CARBON STORAGE IN AGROFORESTRY:
AN ESTIMATE FOR SUBSAHARAN AFRICA

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ABSTRACT

Massive reforestation has been proposed as one means for stabilizing the concentration of carbon dioxide in the atmosphere, but the proposal seems academic in the face of current rates of deforestation in the tropics and the growing need for additional agricultural land. Agroforestry offers a compromise solution because it increases the storage of carbon on land and, at the same time, may enhance agricultural production rather than compete with it. Although the storage of carbon per unit area is generally less for agroforestry than for forests or tree plantations, the area suitable for agroforestry, worldwide, is large.

In this study, we estimated the amount of carbon stored in different agroforestry systems in subSaharan Africa and the potential storage possible, region-wide, if agroforestry were to be implemented throughout. The potential distribution of different agroforestry systems was determined from a comparison of current practices of agroforestry with current land use. Land use was determined from a combination of satellite data and ground studies. A total of about 1550 X 106 ha were classified as suitable for some type of agroforestry. Although certain types of agroforestry accumulate much more carbon than others, practical implementation of agroforestry must consider existing land-use practices. Those types of agroforestry that included fuelwood production were most consistent with current land use and thus had the greatest potential to accumulate carbon. Total potential accumulation of carbon in aboveground woody biomass in agroforestry ecosystems throughout subSaharan Africa was estimated to be 6, 13, or 23 PgC, depending on the density of trees used in the various systems. Including belowground biomass and the potential for soils to accumulate carbon under agroforestry, raised these estimates to 8 to 54 PgC. Accumulation of that much carbon would offset global emissions of carbon from fossil fuels for only 1.7 to 9 years, but would offset African emissions for 20 to 125 years. The secondary effects of agroforestry in reducing rates of deforestation and, hence, emissions of carbon, may be more important than the primary effect of sequestering carbon.

INTRODUCTION

Increasing concentrations of greenhouse gases in the earth's atmosphere are expected to warm the earth and cause other, less easily predicted, changes in climate. The warming will continue until sometime after atmospheric concentrations of the major greenhouse gases are stabilized. Carbon dioxide (CO_2) is the most important of the greenhouse gases released as a result of human activities. It is expected to account for about 60% of the warming over the next century according to a recent assessment by the Intergovernmental Panel on Climatic Change (IPCC) (Houghton et al. 1990). Stabilization of CO_2 concentrations in the atmosphere will require large reductions in the use of fossil fuels and in rates of deforestation. But while reductions in emissions of carbon will enable the concentration of CO_2 in the atmosphere to come to a new equilibrium with the partial pressure of CO_2 in the oceans, the time required for this equilibration may be hundreds of years. Reforestation, on the other hand, defined here as an increase in woody biomass, could remove significant amounts of CO_2 from the atmosphere over decades. A major limit to reforestation is area. On the order of 900 to 1200 X 106 ha of land would have to be reforested to accumulate all of the carbon emitted annually from worldwide combustion of fossil fuels (Marland 1988, Sedjo 1988, Woodwell 1989, Houghton 1990); and, even then, the annual accumulation in new forests would balance emissions only as long as the forests were maturing. After 25 to 50 years or so, the annual accumulation on land would decline to zero, and the emissions would again, as now, accumulate in the atmosphere.

In the tropics, degraded areas suitable for reforestation are estimated to range between 500 and 900 X 106 ha (Grainger 1988, Houghton 1990), the higher estimate including lands currently under fallow and hence already holding some amount of carbon in woody biomass. These lands are defined as suitable because they once supported forests, and presumably could do so again, and because they are no longer used intensively for agricultural purposes. Most of the lands were farmed in the past but have since lost their fertility and been abandoned. Because forests are being cut down largely to increase the area in agriculture, it is unlikely that productive agricultural lands will be reforested to accumulate carbon. On the other hand, the accumulation of carbon in woody biomass need not compete with agricultural production. Almost 2000 X 106 ha of land currently in crops and pastures in the tropics is suitable for accumulating carbon with little or no loss of agricultural productivity. The

practice is called agroforestry.

Agroforestry has the potential to sequester significant amounts of carbon for two reasons: First, the area currently in crops and pastoral systems is large. Second, although the density of carbon storage is low in comparison with forests, the woody biomass of agroforestry systems could provide a source of local fuel. This fuel would reduce pressure on the remaining forests in the area and, at the same time, provide a substitute for fossil fuel. These effects are important because the most effective way to use land for stabilization of atmospheric carbon is not through reforestation but through the substitution of wood fuel for fossil fuel (Houghton 1990, Hall et al. 1991). As much as 150 PgC (1 Pg = 1 X 109 metric tonnes = 1 X 1015 g) might be accumulated in the tropics if 865 X 106 ha were reforested (Houghton 1990), but, as noted above, the rate of accumulation would fall to zero as the forests matured. Forests would continue to hold the carbon accumulated, but they would accumulate no additional carbon after that time. In contrast to the temporary effect of reforestation, the sustainable use of wood fuels provides a solution that could last indefinitely. Under sustainable use, emissions of carbon from burning this year's fuel are balanced by accumulations of carbon in the growth of next years' fuel: the net flux is zero. In 1990 emissions of carbon from worldwide combustion of fossil fuel were about 6 PgC (Houghton et al. 1992). Fossil fuels are non-renewable, carbon-emitting fuels; wood, if managed sustainably, is a renewable, zero-carbon fuel.

