Ecological Assessment of Carbon Sequestration and Partitioning in Regenerating Fallow Systems

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Abstract

Ecological field surveys have been used to assess carbon sequestration of regenerating vegetation of different ages. The regenerating vegetation categories were sampled using the direct field-plot harvest technique and the percentage carbon contents of the associated soils were determined by the wet digestion method. Results showed that fallow vegetation provided a significant carbon sink. The carbon stocks of vegetation and the underlying solum increased with advancement in age of the vegetation. The approximate relative percentages were 11% (in less than 3 years old fallows), 18% (in 3-6 years old fallows), 23% (in 6-8 years old fallows) and 48% (in open canopy secondary forests). The woody trees were more efficient repositories of elemental carbon than any other physiognomic stratum; they hold nearly 49% of the total carbon. The study confirms earlier observations of some experts that a large proportion of the carbon in most tropical ecosystems are held tenaciously in the woody biomass of trees, and that in regenerating vegetation systems carbon sequestration improved with advancement in the age of the fallow cycle.

Introduction

Current trends, spatial magnitude and pace of human-induced land-cover transformations have been worrisome because of the significant ecological implications for ecosystems functioning and global climate change. A more subtle consequence of rapid land cover alterations, that is potentially a significant factor in global climate change, but least acknowledged, is changes in carbon storage by biospheric ecosystems (Warrick & Farmer, 1990; Roberts, 1994).

The linkage between global climate change and atmospheric carbon dioxide (CO_2) loading is not in doubt at all. What is uncertain, however, is the exact relationship between the two (International Geosphere-Biosphere Programme, 1990). While there is much controversy over the exact figures and the spatial and temporal variations, it is estimated that the atmospheric CO_2 loading has increased by about 25% from its pre-industrial level and is rising at approximately 0.4-0.5% per annum (Houghton & Skole, 1990).

The exact effect of this and future increases are not known, yet predictions abound of an atmospheric carbon loading that will be double that of pre-industrial times by the year 2030, with rise in mean global temperature of between 1 and 3 °C. The consequential effects of this may be dramatic and range from significant rises in sea level to increased frequency and intensity of extreme climatic phenomena (Carter *et al.*, 1991; Henderson-Sellers, 1994; Rosenzweig & Parry, 1994).

The necessity to quantify more accurately activity of terrestrial vegetation was underscored by attempts in the late 1970s to calculate a global carbon budget. Although the empirical results from the Mauna Loa

CO_2 studies showed that global CO_2 was increasing, the anthropomorphic sources did not seem to balance the oceanic and terrestrial sinks, resulting in the popular notion of a "missing carbon" sink (Bolin, 1977; Emmanuel *et al.*, 1984; Woodwell *et al.*, 1984). More importantly, and as observed by Lieth (1975), this problem emphasized the lack of defensible methodologies for measurements of terrestrial primary production at global scales.

Globally, it is estimated that terrestrial vegetation sequesters some 100 picograms of atmospheric carbon annually for the production of organic matter through photosynthesis, with about one-half of the photosynthesis occurring in the tropics (Wisniewski & Sampson, 1993). However, the size of carbon pool and strength, and, sometimes, the direction are not accurately known. In view of these uncertainties, the many intellectual deliberations currently focusing on the carbon question have to be conducted in a haze of ignorance.

Over the years, much attention has been focused on the role of tropical forests as a source of atmospheric carbon, by measuring deforestation and biomass burning (Houghton & Skole, 1990; Dale *et al.*, 1991). Recent researches, however, have indicated that historical climatic variations and a carbon-enriched atmosphere may, in the absence of other growth-limiting factors, have a fertilization effect which encourages growth by increasing photosynthesis and water-use efficiency and so transforms these forests into a carbon sink (Grace *et al.*, 1995; Post *et al.*, 1997).

