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Agroforestry for biomass production and carbon sequestration: an overview

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Abstract Ever since the Kyoto Protocol, agroforestry has gained increased attention as a strategy to sequester carbon (C) and mitigate global climate change. 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; however, our understanding of C sequestration in specific agroforestry practices from around the world is rudimentary at best. Similarly, while agroforestry is well recognized as a land use practice capable of producing biomass for biopower and biofuels, very little information is available on this topic. This thematic issue is an attempt to bring together a collection of articles on C sequestration and biomass for energy, two topics that are inextricably interlinked and of great importance to the agroforestry community the world over. These papers not only address the aboveground C sequestration, but also the belowground C and the role of decomposition and nutrient cycling in determining the size of soil C pool using specific case studies. In addition to providing allometric methods for quantifying biomass production, the biological and economic realities of producing biomass in agroforestry practices are also discussed.

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Introduction

Global climate change and energy security are two key issues that are at the forefront of environmental discussions the world over. Although they bring up unique challenges, global warming and energy security are inextricably interlinked. Increasing concentration of atmospheric carbon dioxide (CO_2) is considered the predominant cause of global climatic change. It is believed that agricultural and forestry practices can partially mitigate increasing CO_2 concentration by sequestering carbon (C). Similarly, alternative agricultural practices where biomass crops are cultivated can impact CO_2 levels not only by sequestering C, but also by replacing fossil fuel with the biomass produced. Agroforestry, like many other land use systems, offers great potential for sequestering C and producing biomass for biofuels.

Ever since the Kyoto Protocol, agroforestry has gained increased attention as a strategy to sequester C from both developed and developing nations. The available estimates of C stored in agroforestry range from 0.29 to 15.21 Mg C/ha/year above ground, and 30–300 Mg C/ha up to 1 m depth in the soil (Nair et al. 2010). Since the industrial revolution, atmospheric CO_2 has increased by more than 40 %, from 280 ppm in 1,750 to about 392 ppm in 2012 and at the current rate it is expected to surpass 400 ppm by 2015 (Hutchinson et al. 2007; Tans 2012). In the three years from 2010 to 2012, CO_2 emissions increased at an alarming rate of 2 ppm/year or 4.4 Pg C/year. While agroforestry has been recognized as having the greatest potential for C sequestration (Fig. 1) of all the land uses analyzed in the Land-Use, Land-Use Change and Forestry report of the IPCC (2000), our understanding of C sequestration in specific agroforestry practices from around the world is rudimentary at best.

The incorporation of trees or shrubs on farms or pastures can increase the amount of C sequestered compared to a monoculture field of crop plants or pasture (Sharrow and Ismail 2004; Kirby and Potvin 2007). In addition to the significant amount of C stored in aboveground biomass, agroforestry systems can also store C belowground. While most studies report aboveground C sequestration, belowground C and soil C are often not reported from agroforestry systems. The soil C pool, comprising about 2,500 Gt, is one of the largest C pools and is larger than the atmospheric pool (760 Gt) (Lal 2004). The extent of soil C is dependent on a delicate balance between litter and rhizodeposition and the release of C due to decomposition and mineralization. Several other factors such as quality of C input, climate, soil physical and chemical properties further determine the rate of decomposition and thus stabilization of soil organic C in a particular ecosystem. Since modernization of agriculture in the 19th-century, soil carbon pool has gradually depleted because of several factors such as deforestation, intensive cropping and biomass removal, soil erosion, and unsustainable agricultural practices. Most of the decline in soil organic matter has been observed in regions under intensive crop production such as continuous row cropping or monocropping. Depletion of soil C has been documented to result in decreased productivity, poor soil physical and chemical properties, and negative secondary environmental impacts. It has been well documented that conversion of degraded agricultural soils into agroforestry systems can rebuild soil productivity.

One of the commodities agroforestry is well suited to producing is biomass for biopower and biofuels (Jose et al. 2012). Heavy reliance on foreign based fossil fuels has sparked an interest in domestic renewable energy sources in many countries. For example, in 2003 the Biomass Research and Development Technical Committee (BRDTC), established by US Congress in 2000, envisioned a goal of a 30 % replacement of US petroleum consumption with biofuels by 2030 (DOE; US Department of Energy 2003). Currently, petroleum products supply about 36 % of US energy consumption, while biomass and biofuels provide 4.3 % of total US energy consumption (EIA; Energy Information Administration 2011).

