in agroforestry systems. However, fertilization studies on most tropical tree species are scanty hampering any conclusions on fertilization effects (Nair et al. 2010). Nevertheless, manure additions may influence formation and stability of soil aggregates in agroforestry soils. Also, while herbicide applications show mixed effects on SOC levels and aggregation, there is little information about the effects of pesticides on SOC sequestration (Nair et al. 2010). In summary, the effects of more active and improved management practices on SOC in agroforestry systems are site-specific.

Multispecies agroforestry systems have the potential to be more productive than the best-performing monocultures and, thus, may sequester more SOC due to enhanced belowground interactions but the experimental evidence is not yet conclusive (Ong et al. 2004; Rao et al. 2004). The management of agroforestry systems for SOC sequestration includes the selection of tree species and their silvicultural management such as stand density and rotation length (Nair et al. 2009a). Functionally important tree species, i.e., those having deep and extensive root systems to enhance C input into the soil, may have a high potential to enhance SOC sequestration in agroforestry systems (Kell 2012; Lorenz and Lal 2010). Broadleaf trees, in particular, have a larger and more deeply anchored root system, i.e., higher root biomass/aboveground biomass ratios than coniferous tree species, and may, therefore, generate higher SOC inputs from roots at soil depth (Laganière et al. 2010). Further, palms may have particularly large and heavy root systems (Schroth et al. 2002). However, data on belowground inputs form agroforestry palm and tree species are scanty (Albrecht et al. 2004). Thus, similar to other trees, it is not known whether agroforest tree species differ in their ability to sequester SOC in deeper mineral soils (Jandl et al. 2007). Otherwise, mixed plantings including N-fixing trees produce more biomass and this may result in increased SOC sequestration (Nair et al. 2009a). However, positive, negative, and neutral effects of N-fixing trees on SOC accretion are reported. Thus, appropriate tree species must be selected to enhance SOC sequestration (Oelbermann et al. 2006). Whether mixed tree plantings in agroforestry systems enhance SOC sequestration is also unknown as manipulative biodiversity experiments with multiple tree species are scanty (Scherer-Lorenzen et al. 2005). In conclusion, it remains to be studied whether agroforestry systems can be specifically designed and managed to maximize the belowground C sequestration in the soil by more fully exploring the C storage potential in the entire mineral soil through the inclusion of trees and their associated root-derived C inputs.

6 Conclusions

The old practice of agroforestry for achieving maximum agronomic benefits by a greater efficiency in resource, i.e., nutrients, light and water capture, and utilization, has recently received increased attention due to perceived contribution to climate change mitigation by SOC sequestration. The inclusion of trees, i.e., N-fixing, may specifically enhance SOC storage in agroforestry systems. In addition to climate benefits, agroforestry can deliver benefits for rural development. However, observed SOC sequestration rates are particularly highly variable and only a very limited number of field experiments have been specifically designed to rigorously test the effects of agroforestry practices on SOC. Not before SOC sequestration processes in soil profiles are understood can land use and soil management practices be recommended for site-specific SOC sequestration in agroforestry systems.

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