Moreover, the restoration of productive vegetation upon previously cleared areas results in considerable increase in the conversion of atmospheric CO_2 into biomass and so it may be a significant sink of atmospheric carbon (Harmon *et al.*, 1990). The role of these transitional vegetation classes as carbon sinks, which may be carefully managed to reduce carbon loading, however, has received only limited research attention (Tans *et al.*, 1990; Brown *et al.*, 1993).

Any efforts at elucidating the "missing carbon" sink comprehensively, as rightly emphasized by Turner II *et al.* (1993), will require adequate and reliable data on the types of ecosystems that are transformed through agriculture, especially their potentials as carbon sinks.

Regenerating forests at varying stages of development, often referred to as fallows, have been identified as possible but yet unquantified repositories of atmospheric carbon (Foody *et al.*, 1996).

While the clearance of the forest for agriculture is a source of atmospheric carbon, the use of the land afterwards can result in the formation of a carbon sink. Research should be able to account for the carbon storage potentials of these transitional vegetation types, following forest conversion. Also important will be an accurate data on how elemental carbon is partitioned between the different components of agricultural ecosystems and physiognomic categories.

To contribute to this area of research, this study was undertaken to comparatively assess regenerating fallow classes of different ages that may differ in terms of carbon sink, and assess their respective stocks of carbon using the conventional field-plot harvest approach (Newbould, 1967).

Materials and methods

Description of the study area

The study area is located in the Densu Basin of the Eastern Region of Ghana. Straddling three administrative districts, namely Suhum-Kraboa-Coaltar, Akuapem North and Akuapem South (Fig. 1), the area lies approximately between latitudes 5° 45' and 6° 03' N and longitudes 0° 32' and 0° 03' W, and forms part of the southern Forest-Savanna transition belt (Gyasi *et al.*, 1994). Three study sites were located in a triangular fashion, with the three major towns in the study area, namely Nsawam, Suhum and Akropong, forming the vertices (Fig. 1). The choice of this area for the study was largely influenced by the degree of cooperation and preparedness of the resident farmers to volunteer land for the investigation and also the familiarity of the researcher of the area.

The land-cover of the area is dominated by arable crop farms. Extensive areas of the landscape are either under current cultivation or exist as fallowed fields at various stages of secondary succession. Found also are a few broken-canopy forests, mostly located in inaccessible terrain. A few rare tall trees, reminiscent of members of the upper canopy of the original virgin forest, could also be found (Attua, 1996).

Generally, the relief is gently rolling with slopes between 8-16%. Drained by the Densu river, the area is traversed by tributary rivers such as Suhyen, Nsukwao, Ponpon and Mame. Present are also seasonal streams that are only a few metres wide (Dickson & Benneh, 1988; Adu & Asiamah, 1992).

