

## Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes

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### Abstract

The conversion of forests to agroecosystems or agroforests comes with many changes in biological and chemical processes. Agroforestry, a tree based agroecosystem, has shown promise with respect to enhanced system nutrient accumulation after land conversion as compared to sole cropping systems. Previous research on tropical agroforestry systems has revealed increases in soil organic matter and total organic nitrogen in the short term. However, research is lacking on long-term system level sustainability of nutrient cycles and storage, specifically in traditional multi-strata agroforestry systems, as data on both the scope and duration of nutrient instability are inconclusive and often conflicting. This study, conducted in Ghana, West Africa, focused on carbon and nitrogen dynamics in a twenty-five year chronosequence of cacao (*Theobroma cacao* Linn.) plantations. Three treatments were selected as on-farm research sites: 2, 15 and 25-year-old plantations. Soil carbon (C, to a depth of 15 cm) varied between treatments (2 years: 22.6 Mg C ha<sup>-1</sup>; 15 years: 17.6 Mg C ha<sup>-1</sup>; 25 years: 18.2 Mg C ha<sup>-1</sup>) with a significant difference between the 2- and 15- and the 2- and 25-year-old treatments ( $p < 0.05$ ). Total soil nitrogen in the top 15 cm varied between 1.09 and 1.25 Mg N ha<sup>-1</sup> but no significant differences were noted between treatments. Soil nitrification rates and litter fall increased significantly with treatment age. However, photosynthetically active radiation (PAR) and soil temperature showed a significant decrease with age. No difference was found between decay rates of litter at each treatment age. By 25 years, system carbon sequestration rates were 3 Mg C ha<sup>-1</sup> y<sup>-1</sup>, although results suggest that even by 15 years, system-level attributes were progressing towards those of a natural system.

### Introduction

Agroforestry has shown promise with respect to enhanced productivity and system nutrient accumulation in many geographical regions around the world. Increased nutrient inputs, reduction in nutrient losses, and improved soil physical prop-

erties are all characteristics of agroforestry systems as compared to sole cropping systems (Young 1989; Nair 1993). However, the recovery of soil organic matter in these systems and the accumulation of important nutrients, such as nitrogen, are not well understood. Both the scope and duration of nutrient instability after forest conversion, and

over prolonged agroforest rotations, requires further study. Conflicting and inconclusive evidence remains as to the long-term quantity of soil nutrients and soil organic matter (Schroth et al. 2001), although previous research on comparing tropical agroforestry systems to sole cropping systems has revealed short-term enhancement of soil organic matter and total organic nitrogen (Young 1989; Hagger et al. 1993). The available short-term data are often used to make predictions of organic matter and nutrient behavior over longer periods (Kelty 2000). This type of extrapolation requires further investigation to confirm predictions about the productivity of agroforestry systems.

Studies have shown the importance of long-term nutrient accumulation based on evidence illustrating an indirect supply of nutrients derived from this nutrient buildup (Hagger et al. 1993; Chander et al. 1998). However, research is lacking on long term, system level nutrient sustainability and the maintenance of nutrient cycles, specifically in traditional multistrata agroforestry systems. In response to this, the objectives of this study were to investigate soil carbon and nitrogen dynamics in a twenty-five year chronosequence of cocoa (*Theobroma cacao* Linn.) plantations. As the accumulation and distribution of soil organic matter and its associated nutrients are controlled by residue inputs, decomposition processes and mineralization rates, this study made use of nutrient pools and fluxes as parameters to quantify temporal changes within these systems. Soil carbon, total soil nitrogen and aboveground biomass were selected pools, and biomass inputs via litter-fall, decomposition and nitrogen mineralization processes were measured as fluxes.

The cultivation of cocoa has been documented in agricultural reports since 1556 (Johns 1999). Cocoa-based multistrata systems, a traditional type of agroforestry, incorporate highly productive cash crop trees with shade trees and understory vegetation. Small-scale west Africa farm production of cocoa has developed from a small proportion of world production in the early 19th century to currently over 60% of the global total (International Cocoa Organization 2000). Cocoa farms are developed in a similar fashion throughout West Africa: primary or secondary forests are selectively cleared, commonly burned and cocoa is planted, along with understory food crops. Certain

upper story canopy trees are retained (*Terminalia superba* Engl. & Diels, *Newbouldia laevis* (Beauv.) Seem. Ex Bureau or *Ceiba pentandra* L.) and fruit trees may be planted, such as orange (*Citrus sinensis* (L.) Osbeck), avocado (*Persea Americana* L.) and mango (*Mangifera indica* L.) for shade, food and other purposes (Amoah 1995).