However, despite the large area devoted to agriculture, worldwide, and despite the apparent potential for agroforestry to sequester carbon, the recent proliferation of agroforestry studies includes almost no consideration of either carbon or biomass. The lack of biomass data, coupled with the diversity of agroforestry types (i.e., the wide variation in functional types, species, tree densities, temporal and spatial arrangement of components, management practices, etc.), means that a straightforward estimation of potential carbon storage is not possible.

The purpose of the analysis described here is (1) to present a methodology for estimating the aboveground biomass in different types of agroforestry, and (2) to estimate the total amount of carbon that could be stored in agroforestry over the entire sub-continent of subSaharan Africa. Following a brief overview of the approach, the paper describes the methods developed for this

analysis. The results are compared with other studies and, finally, the secondary effects of agroforestry for the potential storage of carbon are discussed.

APPROACH
The approach combined site-specific information from case studies of agroforestry with a land-use database for subSaharan Africa to estimate the total amount of aboveground biomass that might be accumulated if agroforestry were to be practiced on lands presently suitable. Suitable lands included agricultural lands and degraded lands. They did not include forests, grasslands, or deserts unless those lands were grazed. Site-specific case studies of agroforestry were obtained from ICRAF's database on agroforestry (Nair 1989a) and from other sources in the published literature. The advantage of using this information is that it contained descriptions of existing, functioning
examples of agroforestry as presently practiced. The examples included the many forms of agroforestry that result from the interplay of climatic and land-use options in various regions of Africa. They already embody the many biophysical and human
variables involved in functioning agroforestry systems. In this sense, our analysis was not hypothetical or theoretical but, rather, based on agroforestry as currently practiced.

Over 170 descriptions were used to categorize the types of agroforestry actually practiced. These descriptions encompassed a wide variability in tree density, species, size, temporal and spatial patterning, and management practices. The descriptions were grouped into five different types of agroforestry (Table 1). Silvopastoral agroforestry was further divided into three subtypes due to large differences (largely related to precipitation) in tree biomass for fodder-producing trees in pastoral zones. Most of these major types of agroforestry are not practiced alone, however, but in combination with other types. Thus, a total of 21 different agroforestry types were considered (Table 2). In addition, within each type of agroforestry, a high,
medium, and low estimate of biomass was estimated, to encompass the variability resulting from the number of trees per hectare. These 21 types of agroforestry were distributed over subSaharan Africa on the basis of two kinds of information. First, the geographic regions and precipitation regimes for each type of agroforestry, obtained from the ICRAF study and other agroforestry studies, gave a general description of where
different types are found. Second, a map of current land use in subSaharan Africa was used to place, more specifically, different types of agroforestry within current uses of land. The derivation

of both maps is described in the next section.

The type of agroforestry chosen as appropriate for a given land use involved a set of rules. For example, fodder producing trees were assumed appropriate for pastoralism; shelterbelt agroforestry was appropriate for rainfed crop systems; fruit and fuelwood agroforestry were most appropriate for shifting cultivation systems; and so on. When more than one type of agroforestry was appropriate for an existing use of land, two types were assumed to be practiced together. We arbitrarily limited the number of coexisting types to two. The decisions defined a third GIS layer which identified areas for implementation of specific agroforestry types. These areas were then multiplied by the per-hectare estimates of woody biomass for each agroforestry type to give estimates of biomass potentially accumulated in all types. The estimate is not of current accumulation because agroforestry does not entirely cover these areas at present. The potential storage is what would occur if agroforestry were to fill the suitable areas. The estimates do not include carbon sequestered through the secondary effects of agroforestry. These effects are discussed briefly toward the end of the paper.

Throughout the paper, we refer to the increment in aboveground woody biomass associated with different types of agroforestry. We assume that the biomass of non-woody vegetation is not changed as a result of agroforestry, and thus we ignore non-woody vegetation. The potential increments in belowground biomass and soil carbon are considered at the end of the paper. Until then, the unites used throughout refer to aboveground woody biomass (dry weight). For considerations of carbon, in a final section, we assume carbon to be 50% of biomass.

METHODOLOGY
Determination of biomass
In assessing the various options for estimating woody biomass of agroforestry systems, it became readily apparent that no single method would adequately estimate biomass for all systems. Because of large differences among agroforestry systems in tree size and wood density, environmental conditions, temporal and spatial structure, function, and management practices, calculation of per-hectare tree biomass was different for each type of agroforestry. What follows is a description of the calculation of biomass for the different systems included in this study.

Silvopastoral agroforestry systems
The utilization of fodder-producing trees as animal feed sources
has been known in livestock producing areas for
centuries. Especially important in arid and semi-arid grazing
lands, silvopastoral agroforestry systems are being increasingly
practiced and studied (Torres 1989 and the references cited
therein). These systems usually comprise trees and/or shrubs in
extensive browsing or grazing systems, where the trees act as
protein-rich supplemental feed sources, or primary feed sources in
certain times of the year or during drought (Barrow 1991, Boudet
and Toutain 1980, Coppock et al. 1986, Torres 1983,
Phillips et al. 1989, Poschen 1986).