Predominantly, the area is underlain by

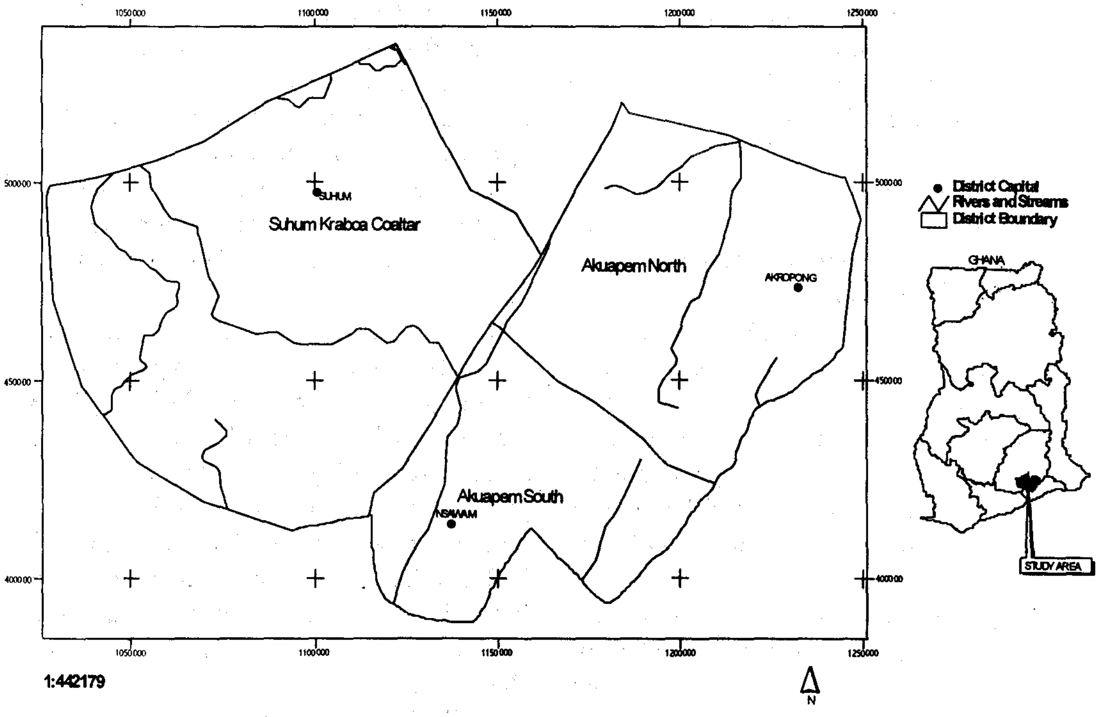

Fig. 1: Location of Study Area

Cape Coast granite complex, which consists mainly of granites, schists, and gneisses (Adu & Asiamah, 1992) and the soils are primarily forest ochrosols (Ahn, 1970; Ahenkorah *et al.*, 1994).

The study area lies within the bimodal rainfall zone of Ghana, with mean annual rainfall of about 1260 mm. The major rainy regime commences from April and ends in July, with a peak in June. The minor season is from September to November. December and January are dry months with high ambient temperatures during the harmattan season (Dickson & Benneh, 1988; Adu & Asiamah, 1992).

Data collection procedures

Emphasis was placed on the growth stages of the regenerating vegetation types that could differ in their ability to sequester atmospheric carbon.

The land cover categories included in the study were (1) fallows of less than 3 years old, (2) fallows between 3 and 6 years, (3) fallows between 7 and 8 years, and (4) forests. Fallows were here defined as regenerating plant communities (regrowths) at different ages of successional development, following arable farming. The conscious inclusion of forests in the study was to obtain an up-to-date ground data of the available forest for comparison with those of the fallows. It was assumed that the forest vegetation represented a more ecologically stable ecosystem, with greater potential for carbon storage, and that, except for cultivation, all other land cover classes would have been forests.

Using measuring tapes, poles and wooden pegs, sampling plots were demarcated for the in-depth field studies. Locating contiguous stretch of forest was more difficult, and sampling was limited to only three patchy stands. All study plots of fallow vegetation were of 25 m × 25 m dimension. However, because the forest stands available for the study were patchy rather than contiguous, only 20 m × 20 m plots could be demarcated for sampling.

A systematic randomized sampling was followed in collection of field data. On each study plot, the vegetation and the underlying solum were first stratified and randomly sampled using the following physiognomic stratification:

(i) canopy and sub-canopy trees, i.e. all trees 10 cm diameter at breast height (dbh);
(ii) saplings, i.e. all trees 2 m and < 10 cm dbh;
(iii) plants < 2 m tall, including all shrubs and herbs;
(iv) above-ground litter; and
(v) soil (0-20 cm depth).

The first two strata constitute the tree component. The direct field-plot harvest method (Newbould, 1967) was used. The application of this method, though more difficult and less cost-effective especially in large-scale mapping, is traditionally the most accurate since it is based on direct field sampling.

The carbon stocks of the different vegetation components, expressed in kilogram carbon per hectare ($kgCha^{-1}$) were studied from knowledge of their dry biomass (Ruimy *et al.*, 1994), using field plot sampling procedures as explained below. Root biomass, however, could not be estimated for lack of logistics. Elemental carbon stored in the different physiognomic strata of the plant-soil system in relation to land cover classes was also investigated.