## Materials and methods

### *Site description*

This study took place in Ghana, West Africa, in the moist semi-deciduous tropical zone in the Western Region, located at 06°12' N and 02°29' W from April to October, 2002. The study region has an annual precipitation of 1054.5 mm (2001) and an average temperature of 26.1 °C (2001). The population of the region is 149,000 (2000) in approximately 60 different villages. Sites selected for this chronosequence study had similar soil type (orchosol–oxysol intergrades), past management history (converted forest), present management with respect to land preparation and management, climate (temperature/precipitation), and species composition.

The treatments selected were: 2-year-old, 15-year-old and 25-year-old multistrata cocoa plantations. These treatments represent three distinct phases of the development in a cocoa farm, specifically the planting and developing phase (2-year), the productive phase (15-year) and the mature phase (25-year). On-farm field sites containing the three treatments were located adjacent to each other in four blocks (Sui, Bosomoiso, Nipa Tirim, Aboprey) surrounding the main regional town, Sefwi Wiawso. The sampling design for the chronosequence study was a randomized complete block design, as it was confirmed with farmers that the conversion of forested land to agroforest, hence application of treatment, was conducted on a random basis.

### *Biophysical characteristics*

Soil bulk density was determined for each treatment (in triplicate) at each block by collecting a

known volume of soil with a metal core placed into the top 15 cm of soil, drying (65 °C, 48 h) and weighing the soil. Soil textural classes were determined by the hydrometer method (Allen et al. 1974). Soil pH was determined on a 1:1 paste of 10 g of air-dried soil and 10 ml of distilled water. The mixture was allowed to sit for 15 min and then an electrode was placed in the slurry and pH recorded using a Digi-Sensor pH meter (Allen et al. 1974).

Aboveground biomass for the upper canopy strata and the cocoa strata at each block and each treatment was estimated from measured diameter at breast height (DBH) and tree height ( $H$ ) using a generalized tree biomass regression for the specific precipitation zone (Brown 1997):

$$y = \exp[-3.1141 + 0.9719 \ln(\text{DBH}^2 \cdot H)]$$

where  $y$  is the aboveground biomass (kg), DBH the diameter at breast height (cm), and  $H$  is the height of tree (m).

Biomass per tree was multiplied by the number of trees per hectare to determine biomass on an areal basis ( $\text{Mg ha}^{-1}$ ). Understory vegetation was measured using 20 m  $\times$  20 m plots. The diversity and frequency of understory species were counted and recorded.

#### Soil carbon and nitrogen

Three composite soil samples to a 15 cm depth were obtained from under and outside a selected upper canopy tree. The soil sampling protocol was repeated for three stratified trees at each treatment, resulting in 54 samples from each block and 216 samples in total. Composite soil samples were air-dried and ground to pass through a 2-mm sieve. Sub-samples of the composite soil samples were ground further, using an electric mortar and pestle, to a powder (to  $<0.5$  mm). This finely ground soil was used in both soil carbon and total nitrogen analysis.

Total soil carbon was analyzed using a LECO Carbon Analyzer. Total soil nitrogen was analyzed using the semi-micro Kjeldahl method; digestion of the soil was completed with sulfuric acid and salicylic acid to convert all nitrogen to ammonium (Allen et al. 1974). Total nitrogen as ammonium in the digest was then determined using a Technicon Autoanalyzer (see (Figure 1)).

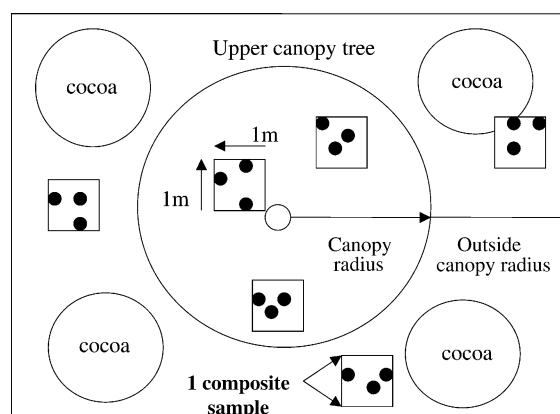


Figure 1. Schematic drawing depicting overview of multistrata system with sampling design. Black dots represent one soil sample, 3 samples making 1 composite sample per 1 m<sup>2</sup> plot.