A review of the relevant literature reveals that variation in per-
hectare biomass for silvopastoral systems is primarily due to
variation in precipitation and the number of trees per hectare
(Bille 1985, Martin 1985, Almanza and Moya 1986). The approach
used here for estimating biomass considered both of these
variables by delineating precipitation zones, and by defining
three values for number of trees per hectare based on the range of
trees per hectare observed in silvopastoral systems. The
precipitation zones were defined following Boudet and Toutain
(1980). Estimates of tree biomass were obtained from Bille
(1985), Martin (1985), and Almanza and Moya (1986). The average
fodder producing tree for the 100400mm zone contains 3.6 kg
biomass, for the 400800mm zone, 3.5 kg, and for precipitation
>800mm, 97kg. These values multiplied by values for numbers of
trees per hectare (50, 100, and 200) gave three estimates for each
of the three precipitation zones, or a total of nine
estimates of per-hectare biomass for the silvopastoral
agroforestry system (Table 1).

Fruit tree agroforestry
There are many examples of agroforestry systems in the tropics
that involve large numbers of fruit trees (Nair 1985). While fruit
trees have a number of functions within various production
systems, their primary purpose is to produce fruit for human
consumption. As such their role in the production system is both
in the direct contribution of foodstuffs, and in income generation
through the marketing of produce. Fruit tree
agroforestry is very suitable to the small holder farming systems
of the tropics and other thickly populated regions of the world
(Nair 1985).

In this study, estimation of biomass in fruit tree agroforestry
systems was based on calculation of the average biomass (Y) for a

fruit tree. The following equation was used (Brown et al 1989):

$$Y = \exp \{ 2.4090 + 0.9522 \ln (D2HS) \}$$

where D is diameter at breast height (cm), H is tree height (m), and S is wood density (0.57 t/m3 = g/cm3). Wood density was calculated as the average of five species of tropical fruit trees commonly used in Africa (species from ICRAF agroforestry database – Africa, wood densities from FAO/UNEP 1981). A tree with a diameter of 15 cm and a height of 6 m was selected as average based on average fruit tree sizes from the agroforestry literature. The equation yielded an average biomass for fruit trees of about 50kg/tree.

A range of numbers of fruit trees per hectare was obtained form a review of the agroforestry literature (Allen 1990; Fernandes et al 1984; Toky et al 1989; Denevan and Padoch 1987; Michon et al 1986; Nair 1985). Three values representing this range (60, 150, 300) were used to derive the estimates of biomass per hectare given in Table 1.

Fuelwood agroforestry
Most Africans are almost wholly dependent on fuelwood for their energy needs and will most likely be so for decades to come (French, 1978). At the same time, however, deforestation in Africa is proceeding rapidly. The potential of fuelwood agroforestry to help satisfy wood demand in Africa is great, primarily because of the enormity of the areas that could be planted (Anderson & Fishwick 1984; Houghton et al., in press). However, the trees providing fuel need not occur in forests or plantations, but can exist as free-standing trees in and around buildings, gardens, and fields (Anderson and Fishwick 1984). Estimation of biomass for fuelwood agroforestry was more straightforward than for other types of agroforestry because fuelwood agroforestry has received considerable technical attention. For this analysis, biomass was estimated by averaging a number of examples from the literature. These examples included both biomass per tree and number of trees/ha (Anderson and Fishwick 1984; Maghembe et al 1986; Millington and Townshend 1989; Shankarnarayan et al 1987). Average biomass for fuelwood trees was estimated at 77 kg/tree, and the range of trees/ha was 200, 500, and 1000 for low, medium, and high densities (Table 1). Because the trees are continually lopped for fuel and, thus, kept small, the normal inverse relationship between tree density and average tree biomass seems not to hold. Apparently individual trees do not interfere with each other, even at the higher

densities. Because the trees are lopped (harvested) continually, aboveground woody biomass does not vary through time as it would if the trees were clearcut on a rotational basis. Thus, the increment in woody biomass associated with fuelwood agroforestry is equal to the standing woody biomass, and not to the average biomass over the harvest cycle.

Timber agroforestry
A number of agroforestry systems in Africa, most notably the widespread taungya system, contain timber trees. While these systems are different from timber plantations in spatial and temporal patterns, and in crop and livestock associations, the biomass of timber trees in agroforestry systems was assumed to be similar to that of plantations. Thus, data from plantations (FAO/UNEP 1981) were used to define the relationship between number of trees and stemwood volume (Fig. 1). The 11 points in Fig. 1 include nine species commonly planted in tropical Africa. Eight of the species are planted in lowland humid tropical areas (mean annual rainfall > 1500 mm); one species (from Mexico) is planted at high elevations (above 1000 m, mean annual rainfall > 1000mm). Stemwood volume (S = m3/ha) was converted to total biomass according to the following equation:

$$Biomass (t/ha) = S * D * E$$

where D is wood density (0.57 t/m3 (Brown and Lugo 1984)); and E is the ratio of total aboveground biomass/ha to stemwood biomass/ha. For plantations older than 30 years, this ratio was estimated to be 1.4 (Brown et al. 1986).

[Figure 1 to go about here.]

Forty, 120, and 200 trees/ha were selected from the literature to represent the range of trees/ha observed in taungya agroforestry examples. These densities gave estimates of biomass of 130, 240, and 270 t/ha, intermediate between the minimum (111 t/ha) and maximum (518 t/ha) estimates of biomass for tropical plantations greater than 30 years of age (Brown et al. 1986). Most plantations in the tropics are younger than 30 years and contain less biomass than determined here, but the values
calculated here were chosen to represent potential biomass rather than current biomass. They are values for mature plantations, ready for harvest. Hence, the trees are considerably larger than the trees of other agroforestry systems, where lopping, coppicing, or other activities often keep the trees small.

