CARBON SEQUESTRATION IN TROPICAL AGROFORESTRY SYSTEMS

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Introduction

Several studies have shown that agroforestry systems, even if they are not primarily designed for carbon (C) sequestration, present a unique opportunity to increase C stocks in the terrestrial biosphere. Agroforestry could play a very important role in reducing the atmospheric concentration of CO_2 by (1) storing C in tree biomass and in soil and; (2) helping protect natural C sinks through the improvement of land productivity and the provision of forest products such as firewood and timber on agricultural land. Expansion of food production and harvest of tree products are often cited among the major drivers for deforestation. If these problems can be addressed through agroforestry, then vast C pools which are increasingly under threat can be protected.

Despite widespread recognition of the potential of agroforestry for C sequestration and other CO_2 mitigating effects, there is still lack of quantitative data on specific systems. This paper reviews and discusses the C storage potential of a few agroforestry systems in the tropics, where widescale practice of agroforestry is most likely to occur. For agroforestry to realise this potential and contribute meaningfully to climate change mitigation, a number of biophysical, socio-economic and institutional constraints will have to be addressed. Some of these issues are discussed in this paper.

The agroforestry systems studied

- Complex agroforestry systems: mixtures of crops and agroforestry trees commonly practised in the humid tropics. Examples include coffee or cacao associated with shade trees, agroforests and homegardens.
- Boundary plantings: windbreaks and live fences are two common examples of boundary plantings.
- Hedgerow intercropping: agroforestry systems where crops are grown between rows of regularly coppiced woody species, to improve soil fertility and structure, and provide other useful products (e.g. fodder) and services (e.g. erosion control).
- Improved fallows: with fast growing leguminous shrubs to improve soil fertility and rehabilitate degraded lands; the major tree products are firewood, poles and stakes.

Potential of agroforestry for C sequestration

With adequate management of trees in cultivated lands and pastures, a significant fraction of the atmospheric C could be captured and stored in plant biomass and in soils (Table 1). The perennial agroforestry systems (tree crop combinations, agroforests, boundary plantings), which allow full tree growth and have an important woody component, store considerable quantities of C in the living biomass. One comparative advantage of these systems is that sequestration does not have to end at wood or tree harvest. C storage can continue way beyond if boles, stems or branches are processed in any form of long-lasting products. Thus, if the necessary arrangements are made to promote small scale wood processing industries (sawmills, wood-carving), the use of high quality wood trees in agroforestry projects can contribute significantly to climate change mitigation while providing small holders with additional cash income. At a national level, this can help create jobs and generate foreign exchange through export of wood products.

Table 1. *Potential C storage for agroforestry systems in different ecoregions of the world*

	Ecoregion	Agroforestry system	Mg C ha^{-1}
Africa	humid tropical high	agrosilvicutural	29–53
South America	humid tropical low	agrosilvicutural	39–102
	dry lowlands		39–195
Southeast Asia	humid tropical	agrosilvicutural	12–228
	dry lowlands		68–81
Australia	humid tropical low	silvopastoral	28–51
North America	humid tropical high	silvopastoral	133–154
	humid tropical low	silvopastoral	104–198
	dry lowlands	silvopastoral	90–175
Northern Asia	humid tropical low	silvopastoral	15–18

Alternatively the wood can serve as fuel, in which case an important part of the plant-stored C returns to the atmosphere. While C sequestration *per se* may be insignificant in such a scenario, producing firewood from arable or grazed land may still present interesting opportunities in CO_2 mitigation through (1) the protection of existing forests and other natural landscapes; (2) the conservation of soil productivity; and (3) the reduction of fossil energy consumption by using wood as energy sources. Adequate understanding of these secondary effects of agroforestry with regards to CO_2 mitigation will require more research.

Agroforestry options that seek to restore degraded croplands and pastures are effective in storing C in the soil. Pre-cultivation C stocks on the present area of cultivated land are estimated at 222 Pg, which may be considered as an upper limit for soil C sequestration. However, instances of increased C stocks relative to those of native soils have been achieved after intensive management of specific biomes. There is enough scientific evidence to suggest that soil C levels can be considerably increased at a global scale if management options that improve land productivity are pursued. Agroforestry trees improve land cover in agricultural fields in addition to providing C inputs (root biomass, litter and prunings) to the soil. The reduction of soil erosion and the improvement of soil structure is a crucial process in the soil C dynamics. Soil C sequestration through agroforestry can significantly contribute to climate change mitigation especially if leakages can be prevented with complementary conservation practices such as minimum tillage, to slow down decomposition and leaching.

Soil C sequestration under improved fallow

Improved fallow is undoubtedly one of the most promising agroforestry technologies and has, in recent years, shown great potential for adoption in southern and eastern Africa. Even in semi-arid areas such as the west African Sahel, recent field experiments have shown that the technology could significantly contribute to improving soil fertility, curbing land degradation and increasing crop yields. Several studies have shown increased soil organic matter after a few seasons of tree planting on degraded soils. The examples used in *Table 2* mainly came from on-farm trials conducted in Togo and Kenya. Several tree species have been tested with various degrees of success. Soil organic carbon accretions through improved fallow were estimated between 0.73 and 12.46 Mg ha^{-1} depending on sampling depth.

