Agroforestry Systems **27**: 89–97, 1994.

Carbon storage benefits of agroforestry systems*

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Key words: carbon dioxide, climate change, carbon dynamics, deforestation

Abstract. The process of land degradation is a local phenomenon that occurs field by field. Because of the extent at which it is occurring, however, it also has a global dimension. Agroforestry represents a link between the local and global scales. From the farmer's perspective, agroforestry can be a way to increase crop yields and the diversity of products grown. An additional benefit is the creation of a carbon sink that removes carbon dioxide from the atmosphere. Successful agroforestry systems will also reduce land clearing and maintain carbon in existing vegetation. An extensive literature survey was conducted to evaluate the carbon dynamics of agroforestry practices and to assess their potential to store carbon. Data on tree growth and wood production were converted to estimates of carbon storage. Surveyed literature showed that median carbon storage by agroforestry practices was 9 tC/ha in semi-arid, 21 tC/ha in sub-humid, 50 tC/ha in humid, and 63 tC/ha in temperate ecozones. The limited survey information available substantiated the concept that implementing agroforestry practices can help reduce deforestation.

Introduction

The process of land degradation occurs at a local scale, field by field, but it also has a global dimension because of the sheer extent at which it is taking place. Estimates of the total area of degraded land in the tropics are variable, but they are generally in agreement that it is at least several hundred million ha and perhaps as much as 1000 million ha to date. The total area is growing each year as 17 million ha are deforested by conversion to agriculture and pasture and due to logging [World Resources Institute, 1992]. On the global scale, deforestation results in the release of approximately 1000 million tons of carbon to the atmosphere each year [Houghton, 1991] in the form of carbon dioxide (CO_2), an important greenhouse gas. This is about 15% of the total human-caused carbon emissions and is a significant portion of the global carbon cycle that could contribute to global climate change. An important question is whether agroforestry, implemented at the local level to satisfy local

* The research described in this article has been funded by the US Environmental Protection Agency. This document has been prepared at the EPA Environmental Research Laboratory in Corvallis, Oregon, through contract number 68-C8-0006 to ManTech Environmental Technology, Inc. It has been subjected to the Agency's peer and administrative review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

needs, can also provide carbon storage benefits to help slow the increase in atmospheric carbon dioxide.

The Earth's terrestrial vegetation plays a pivotal role in the global carbon cycle. Not only are tremendous amounts of carbon stored in the terrestrial vegetation, but large amounts are also actively exchanged between vegetation and the atmosphere. One estimate is that on average the equivalent of the entire CO_2 content of the atmosphere passes through the terrestrial vegetation every 7 years, with about 70% of the entire exchange occurring through forest ecosystems [Waring and Schlesinger, 1985]. This dynamic relationship means that any land use practices that increase vegetative cover, or reduce its removal, could have an influence on the global carbon budget by increasing the terrestrial carbon sink.

In the context of climate change and the global carbon cycle, agroforestry is of interest for at least two reasons. The first is that the tree component fixes and stores carbon from the atmosphere via photosynthesis. Because trees are perennial plants, they can function as active carbon sinks for periods of many years, and continue to store carbon until they are cut or die. The second reason for interest in agroforestry is its apparent potential to reduce the need to clear new forest land for agriculture by providing an alternative to shifting cultivation [Andrasko et al., 1991; Nair and Fernandes, 1984; Sanchez et al., 1990; Wiersum, 1990; Winterbottom and Hazelwood, 1987]. As many as 300 million people are dependent on some form of shifting cultivation, and they account for about 60% of all forest clearing [Myers, 1991]. This initial clearing is often the first stage of transfer of these lands to large scale grazing or other uses.

Much has been written about the theory and potential of agroforestry at the local level, the level at which it is practiced. This paper will evaluate the potential of agroforestry from a global perspective. Its objectives are to assess the ability of agroforestry systems to store carbon directly and to conserve carbon by reducing the need to clear land for agriculture. It is recognized that the intent and motive of practicing agroforesters are not to ameliorate the global carbon cycle. Their objective is sustainable agricultural production. Any additional benefits that accrue to the global carbon cycle are purely ancillary in nature. However, enhanced carbon storage would provide yet another reason to support the development and implementation of agroforestry systems.