#### Inorganic nitrogen

Nitrogen mineralization rates were determined *in situ*. Soil was incubated in PVC tubing covered in plastic, which reduced evapotranspiration and leaching. To account for moisture variation, all tubes were placed in the ground approximately 24 h after a rainfall event. Ten tubes per site in total were used, placed as 5 sets of pairs to a depth of 15 cm. One tube of each pair was immediately taken to the laboratory and frozen for determination of initial nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ) concentrations. The other 5 tubes were retrieved after a 60 day (d) incubation and also analyzed for inorganic nitrogen content. Soils removed from the tubes were subsampled for moisture content, extracted with KCl and analyzed using a Technicon Autoanalyzer for both nitrate and ammonium. Net nitrogen mineralization rate ( $\mu\text{g N g}^{-1} \text{ soil d}^{-1}$ ), was calculated as the difference between final and initial nitrate and ammonium concentrations (Anderson and Ingram 1989) divided by the length of the incubation period.

#### Litter inputs and decomposition

Litterfall was sampled at each treatment in the following manner: three litter traps, 0.50 m<sup>2</sup> with 5 mm mesh size and 20 cm in height were established at each treatment. Litter from traps was collected every two weeks, the material was dried (65 °C, 48 h) and the weight recorded.

Annual litter input per hectare for each treatment was calculated as an average of each block. Litter trap material was also processed using the semi-micro Kjeldahl method to determine nitrogen content of the leaves and combusted in the LECO carbon analyzer to determine percent carbon content.

To measure litter decomposition, litterbags, 30 cm × 30 cm with a mesh size of 5 mm were filled with 30 g (wet weight) of cocoa leaf material, closed with staples, and secured to the ground at random locations within each site. The litterbag mesh size corresponds to that utilized by Tian et al. (1992). A total of 9 bags were used, with 3 bags retrieved on a random basis at 14, 28 and 35 d after placement. The material remaining in each collected bag was cleaned, dried, weighed and recorded, as described by Anderson and Ingram (1989). Wet/dry ratios were calculated for the initial material by drying material at 60 °C for 48 h to correct for moisture. Decomposition of material was described by using the single exponential decay function:

$$A_t = A_0 e^{-kt},$$

where  $A_t$  is the amount remaining after time  $t$  (g),  $A_0$  the initial amount (g),  $t$  the time (d), and  $k$  is the rate constant ( $d^{-1}$ ).

The specific decomposition constant,  $k$ , can be estimated from the slope of the line of the linear regression between  $\ln(A_t/A_0)$  and time (Paul and Clark 1996).

#### *Soil temperature*

Soil temperature was measured using a HOBO temperature sensor. One sensor was placed at a depth of 15 cm under the upper canopy and another sensor was positioned at the same depth outside the upper canopy zone. Temperature was recorded at two sites (2- and 25-year-old treatments) over 2 d. The HOBO's were programmed to take readings at 30 min intervals. In addition, temperature readings from inside decomposition bags were taken to account for temperature variation at the soil surface.

#### *Photosynthetically active radiation (PAR)*

PAR ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) was estimated using a SKYE light meter. Random readings throughout the day

were taken with near-simultaneous readings from inside and outside the canopy in order to determine percent open canopy at each treatment (Ter-Mikaelian et al. 1997).

#### *Statistical analysis*

Variance analysis, using a general linear model and least square adjusted means was employed. A test of residuals was performed to confirm the assumptions of the variance of analysis. Independence, randomness of residuals and a mean error equal to zero were confirmed. Normality of residuals was tested for using the Shapiro–Wilkes test. The Lund's critical value was compared with the highest absolute value of the data set to test for outliers; upon an evaluation of the data set, if a plausible explanation could not be found for the outlier, it was then removed. Tests for significance employing an  $F$ -test were undertaken to test the above hypothesis, and a Tukey's test was employed to determine the significance of treatment means. All statistical analysis was conducted with SAS version 8.0 and a Type I error rate ( $\alpha$ ) was set at 0.05 for all statistical tests.