Table 2. *Soil organic carbon (SOC) increase in a few tropical soils following improved fallows with different tree species in the sub-humid tropics*

Country	Fallow duration	Soil type	Fallow species	Sampling depth	SOC increase (Mg ha^{-1})
Togo	5	Ferric Acrisol (sandy)	*Acacia* *auriculiformis*, *Albizzia lebbek*, *Azadirachta indica*, *Cassia siamea*	0-10 cm	3.41 – 12.46
Kenya	1.5	Arenosol (sandy)	*Crotalaria grahamiana*, *C. paulina*	0-20 cm	1.69 – 2.15
Kenya	1.5	Ferralsol (clayey)	*C. grahamiana*, *C. paulina*, *Tephrosia vogelii*	0-20 cm	2.58 – 3.74
Kenya	1	Ferralsol (clayey)	*Cajanus cajan*, *Leucaena leucocephala*, *Sesbania sesban*	0-30 cm	0.73 – 8.34

The build-up of soil C depends on the interactions between soil type, tree species, water availability and other environmental factors. *Figure 1* summarises results from some improved fallow trials in western Kenya. On the sandy soil (Teso), although biomass production was generally low, *C. paulina* and *C. grahamiana* fallows increased C stocks by about 2 Mg ha^{-1} while *T. vogelii* and *T. candida* induced no significant changes. In the clayey soil (Lubao), there was an increase of C stocks in all the improved fallows, with the extent of accretion (2.5–3.74 Mg ha^{-1}) being positively correlated with the biomass produced by the fallow. These results showed that the choice of the appropriate tree species and management practices for a specific environment will be crucial.

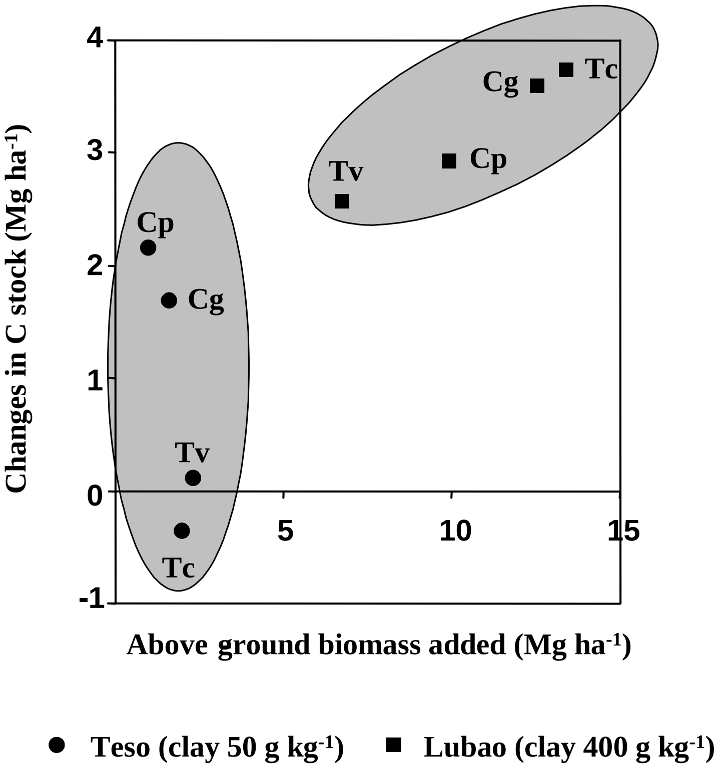

Figure 1. *Changes in carbon stocks in the 0–20 cm soil layer after 18-month old improved fallows relative to continuous crop in western Kenya* (Cg = *Crotalaria grahamiana*; Cp = *Crotalaria paulina*; Tc = *Tephrosia candida*; Tv = *Tephrosia vogelii*)

Advantages of agroforestry as a C sequestration strategy

If the entire earth's area that is suitable for agroforestry (585–1215 x 10^6 ha) were converted to accommodate some form of tree cultivation, 1.1–2.2 Pg C could be sequestered annually over 50 years, which could offset only about 10–15% of the current annual C emissions. Looking at this contribution, it becomes clear that agroforestry alone cannot solve the current climatic problems.

There is tremendous merit, however, in promoting agroforestry projects for C sequestration especially if the ancillary benefits of cultivating trees on farm are considered:

(1) given the improbability of obtaining any single mitigating method, adding modest contributions together appears to be a more realistic way of achieving CO_2 reduction targets;

(2) the implementation of agroforestry projects will have other environmental and socio-economic benefits way beyond the mere climatic concerns. Increasing soil C greatly benefits agricultural productivity and sustainability, and the presence of trees in agricultural landscapes enhances biodiversity, improves microclimate and beauty and provides watershed services;

(3) the financial cost of C sequestration through agroforestry appears to be much lower (approximately $1–69/Mg C, median $13/Mg C) than through other CO_2 mitigating options. Economic analyses showed that these costs could be easily offset by the monetary benefits from agricultural and tree products. Trading in C credits is another

option, which could make C sequestration through agroforestry more attractive to land users.