Approach

Over the past 10–15 years or more the body of agroforestry knowledge has grown steadily. The approach taken here was to exploit this information base by conducting an extensive survey of the published technical literature. Most of this literature understandably focuses on crop production by agroforestry systems. A smaller portion concentrates on production by the tree component, and little or none directly assesses patterns of carbon accumulation. It was necessary, therefore, to use published information on tree growth patterns to estimate carbon storage. Most of this information is reported as stem wood volume which had to be converted to total above-ground carbon mass. Accumulation of below-ground carbon in roots and soil organic matter was not included. Inclusion of below-ground carbon would increase the estimates presented here. In the few studies that have measured root mass, roots have represented about 10% of above-ground biomass in humid areas [Fassbender et al., 1991] and have averaged about 30% of above-ground biomass in semi-arid areas [Ahimana and Maghembe, 1987; Toky and Bisht, 1992]. Additional research on root growth and below-ground biomass in agroforestry systems is much needed.

Stem wood volume data from the literature was multiplied by wood specific gravity for each species [Chudnoff, 1979] to estimate stem biomass (dry weight basis). Published information on biomass partitioning between plant parts (e.g. stem, branches, leaves) was used to establish ratios to estimate total above-ground biomass from stem biomass. Six examples of biomass partitioning in agroforestry systems, from four studies [Alpizar et al., 1986; Maghembe et al., 1986; Ngambeki, 1985; Verma, 1987], had a mean ratio of total aboveground biomass to stem wood biomass of 2.15 (range = 1.93 to 2.40). This ratio was multiplied by stem biomass to estimate total aboveground biomass in most of the studies used here. Where tree stocking density was high (> 500 trees/ha), however, and the growth cycle or rotation length was relatively long (> 10 yrs), conditions more similar to a forest plantation situation, a ratio of 1.6 was used to estimate total biomass [Dixon et al., 1991; Marland, 1988; Sanchez and Benites, 1987]. The carbon content of biomass was assumed to be 50% [Brown and Lugo, 1982]. This string of calculations estimated total above-ground carbon from published data on stem wood volume.

In an agroforestry system, trees are grown for the essential products that they can provide; we can assume that most will be periodically harvested and used. Depending on the end use, much or all of the carbon in harvested material will return to the atmosphere in a relatively short time. How then can we assess the long-term carbon storage implications of agroforestry? The relevant parameter in terms of the carbon cycle is the average amount of carbon on-site over one or more growth cycles [Dixon et al., 1991; Graham et al., 1990; Schroeder, 1992]. The calculation is made by summing the carbon standing crop for each year in the cycle and dividing by the length of the cycle, the simple calculation of a mean. This method was used in the analysis presented here. In some agroforestry systems (i.e. homegardens) trees themselves may never be harvested. However, no such examples were included here because information on their biomass content is unavailable.

The data were stratified by ecozone using the same broad ecozone classification scheme as Swinkels and Scherr [1991] in their survey of agroforestry literature. Ecozones were defined as follows: Humid, precipitation > 1600 mm/yr; Sub-humid, precipitation = 800–1600 mm/yr; Semi-arid, precipitation = 400–800 mm/yr; Temperate, temperate zone climates.

Results

Carbon storage

Table 1 shows the median values of carbon storage for the four ecozones in the analysis. Preliminary analyses showed that the data were not normally distributed. Conventional statistics like mean and standard error are not appropriate for characterizing this kind of data. A more appropriate measure of central tendency is the median because it is resilient to extreme values and skewed distributions [Devore and Peck, 1986].

Table 1. Median values for aboveground carbon storage, annual growth rate, and rotation length for agroforestry practices in different ecoregions. n = number of studies located in the literature; tC = tons of carbon.