Shelterbelt Agroforestry

Shelterbelts, or windbreaks in agroforestry can have numerous functions in addition to preventing wind erosion. Depending on the species and the spacing, trees in shelterbelts can increase soil nitrogen, and produce fruit, fodder, fiber, and fuelwood (Harrison 1987). Harrison (1987) cites studies showing that windbreaks can increase crop yields by 18 to 23 percent, even allowing for the 12 to 15 m in every 100 m taken up by the trees and their deep shade.

Biomass estimation for shelterbelt agroforestry in this study was based on a single example, because very little else was available. The example used, however -- of the Majjia Valley in Central Niger -- is perhaps the best agronomic study to date of windbreaks in the Sahel (Vanderbelt 1990). Using data from Leach and Mearns (1988) on tree volume (110 m3/km of shelterbelt), length of shelterbelt/ha (117 m/ha), and spacing (trees planted in double rows with a spacing of 4 x 4m), the average biomass of shelterbelts was calculated as 59 trees/ha or 12.9 m3/ha. Converting volume to biomass (X 0.57) gave 6,490 kg/ha. Because only one example was obtained, high, medium, and low estimates were the same for this agroforestry type.

Combinations

While many agroforestry systems can be classified as one of the major types mentioned above, other systems are combinations of these different types. The remainder of the agroforestry types in this study were made up of combinations of the core types described above. These combinations were made up of only two types each, thus only approximately representing observed conditions. Biomass was estimated for these combinations by averaging low estimates for one system with low estimates for another, medium with medium, and high with high. The combinations are shown in Table 2.

Development of GIS layers

Precipitation, political regions, current land use and case studies were mapped on a Geographic Information System (GIS) to identify areas suitable for specific types of agroforestry. Precipitation was obtained from monthly global maps of corrected total precipitation (Legates and Willmott 1990). Individual months of precipitation were summed to produce a map of total annual precipitation in 10cm increments (Fig. 2a). The precipitation map was then further simplified into 4 moisture regimes based on Nair (1987): arid (<500mm), semi-arid (500 -1000mm), subhumid (1000 – 1300mm), and humid (>1300mm). Political boundaries defined four

geographic regions of Africa (West, East, Central, and Southern Africa) that coincided with ICRAF agroforestry cases (Fig. 2a). This 4-region map was combined with the map of 4 moisture regimes to produce a 16-class map of regional precipitation zones (Fig. 2b). For most of these regions, descriptive data on prevalent agroforestry types (ICRAF) were of greater detail than the simple 16-class map, and we used a map of current land use/land cover to help decide which type of agroforestry was appropriate in specific locations.

[Figure 2 belongs approximately here.]

A map of present-day land use/land cover with 33 classes (Fig. 2c) was produced from a combination of satellite data and ground studies (Houghton et al., in press). The satellite data were weekly, 15km-resolution, Global Vegetation Index (GVI) data obtained from NOAA. The GVI data are calculated at NOAA from the Normalized Difference Vegetation Index (NDVI), which is the difference between a visible and an infrared band, normalized by their sum. Dense vegetation cover results in high values of NDVI; areas of bare ground, ice and snow, water, or clouds give low values. NDVI is correlated with land cover, phenology, and net primary productivity over broad geographic areas (Goward et al. 1985, Justice et al. 1985, Tucker et al. 1985), but the index has also been shown to have a number of limitations (Goward et al. 1990, 1991, in press).

Three years (198-1988) of recent GVI data were used to reduce the effects of interannual variability and spatial heterogeneity of climate that are especially problematic in Africa. Weekly GVI data were aggregated into months, taking maximum values from the component weeks, thereby reducing the effects of cloud cover. Monthly data were averaged for the three years to produce average monthly GVI values. Unsupervised classification was performed on the twelve monthly layers to produce a 33-class map of landcover. Monthly GVI means and standard deviations for each class were extracted from the GIS and graphed. The resulting 'phenology curves' revealed the timing and intensity of vegetative activity, and were used with case studies from the literature to assign labels of landcover or land use to the classes (Fig. 3).

[Fig. 3 should appear near here.]

The selection of case studies used for the labelling procedure was based on three criteria. The studies had to have been carried out in the 1980's, they needed to describe in some detail the

vegetation and land use of the area studied, and the study sites needed to cover a large enough area to be descriptive of a significant number of pixels within the class being labelled. The large areas also enabled the phenology curves to be matched with the ground descriptions of vegetation and land use. The accuracy of the landcover map obtained from GVI data was assessed in two ways (Houghton et al., in press). First, the map was compared with White's (1983) map of vegetation for Africa. Estimates of the area in forest were 493 and 260 X 106 ha for White's map and ours, respectively. For woodlands, the areas were 798 and 881 X 106 ha, respectively. Unfortunately, the differences are not necessarily an assessment of accuracy. Rather, they represent changes in forest cover between an unspecified time in the past (White 1983) and the late 1980's (satellite-derived map). The loss of forests over time is consistent with this interpretation, and so is the increase in woodlands if some of today's woodlands are actually degraded forests.