In all, 38 sampling plots were used for the estimation. These consisted of fallows that were less than 3 years old (16 plots), fallows between 3 and 6 years old (11 plots), fallows between 7 and 8 years old (8 plots) and forests (3 plots). No fallow above 8 years was located in the landscape. All forests were of the open-canopy secondary type but no reliable clues were obtained from respondents to establish their exact ages.

Traditionally, tree biomass is most precisely estimated by the total destructive method of harvesting and weighing all portions of the tree (Newbould, 1967; Anderson & Ingram, 1989); an approach which is very laborious, time-consuming and prohibitive economically. However, because tree felling was not permissible, biomass of canopy and sub-canopy trees were estimated from the allometric formula below (Anderson & Ingram, 1989).

$$y = 34.4703 - 8.0671D + 0.6589D^2 \quad (n = 32;\ R^2adj = 0.67) \quad \ldots\ldots\ldots (1)$$

where y is biomass in kilograms, D is the diameter of the tree at breast height (dbh) in centimetres and n is the sample size.

This formula takes into account the annual rainfall regime of the study area, which is below 1500 mm (Dickson & Benneh, 1988; Attua, 1996). The use of this equation is recommended by the Tropical Soil Biology and Fertility (TSBF) Programme, where locally developed equations are unavailable. The formula, among others, has been derived from several data sets and rigorously tested for reliability (Anderson & Ingram, 1989). The diameter of each tree in a plot was measured at breast height with a measuring tape and its biomass computed. The total of the plot was computed and expressed in kilograms per hectare.

On each plot, all saplings were identified, enumerated and grouped into five-diameter classes, *viz.* 1-2 cm, 3-4 cm, 5-6 cm, 7-8 cm and 9-10 cm. The frequency of each class was noted and the mid-point of each class used as the mean dbh. An individual whose dbh was closest to the mean was selected as 'representative' of the class for harvesting. This sampling approach was to minimize, as much as possible, the extent of destructive sampling. The representative saplings were cut at 2 cm above ground and the bole length measured to the first major branch. On each plot, all harvested saplings were separated into leaves, branches and bole portions and weighed. Sub-samples were taken, weighed and labelled for the laboratory.

Sampling of low-growing flora and above ground litter were done simultaneously. Sampling was systematic with a random start. Ten 0.5 × 0.5 m^2 quadrats were laid down per plot and all plants < 2 m tall, including shrubs, herbaceous species, creepers, climbers and seedlings enclosed were identified and enumerated. Afterwards, the plants in each quadrat were cut at approximately 2 cm above ground. Harvested plant portions of each stratum were bulked together and weighed. Sub-samples were, as usual, prepared for biomass determination at the laboratory. The above ground litter in each quadrat was also collected as well and processed for laboratory analyses, as described for the low-growing flora above.

Laboratory studies

Laboratory studies involved dry weight determination of all collected sub-samples of plant parts. Sub-samples of all plant parts, including litter, were weighed and oven-dried to constant weight in a hot air-circulating oven at 105 °C and re-weighed. Percentage oven-dry weights or proportion of oven-dry weight per sample collected from the field was obtained by the relationship:

$$\text{Proportion of oven-dry weight} = \frac{\text{Oven-dry weight}}{\text{Sample fresh weight}} \quad ..(2)$$

The corrected oven-dry weight was then multiplied by the total fresh weight of the various components obtained on the field to get their corresponding dry weights.

The relationship between dry matter and carbon is variable, not only on ecosystem basis but also in respect of the different plant parts. The average conversion factor for all plant parts adopted for all ecosystems is quoted as 45% (Ajtay *et al.*, 1979). This average value was applied in this study. The organic dry matter of vegetation under the various land cover systems under study were assessed and expressed in carbon equivalents of total dry matter.