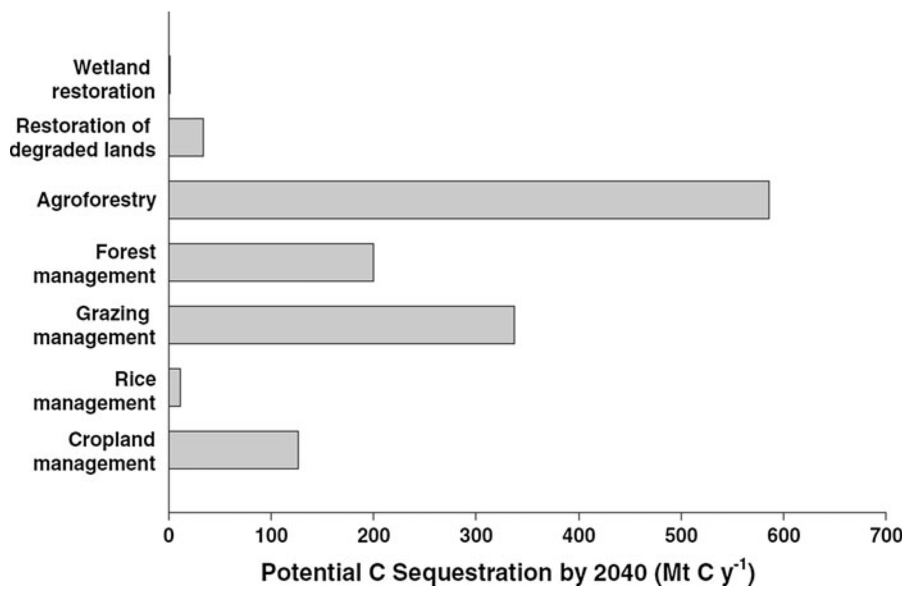

Fig. 1 Carbon sequestration potential of different land use systems by 2040 (adapted from IPCC 2000). Agroforestry offers the greatest potential because of the large extent of area (630 × 10^6 ha) available worldwide for agroforestry adoption

While a study conducted by the US Department of Energy concluded that achieving this goal is possible, the report stated significant expansion of perennial biofuel crop production would be necessary (DOE 2011). Although agroforestry offers a solution to avoid the food versus fuel debate by combining food production and biomass for energy on the same piece of land (Henderson and Jose 2010; Holzmueller and Jose 2012), very little information is available on this topic.

If agroforestry is to be used in C sequestration schemes such as the clean development mechanisms (CDM), better information is required about above and belowground C stocks, soil C, and areas under agroforestry practices. Although there have been a number of publications recently and in the past about the C sequestration potential of agroforestry systems, the information is widely dispersed (but, see Kumar and Nair 2011). The objective of this thematic issue is to compile several original research articles from North America, South America, and Africa that investigate C sequestration and biomass production potential of specific agroforestry practices.

Quantifying carbon sequestration

The first two papers examined C sequestration in silvopastoral systems. Dube et al. investigated the carbon (C) sequestration potentials of three predominant ecosystems in Patagonia in Chile: *Pinus ponderosa*-based silvopastoral systems (SPS), pine plantations (PPP) and natural pasture (PST). Silvopastoral systems are highly efficient in increasing productivity for both plants and animals as mutually optimum conditions for growth and development are created in a properly managed silvopastoral system. Plants gain benefits through nutrient cycling by addition of manure in the system and partial shade from the canopy while animals enjoy ideal temperature and humidity under the tree canopy. In their study, Dube et al. observed higher aboveground tree C, belowground tree C, and soil organic C stock in the silvopastoral system compared to the other systems. Silvopastoral systems also had more favorable air temperature and soil moisture parameters.

