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Agroforestry systems: integrated land use to store and conserve carbon

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ABSTRACT: Agroforestry is a promising land use practice to maintain or increase agricultural productivity while preserving or improving fertility. From the perspective of climate change and the global carbon cycle, agroforestry practices are attractive for 2 reasons: they directly store carbon in tree components, and they potentially slow deforestation by reducing the need to clear forest land for agriculture. 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 t C ha^{-1} in semi-arid, 21 t C ha^{-1} in sub-humid, 50 t C ha^{-1} in humid, and 63 t C ha^{-1} in temperate ecoregions. The limited survey information available tended to substantiate the concept that implementing agroforestry practices can help reduce deforestation.

INTRODUCTION

The loss of forest cover often entails environmental degradation and a subsequent decline in site productivity. This is true in many parts of the world, but particularly in the tropics where most essential nutrients are contained in aboveground vegetation. After clearing and burning, these nutrients are soon depleted and soil fertility is reduced. A fallow period of 10 or more years is required to restore nutrient capital and fertility (Sabhasri 1978). However, human population growth and the need for agricultural expansion, in conjunction with wood harvesting for fuel and export, have led to increasing deforestation rates. The consequences are not only reduced soil fertility, but also rising prices, erosion, floods, reservoir siltation, and desertification (Allen & Barnes 1985). Approximately 65 % of the land in the tropical world, which is home to over 630 million people, is susceptible to such degradation (King 1979).

Agroforestry is a promising land use practice to maintain or increase agricultural productivity while preserving or improving fertility. Broadly defined, agroforestry is 'a land use that involves deliberate retention, introduction, or mixture of trees or other woody perennials in crop/animal production fields to benefit from the resultant ecological and economic interactions' (MacDicken & Vergara 1990). Examples of agroforestry systems include alley cropping, multilayer tree gardens, interplanting of trees on crop land, live hedges, and shelterbelts. A typical agroforestry system allows synergistic interactions between woody and non-woody components to increase, sustain, and diversify total land output (Swaminathan 1987). Important interactions are improved nutrient cycling and retention, moderation of microclimate, and diversification of product outputs.

From the perspective of climate change and the global carbon cycle, agroforestry is attractive for at least 2 reasons. The first is that the tree component fixes and stores carbon from the atmosphere. Because trees are perennial plants they can function as active carbon sinks for periods of many years; trees continue to store carbon until they are cut or die. As much as 500 to 600 million ha of tropical land may be suitable for agroforestry (Houghton et al. 1991), although practices could probably be established on only about 160 million ha by the middle of the next century (Trexler & Haugen 1991). A second 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 (Nair & Fernandes 1984, Winterbottom & Hazelwood 1987, Sanchez et al. 1990, Wiersum 1990, Andrasko et al. 1991). Current estimates are that 1 to 2 Gt of carbon are released to the atmosphere annually due to deforestation (Houghton 1991). This is not all the result of clearing for agriculture, but a significant portion is. 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).

The many and varied contributions of the tree component are the key to the ecological benefits of agroforestry (Kang & Wilson 1987, Young 1989, Ingram 1990). A key structural attribute of agroforestry is multiple vertical strata that occupy space efficiently and provide a range of growing conditions. The tree canopy provides shade and reduces evaporation from the soil. This shading effect also reduces temperature and provides a more moderate microclimate for crop growth. The tree canopy also provides shelter from wind and protects the soil from the impacts of heavy rain and helps to reduce soil erosion. Leaf litterfall acts as a mulch and reduces both evaporation and surface runoff and erosion. Incorporation of leaves into soil adds organic matter and improves soil quality. Belowground, tree roots penetrate to deeper soil layers than crop roots and bring nutrients to the surface via leaf fall. Nitrogen-fixing agroforestry tree species capture that key nutrient from the atmosphere and make it available to crop plants. The economic benefits of agroforestry derive from diversification of outputs, spreading risk, and, in many cases, actually increasing physical output (MacDicken & Vergara 1990). These characteristics may also make agroforestry systems more resistant to climate change than monocropping systems.

Much has been written about the potential and promise of agroforestry systems. This paper evaluates the carbon dynamics of agroforestry practices and assesses their potential contribution to slowing the increase of atmospheric CO_2. The evaluation is based on several criteria: (1) levels of direct carbon storage, (2) levels of carbon conservation resulting from reduced land clearing, (3) crop production, and (4) profitability. The focus of the analysis is primarily on tropical agroforestry practices; where available, information for practices in the temperate zones will be included for comparison.