## **Results and discussion**

#### *Biophysical parameters*

Soil bulk density across treatments ranged from 0.9 to 1.0  $\text{g cm}^{-3}$ . There was no significant difference in bulk density between the 2-year-old and 15-year-old treatments; however, in the 25-year-old treatment, soil bulk density was significantly lower (Table 1). Soil texture ranged from loamy sands to clay loams; however, there was no significant difference in the soil texture (% sand, silt and clay) between treatments (Table 1). Soil pH ranged from 4.2 to 7.0 across all combinations of blocks and treatments (Table 1), with no significant difference between treatments. Aboveground biomass for both the upper story canopy and the cocoa strata was significantly lower ( $p < 0.05$ ) in the 2-year-old treatment when compared to the 15-year-old and 25-year-old treatments. (Table 1). Data on the total aboveground biomass carbon pool, assuming 45% carbon content, is also presented in Table 1. Total carbon in the total (upper canopy and cocoa)

Table 1. Soil physical and chemical properties of the top 15 cm of the soil, biophysical components and vegetative biomass for both the upper story canopy and the cocoa canopy for each treatment in a multistrata agroforestry system in the Sefwi Wiawso Region, Ghana ( $\pm$ SE).

Parameter	Treatment		
	2-year-old	15-year-old	25-year-old
<i>Soil physical and chemical properties</i>			
Bulk density ( $\text{g cm}^{-3}$ )	1.0 ( $\pm 0.04$ )a	1.0 ( $\pm 0.04$ )a	0.9 ( $\pm 0.04$ )b
Texture (%)			
Sand	64.5 ( $\pm 11.22$ )a	44.5 ( $\pm 11.22$ )a	64.5 ( $\pm 11.22$ )a
Silt	12.0 ( $\pm 1.09$ )a	12.0 ( $\pm 1.09$ )a	11.5 ( $\pm 1.09$ )a
Clay	23.5 ( $\pm 4.44$ )a	23.5 ( $\pm 4.44$ )a	24.0 ( $\pm 4.44$ )a
pH	5.9 ( $\pm 0.44$ )a	5.4 ( $\pm 0.44$ )a	5.3 ( $\pm 0.44$ )a
<i>Biophysical</i>			
Photosynthetically active radiation (% of open)	23.4 ( $\pm 1.94$ )a	6.0 ( $\pm 1.96$ )b	10.6 ( $\pm 1.91$ )b
Soil temperature ( $^{\circ}\text{C}$ )	25.2		24.6
<i>Vegetative biomass</i>			
Upper story canopy			
Trees ( $\text{ha}^{-1}$ )	200 <sup>A</sup>	56 <sup>B</sup>	63 <sup>C</sup>
Total biomass ( $\text{Mg ha}^{-1}$ )	4.3 ( $\pm 24.74$ )a	82.0 ( $\pm 24.74$ )b	143.8 ( $\pm 24.74$ )b
Carbon in biomass ( $\text{Mg C ha}^{-1}$ )	1.9	36.9	64.7
Cocoa canopy			
Trees ( $\text{ha}^{-1}$ )	3125	1362	900
Total biomass ( $\text{Mg ha}^{-1}$ )	5.3 ( $\pm 3.65$ )a	37.3 ( $\pm 2.83$ )b	35.3 ( $\pm 3.65$ )b
Carbon in biomass ( $\text{Mg C ha}^{-1}$ )	2.4	16.8	15.9

Values within a row followed by the same letter are not significantly different ( $p < 0.05$ , Tukey's test).

<sup>A</sup>Average trees  $\text{ha}^{-1}$  at Nipa Tirim (200), Sui (100), Bosomoiso (300), Aboprey (200).

<sup>B</sup>Average trees  $\text{ha}^{-1}$  at Nipa Tirim (50), Sui (50), Bosomoiso (75), Aboprey (50).

<sup>C</sup>Average trees  $\text{ha}^{-1}$  at Nipa Tirim (75), Sui (50), Bosomoiso (75), Aboprey (50).

aboveground biomass was 4.3, 53.7 and 80.6  $\text{Mg C ha}^{-1}$ , in the 2 year, 15 year and 25 year treatment, respectively. Soil bulk density, texture, and pH did not differ across blocks. This shows the suitability of these sites to a chronosequence approach and allows for further meaningful evaluation of other characteristics within these systems.

PAR levels were 23.4% of open canopy ( $\pm 1.94$ ), 6.0% of open canopy ( $\pm 1.96$ ) and 10.6% of open canopy ( $\pm 1.91$ ) for the 2, 15 and 25-year-old treatments, respectively. As expected, there is a decrease in light penetration between the 2- and 15-year-old treatments as the canopy ages and vegetation becomes increasingly dense.