For a better evaluation of accuracy, we asked what proportion of the areas (pixels) classified presently as forest were identified as forest in White's map. A pixel-by-pixel
comparison showed 95% agreement. Areas currently classified as woodlands were identified as woodlands with 85% frequency by White.

A second test for accuracy was a comparison of the GVI-based map and a map for South American land cover derived from 1-km AVHRR data (T.A. Stone, unpublished). The comparison showed 65% agreement overall, although any such comparison suffers from the different names given to classes of vegetation. Nevertheless, the two tests show that the GVI-based map compares reasonably well with other estimates of land cover in tropical regions.

Decision matrix
The intersection of the map of potential agroforestry (distribution of cases studies among the 16 regional precipitation zones; Fig. 2b) with the map of current land use (33 classes of landcover; Fig. 2c) determined the type of agroforestry appropriate at any location (Table 3). For example, timber agroforestry would be difficult to implement in arid and semi-arid pastoral areas; and the acacias that predominate in many pastoral agroforestry systems would be difficult to encourage in humid, forested areas where fruit tree or timber agroforestry would more closely complement current land use. Thus, when more than one type of agroforestry was possible, the type most similar to current land use was chosen. Combinations were

also possible (Table 2). If a landcover/landuse labelled "savanna with >10% woody vegetation/ grazed" intersected with fruit tree, shelterbelt, and silvopastoral agroforestry, then silvopastoral agroforestry was chosen. Some potential intersections between types did not occur, and some areas of landcover, such as dense tropical forest or extreme desert, were unsuited for the types of agroforestry considered in this study and were labelled as having no potential for agroforestry.

Decisions made concerning the intersection of potential types of agroforestry with current land use defined the types of agroforestry (Table 3) and the area with potential for application at present (Table 2). If more lands are deforested and degraded in the future, this potential will increase.

RESULTS
Table 1 summarizes the average tree weight, number of trees/ha, and average aboveground biomass/ha for the different types of agroforestry found presently in subSaharan Africa. The average tree weights varied over three orders of magnitude, with very small trees (3 kg) in arid and semi-arid pastoral systems and very large trees (3250 kg) in agroforestry systems producing timber. The number of trees/ha varied as much within types of agroforestry as between them, with the exception of those systems with fuelwood. Fuelwood plantations generally contained the greatest number of (small) trees/ha.

The average biomass/ha was largely a function of average tree weight, so that timber production had the largest potential to accumulate biomass, while arid and semi-arid silvopastoral systems had the smallest potential. Potential biomass accumulation in agroforestry systems increased in the following sequence: semi-arid silvopastoral, arid silvopastoral, shelterbelts, fruit tree, humid silvopastoral, fuelwood, and timber trees.

Table 2 shows the land area currently suitable for each agroforestry type (also shown in Fig. 2d), and the total amount of aboveground woody biomass that could be accumulated under each type. A total of 1549 X 106 ha were estimated to be suitable currently for some form of agroforestry in subSaharan Africa. Six types of agroforestry accounted for more than 100 X 106 ha each. In descending order, these types were fruit tree, fruit tree/fuelwood, pastoral/fuelwood, and each of the three silvopastoral systems alone. Pastoral systems, either alone or in combination with another type, accounted for a total of 830 X 106

ha. Systems with some amount of fuelwood accounted for 639 X 106 ha. And agroforestry where fruit trees were important for at least part of the practice accounted for 617 X 106 ha. The area suitable for agroforestry with timber was about 38 X 106 ha. Applying the mean woody biomass in different agroforestry ecosystems (Table 1) to the areas suitable for each type gave total potential accumulations of aboveground biomass that were estimated to be 12, 26, or 46 Pg depending on the density of tree planting.

Neither the land area occupied by each agroforestry type nor the average biomass/ha of each type predicted the system with the greatest potential to accumulate biomass. For example, timber agroforestry had the highest biomass/ha value, yet ranked seventh in total aboveground biomass. The largest area suitable for agroforestry was estimated to be that suited for fruit trees, but such systems ranked fifth in terms of biomass potentially accumulated. The type of agroforestry with the largest potential to accumulate biomass was the fruit/fuelwood agroforestry combination, which ranked second in land area. The agroforestry type estimated to accumulate the second largest amount of biomass (again using the high estimate) was the pastoral/fuelwood combination, which covered the third largest area.

The five agroforestry types with the greatest potential to accumlate biomass for the high estimate, were, in descending order: fruit/fuelwood; pastoral/fuelwood with >800 mm precipitation; fuelwood; fruit/timber; and fruit. The three systems with the largest potential to accumulate biomass all included fuelwood.

DISCUSSION
Converting now to units of carbon (carbon = 0.5 X biomass), the potential accumulation of carbon in aboveground woody biomass was estimated to be 6, 13, and 23 PgC for the three tree densities. These estimates include only aboveground biomass. Assuming that belowground biomass accounts for about 20% of total biomass, total accumulation of carbon in above- and below-ground woody biomass would range between 7 and 28 PgC. The estimates are lower than the value reported recently by Houghton et al. (in press). In that study, agroforestry in subSaharan Africa (on a total of 888 X 106 ha) was calculated to accumulate 52.6 PgC in woody biomass, above- and belowground. The average accumulation per ha was 59 tC/ha in that study, in comparison to 4.5 to 19 tC/ha obtained here. The earlier estimate of carbon storage was based on the assumption that agroforestry systems accumulate about as

much carbon/ha as held in natural woodlands. The results of the work described here suggest that this assumption is an overestimate.