Carbon contents of collected soil samples were obtained from knowledge of soil bulk density and percentage carbon content. The bulk densities of soils were field-determined. A sampler of weight (W_1) and volume V was driven into the soil. The soil around it was excavated and the excess removed from the ends. Each sample was oven-dried at 105 °C to constant weight and re-weighed (W_2). Four of such samples were taken per plot and averaged. The bulk density was calculated in grams per cubic centimeter as follows (Anderson & Ingram, 1989):

$$\text{Bulk density} = \frac{W_2 - W_1}{V} \quad \ldots (3)$$

The percentage organic carbon in soil samples was determined using the wet digestion method. Organic matter in the sample was oxidized with a mixture of standard potassium dichromate ($K_2Cr_2O_7$) and sulphuric acid (H_2SO_4). The excess dichromate was titrated with ferrous sulphate (Fe_2SO_4), using barium diphenyl-4-sulphonate as indicator. The percentage organic content in the sample was computed as (Kalra & Maynard, 1991):

$$\%\ \text{Carbon} = \frac{M(V_2 - V_1) \times 0.39}{\text{Weight of soil sample(g)}} \quad ....(4)$$

where M is the molarity of the ferrous sulphate solution (mol dm^{-3}); $0.39 = 3 \times 10^{-3} \times 1.3$ (where 3 is the equivalent weight of carbon and 1.3 is the factor due to 77% carbon recovery from samples; V_2 = volume of Fe_2SO_4 required for the blank (cm^3); V_1 = volume of Fe_2SO_4 required for the sample (cm^3). The percentage carbon was converted to g/kg weight of soil by multiplying by a factor of 10. From the knowledge of the respective bulk densities, the total carbon stock of each sample was computed and expressed in $kgCha^{-1}$ (Schlesinger, 1984).

Results and discussions

The mean stocks of elemental carbon in the different physiognomic classes and land cover categories are shown in Table 1. Among all the physiognomic groups, the canopy and sub-canopy trees sequestered 67,474.41 $kgCha^{-1}$. This formed nearly one-half (48.80%) of all the carbon stocked by the vegetation-soil system of the study area. The next important reservoir of carbon was the low-growing flora with a carbon stock of 29,743.02 $kgCha^{-1}$. This constituted 21.51% of total stock of carbon in both the

TABLE 1

Mean stocks of carbon (kgCha^{-1}) in different physiognomic classes of land cover systems

Physiognomic class	*Land cover*				*Total*
	< 3 years fallows	*3-6 year fallows*	*7-8 years fallows*	*Forests*	
Canopy and sub-canopy trees	4330.40 ±408.54	7872.29 ±1457.24	10494.74 ±2925.17	44398.72 ±14785.22	67474.41
Saplings	327.53 ±28.22	350.54 ±27.06	541.04 ±74.74	1478.93 ±424.66	2698.04
Low-growing plants	5228.25 ±658.73	10246.67 ±707.72	10601.43 ±504.82	3666.67 ±794.95	29743.02
Above-ground litter	2825.94 ±460.82	4061.67 ±498.68	4959.29 ±1097.93	10250.00 ±1233.22	22096.90
Soil	2107.81 ±90.93	2928.03 ±115.67	5031.43 ±315.42	6179.00 ±662.28	16246.27
Total	15198.19	25459.20	31627.93	65973.32	138258.64

vegetation and soil. The above-ground litter, soil, and saplings followed in that order, with carbon stocks of 22,096.90 kgCha^{-1} (15.98 %), 16,246.27 kgCha^{-1} (11.75 %), and 2,698.04 kgCha^{-1} (1.95 %), respectively. Collectively, the three strata stored less than 20 per cent of the total stock of carbon. Fig. 2 shows the relative percentage stocks of carbon in the different physiognomic categories.

The results support the observations of Bramryd (1979), Longman & Jenik (1987) and Amanor (1994) that a large proportion of the carbon in most tropical ecosystems are held tenaciously in the tree biomass and that they are released either into the soil or the atmosphere through complex biogeochemical cycling.