APPROACH

Over the past 10 to 15 yr or more, the body of agroforestry knowledge has grown steadily. This information base was exploited by conducting an extensive survey of the published technical literature. Most of this literature 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 was converted to total aboveground carbon mass. Accumulation of belowground carbon in roots and soil organic matter was not included. Adding belowground carbon would increase estimates even more.

Stem wood volume was first multiplied by wood specific gravity for each species (Chudnoff 1979) to estimate stem biomass. Published information on biomass partitioning between plant parts (e.g. stem, branches, leaves) was used to establish ratios to estimate total aboveground biomass. Six examples of biomass partitioning in agroforestry systems, from 4 studies (Ngambeki 1985, Alpizar et al. 1986, Maghembe et al. 1986, Verma 1987), had a mean ratio of total aboveground biomass to stem wood biomass of 2.15 (range = 1.93 to 2.40). Where tree stocking density was high (>500 trees ha^{-1}) and the growth cycle or rotation length was relatively long (>10 yr), conditions more similar to a forest plantation situation, a factor of 1.6 was used (Marland 1988, Sedjo 1989, Dixon et al. 1991). The carbon content of biomass was assumed to be 50 % (Brown & Lugo 1982).

In an agroforestry system, trees are grown for the essential products that they provide; we assume that these trees 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 (Harmon et al. 1990). 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 (Graham et al. 1990, Dixon et al. 1991, 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 this analysis. In sequential or rotational cropping systems, an adjustment would have to be made for the length of the cropping phase when no trees would be present. However, all of the agroforestry practices included in this analysis involved some form of intercropping in which trees and crops are grown simultaneously and trees are always present.

The data were stratified by ecozone using the same broad ecozone classification scheme as Swinkels & Scherr (1991) in their survey of agroforestry literature.

Ecozones were defined as follows: humid, precipitation >1600 mm yr^{-1}; sub-humid, precipitation = 800 to 1600 mm yr^{-1}; semi-arid, precipitation = 400 to 800 mm yr^{-1}; temperate, temperate zone climates.

The literature survey also included information on the economics of agroforestry, particularly the present net value (PNV) of agroforestry practices. All reported results were converted to 1990 US dollars. National inflation rates and exchange rates for different years and countries were taken from the International Financial Statistics Tables published by the International Monetary Fund (IMF 1990, 1991). To calculate PNV, future revenue must be discounted to the present (the opposite of compounding a present value to some point in the future). A 12% discount rate was used to calculate PNV for agroforestry practices in developing countries where poorer farmers are less able to delay consumption and have a high time preference rate (Hoekstra 1985, Hosier 1987). Revenues in the distant future are far less valuable to these farmers who require an income in the present or near future. For temperate regions, a 7.5% discount rate was most commonly encountered in the literature and was used here also.

DIRECT CARBON STORAGE

Table 1 shows the median values of carbon storage for the 4 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 such data. A more appropriate measure of central tendency is the median because it is resilient to extreme values and skewed distributions (Devore & Peck 1986).

The lowest level of carbon storage was 9 t C ha^{-1} in the semi-arid ecozones. Carbon storage for the sub-humid ecozones was 21 t C ha^{-1}, for the humid ecozones it was 50 t C ha^{-1}, and for the temperate ecozones it was 63 t C ha^{-1}. Similarity of carbon storage values for the temperate and humid ecozones is explained by length of the growth or cutting cycles and how cycle length affects accumulation of biomass and carbon. As expected, growth rates for humid tropical ecozones were over twice those for the temperate ecozones, 10 t C ha^{-1} yr^{-1} versus about 4 t C ha^{-1} yr^{-1}. For the examples of agroforestry surveyed, however, the average cutting cycle was 6 times longer in the temperate than humid ecozone, 30 yr versus 5 yr. As a result, biomass accumulation is restricted in the humid ecozones. The relationship between carbon storage, growth rate, and cycle length is nonlinear. As length of the cutting cycle increases, the growth rate required to maintain a given level of carbon storage decreases at a decreasing rate. For longer cutting cycles, a given change in growth rate causes relatively greater change in carbon storage than for short cutting cycles.