Ecozone	Carbon storage (tC/ha)	Growth rate (tC/ha/yr)	Cutting cycle (yrs)	n
Semi-arid	9	2.6	5	15
Sub-humid	21	6.1	8	15
Humid	50	10.0	5	8
Temperate	63	3.9	30	4

The highest level of carbon storage was for the temperate ecozones, 63 tC/ha. Carbon storage for the humid ecozones was 50 tC/ha, for the sub-humid ecozones it was 21 tC/ha, and for the semi-arid ecozones it was 9 tC/ha. The effect of cutting cycle length on the accumulation of biomass and carbon is apparently the reason that the temperate and humid ecozones have similar carbon storage values. As might be expected, growth rates for humid tropical ecozones were over twice those for the temperate ecozones, 10 tC/ha/yr versus about 4 tC/ha/yr. However, for the examples surveyed, the cutting cycle was six times longer in the temperate than humid ecozones, 30 versus 5 years. As a result, biomass accumulation is restricted in the humid ecozones.

The net effects on carbon storage of implementing agroforestry depend on the carbon content of the land use practices that is replaces. There are at least three land type categories that would be top candidates for agroforestry: currently degraded and non-productive land, lands that are in more or less permanent agriculture or pasture that could be supplemented with tree planting, and lands under short fallow agriculture. The first two of these categories generally have depleted above-ground carbon pools, and therefore the net carbon increase would be approximately as much as the results reported above (Table 1).

Short fallows of even less than five or so years, however, represent a substantial carbon storage pool. Five estimates of regrowth of 5–6-year-old fallows in the humid and sub-humid tropics [Brown and Lugo, 1990; Trexler and Haugen, 1991; Uhl, 1987] were used to calculate their mean carbon standing stock. The results ranged from 7–12 tC/ha with a mean of 10 tC/ha. Subtracting this from the results in Table 1 results in net carbon storage of 11 and 40 tC/ha for sub-humid an humid ecozones respectively. Data in Brown and Lugo [1990] were also used to estimate a mean carbon standing stock of a 4-year-old dry tropical secondary forest of about 5 tC/ha. Subtracting this amount from the estimate in Table 1 results in net carbon storage of about 4 tC/ha for semi-arid ecozones. Agroforestry systems, as expected, therefore, generally store less carbon than natural forests or plantations because growing space must be shared with crop plants.

Agroforestry systems also have an effect on soil organic carbon pools. Fassbender et al. [1991] observed that soil carbon increased 10 t/ha (9%) and 22 t/ha (21%) under cacao and cacao/*Erythrina* respectively over a 10-year period. Atta-Krah [1990] reported that an alley cropping system maintained soil organic carbon levels over four years while a monocropped control showed a decrease. In a study by Kang et al. [1985], soil carbon content was 1.07% when prunings were returned to the soil, but only 0.65% when they were removed from the field. Lal [1989] reported that soil organic carbon decreased during a six-year alley cropping experiment, but that the alley cropping treatment had significantly higher soil organic carbon than either of the plow-till or no-till treatments. He attributed superior carbon status to the addition of prunings to the soil in the alley cropping treatment as well as to greater root biomass.

Carbon conservation

When agroforestry is developed as a sustainable, permanent agricultural practice, then two expected results should be reduced clearing of mature forest to create new agricultural land and extended regrowth of fallows that no longer need to be recleared on short cycles. Brown and Lugo [1984] reported that the average aboveground biomass for humid tropical forests, including both disturbed and undisturbed, was about 140 t/ha. If this biomass is composed of about 50% carbon, then average carbon density is 70 tC/ha. In another study, Brown and Lugo [1990] cited maximum biomass accumulation for secondary tropical forests of 200 t/ha, or about 100 tC/ha, at age of 80 years. A chronosequence study in Venezuela and Colombia provides additional information about the rate of biomass accumulation in secondary tropical forests. Saldarriaga [1985] found that by age 40 years forest fallows had accumulated about 50% of the biomass of mature forest stands. Putting this information together, we can make some first approximation estimates of carbon conserved or 'secondarily accumulated' (i.e. by fallows) by establishment of agroforestry practices. Each hectare of mature forest conserved as a result of agroforestry should contain, on average, 70–100 tC. Forest fallows that are allowed to regrow should accumulate 35–50 tC/ha over the first 40-year period. These levels of carbon storage and conservation would be in addition to carbon stored directly by the tree component of agroforestry systems.