Nevertheless, the estimates for carbon storage presented here, even accounting from belowground carbon accumulation, are probably underestimates. First, they are based only on woody biomass, and the practice of agroforestry is likely to accumulate additional carbon in soils. The potential of agroforestry to accumulate soil carbon is unknown, but can be approximated in two ways. First, if the accumulation in agroforestry is as great as the loss associated with cultivation of forest soils, the accumulation could be about 25% of the carbon content of the soils found in different ecosystems (98, 69, and 42 tC/ha, respectively, for tropical forests, woodlands, and grasslands) (Schesinger 1984). The potential distribution of agroforestry among these ecosystems (Houghton et al., in press) gives an average accumulation in soils of 26 PgC for this region. It is important to recall that the value important here is the increment in soil carbon attributable to agroforestry, not the total amount of carbon in soil.

A second estimate may be based on the assumption that soils and biomass accumulate carbon in the same ratio that they lose carbon following deforestation. Soils account for between 15 and 20% of the net loss of carbon from changes in land use (Houghton 1991). According to this assumption, total accumulation of carbon in the soils of agroforestry systems of subSaharan Africa would be 1 to 6 PgC. Thus, total accumulation of carbon in agroforestry systems could betwee 8 and 54 Pg when soils, as well as belowground biomass, are considered.

It is clear that timber systems store almost an order of magnitude more carbon/ha than other systems and are the systems that should be promoted if carbon accumulation is to be maximized. This conclusion may be misleading, however. The area where timber complements existing land use is apparently small, and the strategy of replacing current land uses with timber plantations can be expected to meet considerable resistance from local land managers. Such a "foreign" land use, imposed from "outside", would have little success without significant changes in infrastructure, education, and technology. Rather than trying to promote the most carbon-intensive systems, a more appropriate strategy for storing carbon would be to complement in-place land uses. Under such a strategy, it is more likely that some form of carbon-storing system will be adopted. Strategies that consider

the interplay of biomass/ha and land area will be more successful in determining the accumulation of carbon than biomass/ha alone. Afterall, the current trend in land use in the tropics is not reforestation but the loss of carbon through deforestation. The advantage of using agroforestry, rather than other types of reforestation, to accumulate carbon is that most deforestation takes place to increase the area in agriculture. To the extent that agroforestry is successful, it will tend to offset the carbon lost from deforestation. As discussed below, it may also help to reduce the extent of deforestation.

Secondary effects of agroforestry on the storage of carbon
Agroforestry also has secondary effects on carbon storage. It not only accumulates carbon on site but conserves carbon in existing forests by reducing the need for fuel and agricultural land normally obtained from neighboring forests. Two aspects of agroforestry are important in reducing losses of carbon from neighboring forests. First, agroforestry adds to the permanence of agriculture; second, it reduces the area required for agriculture.

Trees greatly enhance the agricultural permanence of a shifting agricultural production system. Because trees represent an investment over time, agroforestry serves as a disincentive to abandon agricultural lands. The additional food production and income generated by agroforestry trees reduces the reasons for abandoning land and moving on to cut new fields from forest. Trees also provide various service functions, such as increasing soil organic matter and nutrient levels and reducing runoff and soil loss, and these increase the productivity of fields beyond what occurs in fields without trees.

Trees included in agroforestry systems also reduce rates of deforestation. The supply of woody biomass for fuelwood within agroforestry can divert wood collection from forests and other natural stands, allowing these stands to maintain, and/or increase in biomass. The effect of local fuel production is also beneficial to the farmer in time. In many parts of the developing world, households spend enormous amounts of time collecting fuelwood because of the distance between home and wood source. The time spent retrieving fuelwood reduces the time available for farming or other income-generating activities (Nair 1989b). Fuelwood trees in or around the farm allow more time for these activities (such as investment of time and assets in farming activities), increasing production and thereby adding to the permanence of agriculture. With agroforestry, lack of fuelwood

ceases to be one of the reasons for moving on to a new location. Agroforestry may also reduce the land required for self sufficiency. This reduction in required land area is due both to a greater physical output and to a greater concentration of agricultural capital and labor in the existing land area (Hoekstra 1990). The utilization of agroforestry trees has been observed to act as the glue that enables several different production systems or system components to take place on a single piece of land (Winterbottom and Hazelwood 1987, Lundgren 1982). Interactions of livestock, fruit, timber, fuelwood, medicinal plant production, etc., can all take place on a single piece of land. Agroforestry does not always lead to an increase in agricultural productivity (Lal 1989), but when it does, the enhanced crop production further reduces the total land area needed to support a given population. And the greater income generated by many agroforestry designs means that less land may be needed for a given household to sustain itself (Hoekstra 1990). Thus, as long as the number of households remains constant, more land can remain in forest or is available for agroforestry.

This reduction in required land area, together with the increased agricultural permanence, may be more important in reducing emissions of carbon from deforestation than in accumulating carbon. In Africa, emissions of carbon from deforestation (0.3 PgC/yr; Houghton, in press, b) are three times higher than emissions from combustion of fossil fuels (0.12 PgC in 1985). Although most of the deforestation is for new agricultural lands, only 10% of the area deforested contributes to a net increase in agricultural area. Ninety percent of deforestation seems not to increase the area in agriculture but to replace worn out agricultural lands (Houghton, in press, a). If agricultural lands could be made sustainable, perhaps through agroforestry, rates of deforestation might be reduced by 90% without reducing the growth of productive agricultural areas. Emissions of biotic carbon would be reduced by 90%, or by 0.27 PgC/yr.