The net effects on carbon storage of implementing agroforestry practices depend on the carbon content of the land uses that they replace. At least 3 land type categories are 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 2 categories have depleted aboveground carbon pools; therefore the net carbon increase should be approximately as much as results shown in Table 1.

However, the third land use category, short fallows of less than 5 yr, represents a substantial carbon storage pool. Five estimates of regrowth of 5 to 6 yr old fallows in the humid and sub-humid tropics (Toky & Ramakrishnan 1983, Uhl 1987, Brown & Lugo 1990) were used to calculate mean carbon standing stock. Results ranged from 7 to 12 t C ha^{-1} with a mean of 10 t C ha^{-1}. Subtracting this mean from the results in Table 1 results in net carbon storage of 11 and 40 t C ha^{-1} for sub-humid and humid ecozones respectively. Data in Brown & Lugo (1990) were also used to estimate a mean carbon standing stock of a 4 yr old dry tropical secondary forest of about 5 t C ha^{-1}. Subtracting this amount from the estimate in Table 1 results in net carbon storage of about 4 t C ha^{-1} for semi-arid ecozones.

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

Ecozone	Carbon storage (t C ha^{-1})	Growth rate (t C ha^{-1} yr^{-1})	Cutting cycle (yr)	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

CARBON CONSERVATION

If agroforestry is developed as a sustainable, permanent agricultural practice, then 2 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 & Lugo (1984) reported that the average aboveground biomass for humid tropical forests, including both disturbed and undisturbed, was about 140 t ha^{-1}. If this biomass is composed of about 50 % carbon, then average carbon density is 70 t C ha^{-1}. In another study, Brown & Lugo (1990) cited maximum biomass accumulation for secondary tropical forests of 200 t ha^{-1}, or about 100 t C ha^{-1}, at age 80 yr. 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 yr 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 to 100 t C. Forest fallows that are allowed to regrow should accumulate 35 to 50 t C ha^{-1} over the first 40 yr 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 3 examples where a land clearing effect was quantified or where information was presented that allows an estimation. Trexler & Haugen (1992) state that the ratio of cleared area foregone to agroforestry implemented could be 7:1. In a 1 ha experimental study, Sanchez & 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 as 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 were as great as 5:1, the amount of carbon conserved in mature forest would be 350 to 500 t C ha^{-1} (based on a carbon content of 70 to 100 t C ha^{-1}). For secondary forest, 5 ha of conserved forest represents 175 to 250 t C ha^{-1} (based on a carbon content of 35 to 50 t C ha^{-1}). 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.

CROP PRODUCTION

Current interest in agroforestry arises from its apparent potential to increase agricultural productivity. In many cases this potential has been realized. The effect whereby intercropping 2 or more species increases yield has been called facilitation (Vandermeer 1989) or complementarity (Filius 1988). It results when an organism affects the environment in a positive way with respect to other organisms. Examples exist in the literature where, at least in experimental applications, agroforestry practices have been significantly more productive than conventional agriculture. For example, in Nigeria, intercropping with Leucaena trees increased maize yield by 68 % (Ngambeki 1985). Pasture grass in Australia was more productive when grown in conjunction with trees (Wilson et al. 1990). Tea yields in China were 30 % higher under trees than without trees (Yu et al. 1991). MacDicken & Vergara (1990) reviewed 11 examples of crop yield improvements of 14 to 367 % under coconut, with a mean increase of 89 %. They also cite 5 examples of crop yield increases under *Acacia albida* that average 78 %. These yield improvements presumably occurred because of microenvironmental improvements caused by the trees (e.g. shading or nitrogen fixation).

Other results, however, suggest that agroforestry practices may be less effective than monocropping in some circumstances. Competition occurs when an organism affects the environment in a negative way with respect to other organisms (Vandermeer 1989). The primary environmental resources for which plants compete are light, water, and soil nutrients (Trenbath 1974); competition may be most intense where these factors are most limiting. For example, Kang et al. (1989) found that the agroforestry practice of alley cropping is not as promising in semi-arid as humid zones because of greater competition for moisture between crops and trees. Nair (1990) also cites 9 examples from India, Nigeria, and Kenya where crop yields were lower for agroforestry than for monocropping. Differences in the morphology and physiology of mixture constituents can cause their individual members to experience different microenvironments and resource availabilities than those grown in monoculture (Trenbath 1974). The end result may be reduced production in the agroforestry system.