Published literature contains very few reports on the effects of agroforestry on forest clearing. Although several publications suggest the potential of agroforestry to have a beneficial influence on land clearing practices, this survey found only three examples where a land clearing effect was quantified or where information is presented that allows an estimation. Trexler and Haugen [1991] state that the ratio of cleared area foregone to agroforestry implemented could be 7:1. In a 1-ha experimental study, Sanchez and Benites [1987] demonstrated a low-input cropping system that produced the agricultural equivalent of 14 ha of slash and burn practices implying a 14:1 ratio. Finally information reported by Morningstar [1989] implies an 11.5:1 ratio for implementation of agroforestry in Sarawak.

This limited information on land clearing does not allow us to draw any conclusions on how much carbon could be conserved a result of implementing agroforestry. However, it gives a preliminary indication that the outcome is potentially significant. If the ratio of clearing foregone to agroforestry implemented was as great as 5:1, the amount of carbon conserved in mature forest would be 350–500 tC/ha (based on a carbon content of 70–100 tC/ha). For secondary forest, 5 ha of conserved forest represents 175–250 tC/ha (based on a carbon content of 35–50 tC/ha). All of these values are considerably higher than those for carbon stored directly by agroforestry practices. They are also higher than the estimated carbon storage potential of tree plantations [Dixon et al., 1991; Schroeder, 1992]. These first approximations are promising, but clearly there is a need for additional information on this topic. More information is needed from actual agroforestry programs to determine what levels of forest clearing offset are realistically attainable.

Discussion

Despite its promise and its environmental desirability, agroforestry may not always be the most desirable alternative; it depends on specific situations (environmental, economic, and social) and other available options. For example, an analysis in Nigeria found that where access to new forest land is essentially costless (i.e. low population pressure and abundant forest), traditional bush fallow agriculture with a long fallow period is advantageous, but where there is heavy population pressure on land resources, an alley cropping agroforestry system was the most desirable option [Dixon et al., 1991]. There may also be instances where farmers have too little land, technical knowledge, or labor to adopt agroforestry. In such tightly constrained circumstances, agroforestry may place too much of a burden on these limited resources [Hosier, 1989]. In general, however, the prospects for the implementation and use of agroforestry practices should be good. It is a very adaptable technology that can take many forms and fulfill the requirements of many different situations.

It is risky to attempt to estimate the total amount of carbon that could be stored by agroforestry because current estimates of land available for conversion to agroforestry are uncertain. The most realistic estimate may be the 160 million ha in the tropics derived by Trexler and Haugen [1991]. They included economic, social, and political factors that affect land availability in addition to its biological suitability. Their analysis distributed the total 160 million ha roughly equally between the three tropical zones, but it did not distinguish between ecozones. A very rough approximation of the potential range for total carbon storage is possible by multiplying their total estimate of available land by each of the carbon storage estimates in Table 1. The result is between about 1500 million tC and 8000 million tC. Improved and refined estimates of land availability are required to reduce the uncertainties in these values.

Estimates of total carbon conservation potential of agroforestry resulting from reduced deforestation are unavailable. Currently available limited evidence indicates that the potential is real, but impossible to quantify. Additional efforts should be directed to resolving this uncertainty because reducing deforestation might have a larger impact on the global carbon cycle than direct carbon storage by agroforestry practices. However, additional research on the carbon storage patterns and carbon dynamics of agroforestry practices is also needed.

Acknowledgements

I am particularly grateful to Greg Baumgardner, ManTech Environmental Technology, Inc., for his assistance in designing and implementing the database that was used to organize the results of the literature survey. Without his assistance completing this project would have been a much more tedious and time consuming undertaking. I would also like to thank Barb Hagler, Computer Services Corporation, for her invaluable help in locating and obtaining virtually all of the reference material that went into this analysis. Ken MacDicken, Marcelino Avila, and L. Krishnamurthy reviewed an earlier draft of this paper and provided many valuable suggestions. Two anonymous reviewers were also helpful.

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