Ermson et al. conducted a similar study in the southeastern US where they explored the effect of grazing and forage enhancement on total soil C (TSC), soil nitrogen(N), and phosphorus (P) dynamics in a goat (*Capra aegagrus hircus*)—loblolly pine (*Pinus taeda* L.) silvopasture system on a Kipling silt loam soil (fine, smectitic, thermic, Typic Paleudalfs) in Alabama from 2006 to 2010. In this study however, silvopasture plots were characterized by low initial pH, low TSC, and the soils were deficient in N and P. Four years after tree thinning and 3 years of grazing in June 2010, the silvopasture treatment still exhibited low soil pH (<6) and TSC levels of less than 20 g/kg. The authors speculated that in the long-term, grazing without additional soil management practices may still improve soil fertility through nutrient recycling and C sequestration and thereby making the goat-loblolly silvopasture system both environmentally and economically sustainable.

The next two papers investigated C sequestration in coffee agroforests, one in Guatemala and another in Costa Rica. Schmitt-Harsh observed that coffee agroforests in Guatemala stored somewhere between 74.0 and 259.0 Mg C/ha with a mean of 127.6 Mg C/ha. The average carbon stocks of coffee agroforests were significantly lower than estimated for the mixed dry forests (198.7 Mg C/ha); however, individual tree and soil C pools were not significantly different suggesting that shade trees played an important role in facilitating C sequestration and soil conservation in these systems. This research demonstrates the importance of conservation-based production systems such as coffee agroforests in sequestering C alongside natural forest systems.

Hãger attempted to unravel the relationship between species composition, diversity, and C storage in coffee agroforests of Costa Rica. Total C stocks were 43 % higher on organic farms than on conventional farms ($P < 0.05$) and although vegetation structure was different, there was no difference in species diversity between organic and conventional farms. Combined effect of farm type, species richness, species composition and slope explained 83 % of the variation in total C storage across all farms. Organic coffee agroforestry farms may contribute to GHG mitigation and biodiversity conservation in a synergistic manner which has implications for the effective allocation of resources for conservation and climate change mitigation strategies in the agricultural sector.

There are three papers included in this thematic issue that provide unique perspectives on soil C sequestration and its interrelationship with organic matter decomposition and nutrient cycling. The first paper by Kim examined how an intercropping system with a nitrogen (N)-fixing tree (*Gliricidia*) and maize could help mitigate climate change through enhanced soil C sequestration in sub-Saharan Africa while dealing with GHG emissions from the soil. Using data from Makumba et al. (2007), the author estimated that 67.4 % of the sequestered soil C (76 Mg C/ha in 0–2 m soil depth) was lost from the system as CO_2 during the first 7 years of intercropping. An annual net gain 3.5 Mg C/ha/year was estimated from soil C sequestered and lost. The author further observed that if N_2O emission was reduced as well, the overall mitigation benefit achieved from the intercropping system would be larger. These results suggest that field measurements and modeling of CO_2, N_2O and CH_4 emissions should be taken into account while estimating C sequestration in agroforestry systems.

Gaiser et al. tested Leucaena (*Leucaena leucocephala* (L), *Senna siamea* (S) and maize (M) residue addition on soil organic matter accumulation under sub-humid tropical conditions in Benin, West Africa. On an *Imperata cylindrica* (I) dominated grass fallow, a total amount of 30 Mg/ha dry matter was applied within 18 months. Changes in the light and heavy soil organic C fraction (LF and HF) and in the total soil organic C content (LF + HF) in the topsoil were observed. All organic materials increased the proportion of the LF fraction in the soil significantly. The increase in HF was 39–51 % of the increase in total organic C, depending on the source of the organic material. The potential of the tested organic materials to increase total soil organic C content (including all soil organic C fractions) was in the order L > S > M > I, whereas the order of the HF fraction was L = S > I > M. Cation exchange capacity of the newly formed heavy soil organic C was highest with L and lowest with M. Ranking of the transformation efficiency of applied plant residues into the heavy soil organic C fraction was I > L = S > M. Transformation efficiency of the residues could neither be explained by lignin nor lignin/N ratio, but rather by extractable polyphenols. The results show that accumulation of the HF fraction in tropical soils is feasible through the application of large quantities of plant residues, but depends strongly on the quality of the organic matter added.