PROFITABILITY

The present net values reported in the literature were extremely variable and it was not possible to make any quantitative generalizations for the different ecozones or practices. PNV varied by 2 orders of magnitude from a low of US$54 ha^{-1} to a high of over US$6000 ha^{-1}. The median of all values ($n = 34$) was about US$1200 ha^{-1}. Trexler & Haugen (1992) reached a similar conclusion in an analysis of forestry projects. The economics of forestry projects were so dependent on country- and project-specific variables that no general conclusions could be justified. The term agroforestry encompasses a wide variety of practices in a wide variety of circumstances and countries. Economic attractiveness is affected by the type and level of product outputs, existence and access to markets, transportation infrastructure and costs, and alternative employment opportunities.

Numerous individual examples in the literature illustrate situations where agroforestry is more profitable than alternative forms of agriculture. In the temperate zone, several studies have shown that growing trees in conjunction with livestock grazing is more profitable than grazing alone (e.g. Arthur-Worsop 1984, Doyle et al. 1986, Anderson et al. 1988). For a study in China, He (1991) reported that intercropping with trees in the warm temperate zone was 136 to 158% more profitable than growing wheat or other crops singly. Similar instances exist in the tropics. In India, intercropping was more profitable than either tree or crop monocultures (Srivastava & Pant 1979, Shekhawat et al. 1988). Ngambeki (1985) related the same result for Nigeria where the reduced nitrogen requirement and increased maize output made intercropping more economically attractive than monocropping. In Tanzania, gross revenues from agroforestry were over 7 times greater than those from conventional maize/bean agriculture (Cook & Grant 1989).

The only conclusion reached from a survey of economic information is that agroforestry can be economically profitable in a wide variety of circumstances. The biological significance is that profitable agroforestry systems also store carbon at no additional cost. However, agroforestry practices may not always be the most economically attractive option, as is discussed below.

We should not be surprised that agroforestry systems can produce positive PNVs. If such was not the case, interest in agroforestry would have waned long ago. Positive PNV alone, however, may not be a sufficient incentive for smallholders to adopt agroforestry (Hosier 1987, 1989). Agroforestry is an approach for increasing the intensity of land use by applying labor. Although labor is generally assumed to be plentiful and, therefore, of low value, its value is not zero. Farmers can apply their labor on the farm to various agricultural practices, or sell it on the market by accepting off-farm employment. Theoretically, farmers will choose the alternative that is most profitable to them and their families. To be induced to choose agroforestry, farmers must perceive that they will be adequately compensated for their labor (Hosier 1989). Not only must benefits exceed costs, but they must exceed costs by a greater margin than other options.

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 (Ehui et al. 1990). 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.

CONCLUSIONS

The preceding discussion highlighted some of the promising aspects of agroforestry practices from the perspectives of both farmers and those concerned about climate change. From the farmers' perspective, agroforestry can be a way to increase crop yields from their land while increasing the diversity of products grown. A secondary outcome is the creation of a carbon sink that removes carbon from the atmosphere and stores it in the terrestrial biota. Successful agroforestry is a sustainable and permanent type of agriculture that does not require repeated land clearing. As a result, potentially large amounts of carbon could be conserved in the terrestrial biota that would otherwise be released to the atmosphere. Whether this potential is realized or not depends on non-biological factors such as government policies and future population trends. In many instances agroforestry is more profitable than alternative practices. Where this is true, the cost of storing and conserving the associated carbon is essentially zero. This would rank agroforestry with other mitigation strategies, such as increased building energy efficiency and vehicle efficiency, that yield net benefits (NAS 1991). The profitability of agroforestry is very important for its widespread adoption; short-term cash profits are more attractive to farmers than are long-term environmental benefits (Hosier 1989).

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 & 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 3 tropical zones (tropical Africa, Asia and America), 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 ca 1.5 billion t C and 8.0 billion t C. Improved and refined estimates of land availability are required to reduce the uncertainties in these values.

Estimates of the total carbon conservation potential of agroforestry resulting from reduced deforestation are unavailable. Limited evidence currently available indicates that the potential is real but impossible to quantify. Additional efforts should be directed to answering this question because reducing deforestation might have a larger impact on the global carbon cycle than direct carbon storage by agroforestry practices.

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