Limitations and uncertainties for carbon sequestration

Replacing grasslands by tree-based systems does not automatically guarantee an increase in C stocks. In a study conducted in the United States, it was shown that the invasion of grasslands by shrubs resulted in a negative net C balance in some areas. Such findings suggest that the current land-based methods of C assessment may have led to an overestimation of C sinks in many areas of the globe. These inaccuracies will be compounded further if we consider that changes in C fluxes are likely to occur in the next 50 years as a result of shift in global climate, land-use and land cover. The magnitude and direction these changes will take remain largely unknown.

Degraded soils and wastelands occupy a large proportion of the earth's area and there is general belief that converting them into agroforestry would be a major global opportunity to absorb a significant portion of the atmospheric CO_2. However, cultivating trees or crops in sub-standard soils still remains a major challenge. On infertile soils (for example acid soils) or in semi-arid areas, trees usually perform poorly, making such environments little suitable for some types of agroforestry. There have been many reports indicating unchanged, or even declining, soil organic matter (SOM) levels after hedgerow intercropping on substandard soils and in dry environments. Moreover, in dry environments, the tree – crop competition for water usually results in low crop yields, which makes HI unattractive for dryland farmers. Some of these problems can be overcome if the specific limiting factors are identified and dealt with adequately. For example, in some areas of western Kenya phosphorus deficiency limits tree growth, but encouraging results are observed with the application of rock phosphate.

As shown in the above sections, improved fallow is a promising technology for increasing C stocks in degraded soils. But, a major problem with implementing sequential agroforestry systems in general is that farmers have to forego growing crops during the fallow phase, which can stretch on one or more cropping seasons. Although IF can ameliorate soil conditions in a much shorter time than natural fallows, they are still not very realistic in areas with high population density. Pests and diseases are other key issues that deserve to be addressed more adequately if the improved fallow technology is to spread and reach a wider number of farmers. Various species of damaging insects and plant-parasitic nematodes have been associated with fallow trees. These represent a major threat to the development of agroforestry in the tropics.

What about the other GHG's?

If carbon fluxes in agroforestry systems are well documented, this is not the case for other trace gases such as nitrous oxide (N_2O) and methane (CH_4). Legumes play a prominent role in agroforestry and are effective in improving the nutrient status of nitrogen-depleted soils. Recent studies have shown that nitrogen (N) inputs derived from agroforestry practices such as improved fallows can entirely substitute mineral N fertilisers. However, if the tree-derived

N exceeds the agronomic requirements of subsequent crops or is not used efficiently, there is a risk of volatilisation in the form of N_2O. N_2O is one of the most important trace gases and has a global warming potential (GWP) 200-300 times higher than that of CO_2. Thus, there is growing concern that the widescale use of woody legumes might result in massive release of N_2O gas into the atmosphere.

Similarly, ungulate production and cultivation of rice paddy in agroforestry systems can produce significant quantities of CH_4 on a global scale. More research will, therefore, be needed to clearly understand the implications of agroforestry vis-à-vis the emission of trace gases. The success of agroforestry in addressing issues related to climate change will be determined, among other factors, by the trade-offs between C sequestration and the emission of other greenhouse gases such as N_2O and CH_4 to the atmosphere.

Conclusions

This review gave a description of a few agroforestry systems practised in the tropics in relation to their C sequestration potential. The analysis of C stocks from various parts of the world showed that significant quantities of C (1.1–2.2 Pg) could be removed from the atmosphere over the next 50 years should agroforestry systems be implemented on a global scale. C storage depends on several factors including climatic, edaphic, and socio-economic conditions. Perennial systems like homegardens and agroforests can store and conserve considerable amounts of C in living biomass and also in processed wood products. C sequestration in soils is also realistic with most agroforestry practices including short-rotation systems such as improved fallows and hedgerow intercropping. However, it is apparent that C storage in agroforestry systems and its eventual consequences on the global climate are fraught with a number of uncertainties. Consequently, there is still some work to be done to improve our understanding of C sequestration and GHG mitigation. Data and research needs include:

(1) Standardised methodologies for estimating above – and below–ground C stocks to improve the reliability of data.
(2) Consideration of other C stocks often left out in estimates; these include deep soil C (especially when trees are involved) and C in durable wood products.
(3) Predictive models to accommodate future climate and land-use changes and their implications for CO_2 mitigation through agroforestry systems
(4) Adequate understanding on issues such as pests and diseases and the emission of other GHGs, especially N_2O and CH_4 in agroforestry systems
(5) More powerful methods to implement cost/benefit analyses of agroforestry-based GHG mitigation and to define incentives for widescale adoption of agroforestry.