These secondary aspects of carbon storage due to agroforestry--- greater agricultural permanence, and a reduction in land area--- have been the focus of a great deal of agronomic research. Neither goal is easily attained. Attempts at creating greater agricultural permanence on less land in the tropics using techniques and technology (chemical, mechanical, institutional) imported from industrialized countries have not had a record of success. The simplistic view that the introduction of permanent agriculture

will help address the large number of the
interrelated environment-poverty problems of lesser developed
nations ignores this record, the great deal of work that has been
done on the topic, and the complexities of the human ecology
issues involved.

In summary, there are three ways in which agroforestry acts to
keep carbon out of the atmosphere: (1) through accumulation of
carbon in woody biomass and soil, (2) through reduced
deforestation of neighboring forests, and (3) through production
of wood for fuel, as a substitute for fossil fuel. The first of
these may lead to an accumulation of 8 to 54 PgC in subSaharan
Africa, but the accumulation continues only while the systems are
developing. Eventually, agroforestry systems will reach a new
equilibrium with respect to carbon, after which no further
accumulation will occur.

The second way agroforestry keeps carbon out of the atmosphere,
through reducing rates of deforestation, has the potential to
continue indefinitely. If widespreade implementation of
agroforestry eliminated deforestation completely, emissions would
be reduced by 0.3 PgC/yr. After 25 to 180 years, this secondary
aspect of agroforestry would equal the primary effect of carbon
storage. However, the major benefit of agroforestry, if it were to
eliminate the need for additional agricultural land, would be the
preservation of forests. African closed forests hold only about 30
PgC in vegetation (Brown et al. 1989) and perhaps a similar amount
in soils. At current rates of deforestation(FAO/UNEP 1981), these
forests will be gone in less than 150 years, releasing all of the
carbon contained in vegetation and additional carbon from soils.

The third way agroforestry keeps carbon out of the atmosphere, by
supplying wood fuels as a substitute for fossil fuels, is largely
in effect in Africa, where up to 80% of energy use is from
biomass. But in order for the substitution to work, the production
of wood must be sustainable, and such is not the case at present.
The argument advanced here is not that Africa continue to rely on
wood as it has until now, but that new technologies based on wood
fuels be developed so as to replace fossil fuels with efficient
substitutes (Hall et al. 1991). The fact that fuelwood
agroforestry systems are consistent with current land use in
Africa is encouraging.

Overall, the spread of agroforestry in Africa would offset global
emissions of carbon from worldwide combustion of fossil fuels for
only a few years at most. It could offset total African emissions

from deforestation and fossil fuels for 20 to 125 years. More importantly, the secondary effects of agroforestry in reducing deforestation might largely eliminate these emissions altogether. Thus, agroforestry could significantly affect the carbon balance for a large area of the world. Whether agroforestry can work in the long term, however, depends on the demands placed upon it by increases in the number of people seeking food and fuel and by changes in climate. Long-term persistence will require systems of land tenure consistent with the long-term nature of trees. It will require a stable number of farmers and a climate that is reasonably constant. Faced with growing numbers of refugees or with changes in precipitation or drought, the potential of agroforestry to accumulate carbon will be compromised.

ACKNOWLEDGEMENTS

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Table 1. Individual tree weight, number of trees/ha, and average
biomass (kg/ha) for different agroforestry types.

Agroforestry type	Tree weight (kg/tree)	Number of trees/ha	Biomass kg/ha
1. Silvopastoral			
Average annual precipitation			
a. 0400 mm	3.6	50	180
		100	360
		200	720
b. 400800 mm	3.5	50	175
		100	350
		200	700
c. > 800 mm	97	50	4850
		100	9700
		200	19400
2. Fruit tree	50	60	3000
		150	7500
		300	15000
3. Fuelwood	77	200	15400
		500	38500
		1000	77000
4. Shelterbelts	110	59	6490
5. Timber trees*	3250	40	130000
	2000	120	240000
	1350	200	270000

* For timber trees, the average weight of an individual tree is inversely related to the total number of trees/ha.

Table 2. Land areas currently suitable for agroforestry, average biomass (t/ha), and total aboveground biomass potentially stored in different types of agroforestry.