Zaia et al. evaluated the impact of plant litter deposition in cacao agroforestry systems on soil C, N, P and microbial biomass in Bahia, Brazil. They studied five cacao agroforestry systems of different ages under two different soils (Oxisol and Inceptisol). Overall, the average stocks of organic C, total N and total organic P for 0–50 cm soil depth were 89072, 8838 and 790 kg/ha, respectively. At this soil depth the average stock of labile organic P was 55.5 kg/ha. Microbial biomass was mostly dominated in the 0–10 cm soil depth, with a mean of microbial biomass C of 286 kg/ha, microbial biomass N of 168 kg/ha and mineralizable N of 79 kg/ha. The dynamics of organic P in these cacao agroforestry systems were not directly associated with organic C dynamics in soils, in contrast to the N dynamics.

Ecosystem models that can estimate plant and soil C stocks can be an invaluable tool for estimating C sequestration potential of agroforestry systems at larger scales. The CO_2FIX model has been used to estimate the dynamics of C stocks and flows for a variety of ecosystems around the world (Schelhaas et al. 2004). However, this model has not been tested using empirical data from agroforestry systems. Kaonga et al. tested the validity of the CO_2FIX model in predicting the aboveground and soil C stock using empirical data from 7-year-old *Leucaena* woodlots at Msekera, Zambia. They also assessed the impact of converting a degraded agricultural land to woodlots on C stocks. Measured above and belowground tree C stocks and increment of aboveground biomass differed significantly among different species. Measured stem and total aboveground tree C stocks in the *Leucaena* woodlots ranged from 17.1 to 29.2 and from 24.5 to 55.9 Mg/ha, respectively. Measured soil organic carbon (SOC) stocks at 0–200 cm depth in *Leucaena* stands ranged from 106.9 (*L. diversifolia*) to 186.0 Mg/ha (*L. leucocephala*). Although, modeled stem and branch C stocks closely matched measured stocks, the soil module of CO_2FIX could not predict the soil C accurately. The authors concluded that inadequate long-term empirical data on climate, litter quality, litter quantity, and tree growth, and the transient nature of SOC stocks that were disturbed in recent decades were most likely reasons for the inconclusive results from the model.

Udawatta and Jose synthesized the available information to estimate C sequestration under agroforestry systems in the US. They estimated that 530 Tg/year could be sequestered by four major agroforestry practices which could help offset current US emission rate of

1,600 Tg C/year from burning fossil fuel (coal, oil, and gas) by 33 %. These authors estimated C sequestration potential for silvopasture, alley cropping, and windbreaks in the US as 464, 52.4, and 8.6 Tg C/year, respectively. According to them, riparian buffers could sequester an additional 4.7 Tg C/year while protecting water quality. While acknowledging the need for accurate area estimates under different agroforestry practices in the US, they also emphasized the need for long-term data, standardized protocols for C quantification and monitoring, predictive models to understand long-term C sequestration, and site-specific agroforestry design criteria to optimize C sequestration.

The paper by Nair elaborated on the need for rigorous and consistent procedures to measure the extent of C sequestration in agroforestry systems. The author accurately pointed out that the current methods of estimating C varied widely and the estimations were based on several assumptions. According to him, large-scale global models based on such measurements and estimations were more likely to result in serious under- or overestimations of C in agroforestry practices. The author reveals several erroneous assumptions, operational inadequacies and inaccuracies commonly found in the current literature. He provides several practical recommendations for researchers that include using accurate description of the methods and procedures among others. This would help other researchers to examine the datasets and incorporate them in larger databases and help agroforestry earn its deserving place in mainstream efforts.

Estimating biomass production

Allometric equations are commonly used in estimating biomass production by trees in agroforestry systems. However, these equations are most often derived from forest grown trees that are different in their growth form from those open-grown trees in agroforestry configurations. This can introduce errors in estimating not only biomass production potential, but C sequestration as well. It is imperative that species specific allometric equations for different agroforestry practices must be developed in order to overcome this serious weakness in agroforestry research. There are two papers in this thematic issue that provide allometric equations for estimating aboveground biomass for trees in agroforestry.