Longman & Jenik (1987) and Dale *et al.* (1991) have further explained that once the nutrient bank of woody trees is removed, the land is stripped of its major stock of carbon. The human conversion of woody vegetation systems for agricultural purposes or harvesting for fuelwood could significantly diminish their store of carbon and, subsequently, accelerate the flow of carbon in the form of carbon dioxide into the atmosphere, through oxidative decomposition and burning. Moreover, an extra diminution of carbon could occur through increased decomposition of soil organic matter after bush clearance (Ajtay *et al.*, 1979).

The observation that the low-growing plants formed the second most important group for the storage of carbon in the ecosystem is worth noting. The significance of this category of plants in the carbon cycle is seen in its rapid turnover rate of atmospheric carbon. Ajtay *et al.* (1979) have noted that these low-growing flora, mostly the herbaceous species, have rapid turnover rates as they grow faster and readily convert atmospheric carbon into organic matter. However, their carbon pool

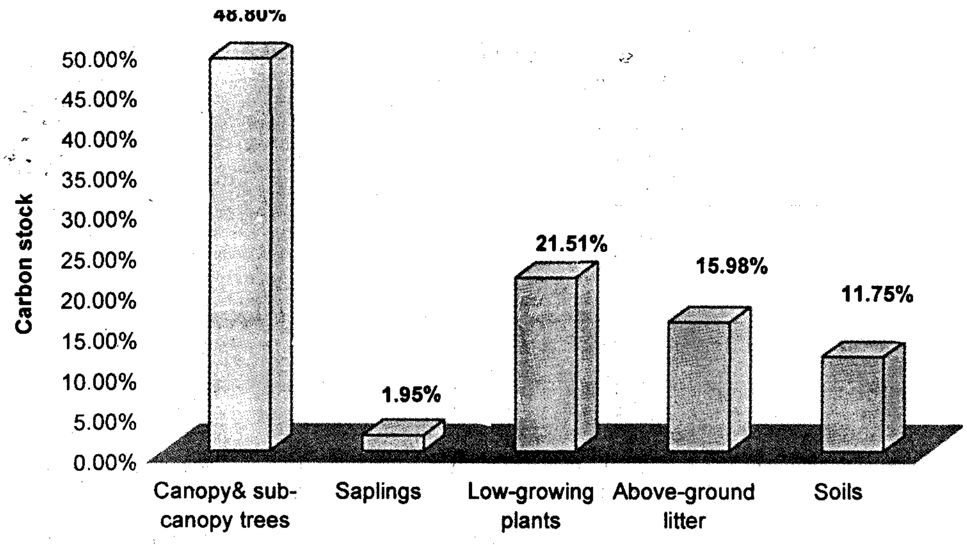

Fig. 2. Relative percentage stocks of carbon in different physiognomic strata

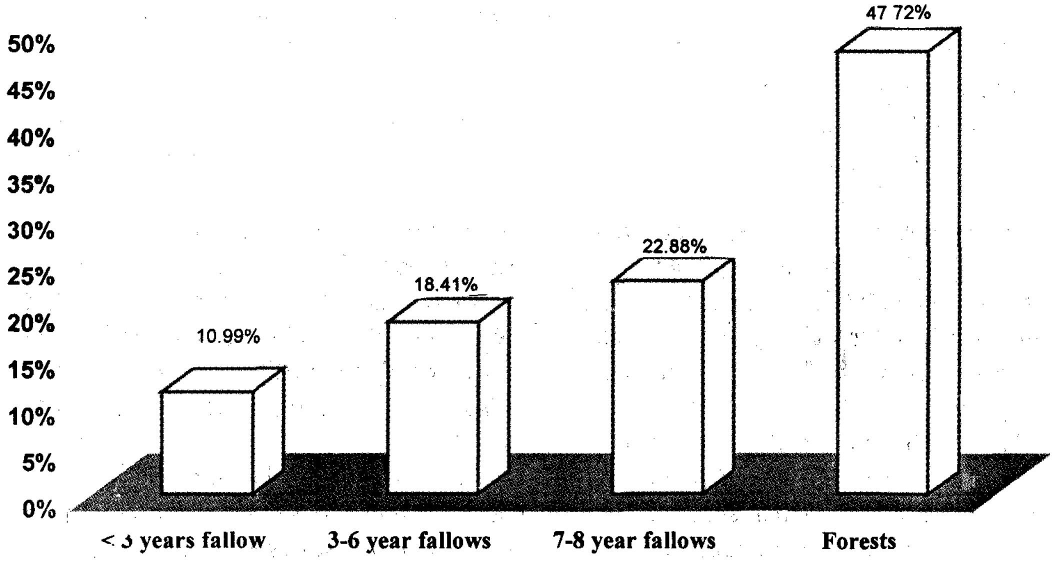

Fig. 3. Relative percentage stocks of carbon held in different land cover systems

is easily lost to the atmosphere through mainly slash-and-burn agriculture and oxidative decomposition, especially in tropical ecosystems (Korem, 1985).

Table 1 also indicates that carbon is disproportionately partitioned in vegetation-soil systems, depending on how long secondary succession has progressed. Fields under forest cover (presumably secondary forests) had the highest reservoir of carbon of 65,973.32 kgCha^{-1} (48%) compared to the fallow fields. The fallow systems showed a progressive increase in the quantum of carbon storage as the fallow cycle increased.

The fields fallowed for less than 3 years stocked 15,198.19 kgCha^{-1} (nearly 11%), those fallowing with age between 3 and 6 stocked 25,459.20 kgCha^{-1} (about 18%), and the 7–8 years fallows had 31,627.93 kgCha^{-1} (nearly 23%), respectively. Fig. 3 depicts this pattern of carbon stock distribution.

Thus, with advancement in length of the fallow period, fallow fields are capable of increasing their carbon storage through rapid sequestration of atmospheric carbon dioxide. In the face of increasing agricultural land use pressure from escalating farming populations, however, fallow cycles are most likely to be further curtailed and, consequently, increase the atmospheric load of carbon dioxide.

Conclusion