Expected temperature fluctuations throughout the day in soil temperature were observed over time, with a dip in temperature in early morning and a peak in mid-afternoon. This pattern was observed in all three treatments. However, a *t*-test performed on the temperature data from under the upper story canopy zone ( $n = 192$ ) indicated a significant difference ( $p < 0.05$ ) between the

youngest and oldest treatments, with a higher average soil temperatures at 15 cm depth in the 2-year-old treatment compared to the 25-year-old treatment. The mean temperature for the 2-year-old treatment was 25.2 and 24.6  $^{\circ}\text{C}$  for the 25-year-old treatment.

### Pools

#### Soil carbon

Soil carbon differed significantly ( $p < 0.05$ ) between the 2-year-old and 15-year-old treatments; however, no difference in this parameter was observed between the 15-year-old and 25-year-old treatments. The average carbon stock ( $\pm$ SE) in the top 15 cm of soil was 22.6  $\text{Mg C ha}^{-1}$  ( $\pm 1.13$ ), 17.6  $\text{Mg C ha}^{-1}$  ( $\pm 1.40$ ) and 18.2  $\text{Mg C ha}^{-1}$  ( $\pm 1.08$ ) in the 2-, 15-, and 25-year-old treatments, respectively. A significant quadratic relationship [ $Y = 24.33 + (-0.89 \text{ age}) + (0.026 \text{ age}^2)$ ] ( $p < 0.05$ ) between soil carbon content [ $Y$  ( $\text{Mg ha}^{-1}$ )] and time [age (years)] after forest conversion exists.

Although the predictive ability of the equation is low ( $R^2 = 0.32$ ), this relationship demonstrates the association between time after land conversion and soil carbon pools.

Twenty-two percent of soil carbon was lost from the system between 2 and 15 years after land conversion to productive agroforest. However, by 25 years, 3.3% of the soil carbon had re-accumulated. Charter (1955) conducted a similar study in the Ghanaian moist semi-deciduous forest zone on old secondary forest orchosols, similar in location, vegetation and soils to the original forest zone associated with this study and indicated soil carbon to be 1.8%. Assuming a bulk density of  $1.00 \text{ g cm}^{-3}$  and 15 cm depth, soil carbon stocks in this forest zone would have been approximately  $27 \text{ Mg C ha}^{-1}$  and this can be assumed to represent initial soil carbon content before land conversion. By observing the changes in soil carbon stocks at 25 years after land conversion to those calculated as pre-land conversion values, approximately 67% of soil carbon has been maintained and/or regained by this point.

Within the first 2 years after land conversion, 16% of the original carbon stock had been lost. These results are comparable to those of Houghton et al. (1991), who found that soil carbon decreased 20% during the first 5 years after land conversion. Many studies have reported similar results that show significant declines in initial soil carbon during the first 5 years after stand conversion (Juo and Kang 1989; Van Noordwijk et al. 1997). Woomer (1993), for example, found declines in carbon stocks to be as high as 63% during the first cycle of slash and burn in Mozambique. In this study, an examination of the 15-year-old data on soil carbon may be more realistic, as the initial high level of soil carbon at 2 years may be an artifact of the slash and burn process, when the system was flushed with a high quantity of organic matter and ash. Over the following 13 years, carbon losses from the system were more gradual and occurred in a more regulated fashion. By 25 years, however, soil carbon had begun to re-accumulate in the system.

In addition to the losses indicated above, Houghton et al. (1991) also found a further 5% decrease in carbon from age 5 to age 25 (a total 25% decrease) after which a steady state was reached. Similar results were found in this study, where the 15-year-old treatment exhibited a

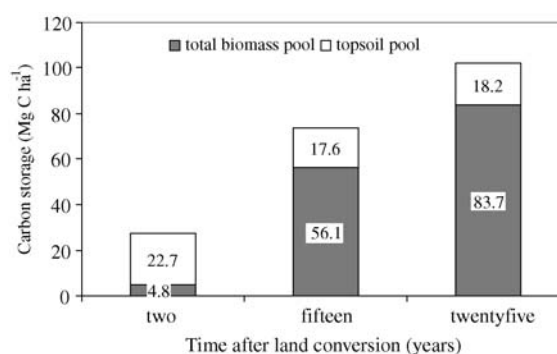


Figure 2. Carbon ( $\text{Mg C ha}^{-1}$ ) in total biomass pool and topsoil pool (values shown on graph) for 2-, 15- and 25-year-old treatments in a chronosequence of multistrata agroforestry systems in the Sefwi Wiawso Region, Ghana.

decrease in soil carbon content totaling 35%, compared to the estimated initial value of carbon. Although some previous research has found that soil carbon pools remain approximately constant during most land conversion practices in the tropics (Kotto-Same et al. 1997), the majority of research papers surveyed support the results of this study, which indicates significant changes in soil carbon content over time (Juo and Kang 1989; Houghton et al. 1991; Van Noordwijk et al. 1997).