Tamang et al. conducted their study in Florida, USA, to develop biomass equations for cadaghi (*Corymbia torelliana*) trees in various aged windbreaks. Trees were destructively sampled based on diameter at breast height (DBH) and crown biomass was estimated using randomized branch sampling (RBS) while trunk biomass was measured by taking disks every 1.5 m along the stem. Separate nonlinear equations were developed for crown, trunk and whole tree biomass estimation using DBH and height as predictors. The study found that DBH alone was sufficient to predict aboveground biomass while the inclusion of height provided more accurate results. Using their equation the authors recorded a total biomass per 100 m windbreak length to be between 166 and 26,605 kg. They concluded that fast-growing cadaghi could provide landowners higher returns from biomass or carbon trade to offset the cost of land occupied by the windbreaks.

Kuyah et al., on the other hand, developed new allometric equations using remotely sensed crown area and/or tree height as predictor of aboveground biomass. These equations corresponded well with the data obtained from destructive sampling with about 85 % of the observed variation in aboveground biomass explained by crown area. Addition of height and wood density as second predictor variables improved model fit by 6 and 2 % and lowered the relative error by 7 and 2 %, respectively. Total estimated aboveground biomass carbon was measured at 20.8 t C/ha, which was about 19 % more than the amount estimated using DBH as predictor. These results confirm that the new allometric equations using crown area could be a better predictor of aboveground biomass and can be used as an important tool for predicting carbon stock in such systems.

The last two papers explore biomass production potential of two temperate alley cropping systems, one from Canada and another from the US. As pointed out by Holzmueller and Jose (2012), alley cropping is one of the most suitable agroforestry practices for growing biomass for biopower and biofuels. Cardinael et al. examined short rotation willow production in the alleys of 21-year-old trees on marginal land in Guelph, Canada. As a control, the same willow clones were established on an adjacent piece of land without established trees (conventional willow system). They quantified carbon pools, fine root and leaf biomass inputs, and clone yields in both the intercropping and conventional monocropping systems. Willow biomass yield was significantly higher in the agroforestry field (4.86 odt ha^{-1}/year) compared to the conventional field (3.02 odt ha^{-1}/year). Clonal differences in biomass were also apparent with clones SV1 and SX67 with the highest yields and 9,882–41 with the lowest. Willow fine root biomass in the top 20 cm of soil was significantly higher in the intercropping system (3,062 kg/ha) than in the conventional system (2,536 kg/ha). Soil organic carbon was also significantly higher in the agroforestry field (1.94 %) than in the conventional field (1.82 %).

Susaeta et al. assessed the economics of loblolly pine (*Pinus taeda* L.)—switchgrass (*Panicum virgatum*) alley cropping in the southern US. Assuming a price range of switchgrass between \$15 and \$50 Mg^{-1} and yield of 12 Mg ha^{-1}/year, loblolly pine monoculture would be the most profitable option for landowners instead of intercropping if the price of switchgrass was below \$30 Mg^{-1}. However, when switchgrass prices were $\geq$\$30 Mg^{-1}, landowners would be financially better off adopting intercropping if competitive interaction between crops were minimal. Various assumptions were used in their analysis ranging from no competition between species for resources and reduced loblolly pine productivity due to competition with switchgrass to reduced productivity of both species due to competition for nutrients, water and light. Findings also suggested that the optimal system would depend on the competitive interactions between switchgrass and loblolly pine crops, and the expected prices for each crop.

Conclusion

Research findings from around the world have clearly demonstrated that agroforestry offers unique opportunities to increase C stocks in the terrestrial biosphere. Agroforestry could play a substantial role in reducing atmospheric concentration of CO_2 by (1) storing C in above and belowground biomass and in soil, and (2) growing biomass for biopower and biofuels and thereby replacing fossil fuel. Agroforestry could also protect existing C stocks if improved fallows and similar agroforestry practices could provide food and fuelwood, thereby reducing the rate of deforestation. Despite widespread recognition of agroforestry's potential for C sequestration and biomass production, our understanding of these topics is limited. There is still a lack of quantitative information from specific systems. This thematic issue is an attempt to bring together several original research articles from North America, South America, and Africa that investigate C sequestration and biomass production potential of specific agroforestry practices. While there are issues related to inconsistencies in methodologies, lack of soil C estimates and GHG emissions from soil, and reliable large-scale C estimates for different agroforestry practices, it is apparent that the research community is aggressively generating the much needed data at different scales. This will definitely help quantify agroforestry's role in C sequestration and biomass production and contribute meaningfully to global climate change mitigation efforts.

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