	Area (1000ha)	Biomass (t/ha) Low Estimate	Med Estimate	High Estimate	Total Biomass (10^6 t) Low Estimate	Med Estimate	High Estimate
Pastoral 0400mm	166463	0.18	0.36	0.72	30	60	120
Past. 400800mm	178503	0.18	0.35	0.70	31	62	125
Past. >800mm	112852	4.85	9.70	19.40	547	1095	2189
Fruit	296788	3.00	7.50	15.00	890	2226	4452
Fuelwood	74576	15.40	38.50	77.00	1148	2871	5742
Timber	7537	130.00	240.00	270.00	980	1809	2035
Shelterbelt	105	6.49	6.49	6.49	1	1	1
Pastoral/ Fruit 0400mm	0	1.59	3.93	7.86	0	0	0
Pastoral/ Fruit 400800mm	0	1.59	3.93	7.85	0	0	0
Pastoral/ Fruit >800mm	4494	3.93	8.60	17.20	18	39	77
Pastoral/ Fuelwood 0400mm	2255	7.79	19.43	38.86	18	44	88
Pastoral/ Flwd 400800mm	49689	7.79	19.43	38.85	387	965	1930
Pastoral/ Fuelwood >800mm	229900	10.13	24.10	48.20	2328	5541	11081
Pastoral/ Sheltblt.0400mm	52525	3.34	3.43	3.61	175	180	189
Pastoral/ ShBlt.400800mm	16449	3.33	3.42	3.60	55	56	59
Pastoral/ Shltblt. >800mm	17190	5.67	8.10	12.95	97	139	223
Fruit/ Fuelwood	258022	9.20	23.00	46.00	2374	5935	11869
Fruit/ Timber	30415	66.50	123.75	142.50	2023	3764	4334
Fruit/ Shelterbelt	26937	4.75	7.00	10.75	128	188	289
Fuelwood/ Timber	767	72.70	139.25	173.50	56	107	133
Fuelwood/ Shelterbelt	23407	10.95	22.50	41.75	256	527	977
Total:	1548874				11541	25607	45914

Table 3. Decision matrix.

Regional Precipitation zone

Landcover Class Name	ARID				SEM-ARID				SUB-HUMID				HUMID			
	West	Central	East	South	West	Central	East	South	West	Central	East	South	West	Central	East	South
Desert	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grass/shrub, <10% woody	1	1	1	1	1	7	1	7	1	7	3	3	1	1	3	1
Sudan Savanna	1	0	1	7	7	0	1	1	1	0	3	3	1	0	3	0
Grassland/Sudanian Woodland	1	0	1	0	7	0	7	0	7	0	3	0	7	7	9	0
Salt Desert	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Edaphic grass/semi-aquatic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pasture/Veld/Ag	0	1	1	8	0	1	8	1	6	7	13	13	8	6	9	6
Sudanian Woodland	0	0	0	0	0	0	7	0	7	0	9	0	7	0	9	0
Shrubland/Bushland/Rainfed Ag	0	0	1	0	11	9	9	9	9	9	13	13	11	9	9	9
Wooded/Bushed Grassland	0	0	0	0	0	7	3	7	0	7	3	3	7	7	3	7
Mos. Forest/2ndy Grassland	9	0	1	9	2	0	2	9	12	9	4	4	10	4	10	4
Moist Miombo	0	0	1	0	0	9	2	9	2	9	2	2	2	2	2	2
Miombo	0	7	1	7	0	9	9	9	2	9	2	2	2	2	2	2
Dwarf/Sparse Shrubland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plantation/Dist. Forest/Ag	9	0	0	0	2	0	2	0	0	2	10	10	10	10	10	10
2ndy/Degraded Forest	0	0	1	0	2	9	2	0	4	9	4	4	10	10	4	10
Montane Vegetation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Humid Lowl. Trop. Forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>75% Cultivated	0	0	1	5	0	2	11	2	2	2	13	13	13	2	9	2
Fynbos Shrubland	1	0	1	1	1	0	1	7	7	0	3	3	7	1	3	1
Dune Fynbos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Proteoid Fynbos	0	0	0	1	0	7	1	7	0	7	3	3	7	1	3	1
Very Moist Miombo	0	0	0	0	0	9	2	9	0	9	9	9	0	2	2	2
Shrubland/Mesotrophic Fynbos	0	0	1	0	1	0	0	7	0	7	3	3	7	1	0	0
6080% Eroded/Degraded	0	0	1	0	0	0	3	0	0	0	13	0	0	0	3	0
4060% Eroded/Degraded	0	0	0	0	0	0	3	0	0	0	13	0	0	0	3	0
Cult w/sm relicts Mont. Forest	0	0	0	0	0	0	9	0	0	0	11	0	0	0	2	0
Upland Dry Forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lake/Aquatic veg.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hi-elev scatttered Woodl/Forest	0	0	0	0	0	0	9	0	0	0	3	0	0	0	2	0
Forest, various types	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Savanna/Wooded Steppe/Rainfed Ag	0	0	0	0	0	0	11	0	0	0	13	0	0	0	9	0

1=Pastoral
2=Fruit
3=Fuelwood
4=Timber
5=Shelterbelt
6=Pastoral/Fruit
7=Pastoral/Fuelwood
8=Pastoral/Shelterbelt
9=Fruit/Fuelwood
10=Fruit/Timber
11=Fruit/Shelterbelt
12=Fuelwood/Timber
13=Fuelwood/Shelterbelt

FIGURE LEGENDS

Figure 1. Number of trees and volumes of stemwood for mature tropical plantations (FAO/UNEP 1981). The curve is a polynomial regression of stemwood as a function of number of trees.

Figure 2. Layers in the GIS used to assign different types of agroforestry to the appropriate location. a - mean annual precipitation; b - regional precipitation zones; c - current land cover; d - type of agroforestry compatible with current land use.

Figure 3. Examples of seasonal variation in GVI (average + standard deviation) for different classes of land cover. NDVI is the difference between the reflected radiances measured in the near-infrared (CNIR) (0.731.1 um) and visible (CVIS) (0.550.68 um) spectral regions (channels 1 and 2, respectively), divided by their sum:

$$NDVI = \frac{CNIR - CVIS}{CNIR + CVIS}$$

High values of GVI indicate that a greater proportion of the land is covered by photosythetically active vegetation.