Tree components of tropical arable fields are better repositories of elemental carbon. This is in terms of both the quantum of storage and resident time of the element. Trees, therefore, will not only store more carbon in woody biomass but also hold tenaciously the trapped element in component tissues over relatively longer period than the low-growing flora of the same ecosystem. Significantly, this reduces the emission rate of carbon in the form of gaseous carbon dioxide into the atmosphere and so helps to forestall global warming.

The inconsiderate destruction of woody vegetation that attends slash-and-burn agriculture in most tropical arable fields, therefore, will not serve the interest of carbon sequestration but rather is likely to increase the conversion of arable lands, in the first place, into monotonous tree-less landscapes. Such trajectory of vegetation transformation could be a potential threat to forestalling global warming.

Carbon storage in fallow fields was also found to have a positive correlation with age of the fallow cycle. With increasing demand for arable land because of worsening population pressure, fallow periods are likely to deteriorate further on agricultural lands; consequently reducing the resident time for carbon in the vegetation-soil compartment of these terrestrial agro-ecosystems.

For better management to reduce carbon emission into the atmosphere in agricultural cropping systems, two options may be considered. The first is to draw lessons from the carbon storage potential of trees. An integrated agricultural system that incorporates tree development in cropping systems will not only improve carbon sequestration but also provide sustenance to local communities. Such tree-based agro-systems have particularly been identified as better alternatives to traditional slash-and-burn agriculture, for better management of carbon in cropping systems (Dixon *et al.*, 1993). For example, in Cameroon cocoa agro-forests had been found to sequester more than twice the carbon of traditional cropping systems without reducing the yield of the cash crop.

Similarly, in Brazil pastures planted with indigenous timber and fruit species (types not specified in the literature) could sequester 125 tonnes carbon per hectare in tree biomass within 20 years (ASB/ICRAF, 1996). The adoption of any type of agro-forestry system must, however, be informed by successful experimentation that takes into account local agricultural needs.

The second option is to increase the fallow period of bush-fallow systems to improve their store of elemental carbon. In most farming communities, this is an option that is most unlikely because of increasing agricultural land-use pressure often associated with increasing farming populations.

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