#### System carbon

Carbon held within total aboveground biomass increased more distinctly over time, compared to soil carbon, which fluctuated moderately (Figure 2). Aboveground biomass is the larger pool, over the total chronosequence, for carbon storage. However, it should be noted that during the first years of re-growth after land conversion, soil carbon is more crucial to system carbon stocks than carbon associated with vegetation, an important consideration if the management focus is carbon sequestration. Annually, up to 15 years after land conversion, the entire system had a carbon fixation rate of  $3.4 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ . After this period, the carbon fixation rate was reduced to  $2.8 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ .

#### Total soil nitrogen

Total soil nitrogen in the 2-, 15- and 25-year-old treatments was  $1.1 \text{ Mg ha}^{-1} (\pm 0.08)$ ,  $1.3 \text{ Mg ha}^{-1} (\pm 0.07)$  and  $1.2 \text{ Mg ha}^{-1} (\pm 0.07)$ , based on concentrations of 0.075%, 0.084% and 0.086% for the 3 treatments, respectively (Figure 3). No significant differences between treatments were found.

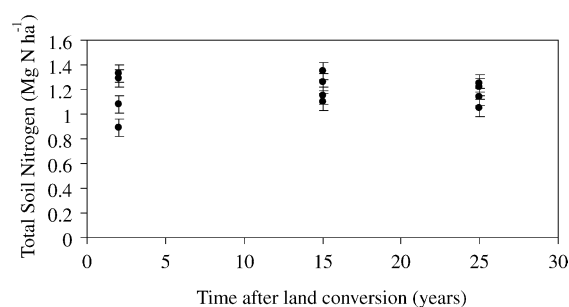


Figure 3. Total soil nitrogen content for each site and treatment ( $\pm$ SE bars) from a chronosequence of multistrata agroforestry systems in Sefwi Wiawso Region, Ghana.

Nitrogen concentrations are generally low, although they do correspond to values found in an Indian tropical agroforestry system, with total soil nitrogen (%) ranging between 0.068 and 0.073 depending upon the density of shade trees (Chander et al. 1998).

Although large amounts of biomass residues are being added to the system in later years, many paths of nitrogen loss exist within agroforestry systems. Palm et al. (1996) and Paul and Clark (1996) suggest that considerable losses of nitrogen can occur as a result of leaching and gaseous losses as well as runoff and erosion due to land clearing. The rapid decrease in soil carbon suggests rapid mineralization during initial periods of the chronosequence, resulting in an abundance of available nitrogen that is not utilized by the plants. This nitrogen may leach from the system, leaving behind more recalcitrant forms of soil organic matter. The labile fraction is not regenerated due to drastic decreases in biomass inputs during the first several years after land conversion. The high C:N

ratio of the litterfall (Table 2) also suggests that small amounts of nitrogen will be added to the system via this flux regardless of the quantity of biomass inputs.

Sampling techniques for both total soil nitrogen and soil carbon may not have been sufficient to capture significant changes in total nitrogen content and carbon content. Multiple depths of soil samples within the soil horizon should be collected for more rigorous investigation into soil nitrogen contents. Further research is required in this area to confirm these suggestions.

### Fluxes

#### Nitrogen mineralization

Mineralization of organic nitrogen is an important flux within productive agroforestry systems, and attempts to measure this process were undertaken. Net nitrogen mineralization rates ( $\mu\text{g g}^{-1}\text{ soil d}^{-1}$ ) were negative, suggesting that no mineralization of organic nitrogen occurred over the 60-d incubation (Table 2). Soil nitrate production did significantly increase between the 2-year-old and 25-year-old treatments (Table 2), indicating possibly nitrification of initial ammonium present at the time of incubation. Soils in the 2-year-old treatment exhibited a nitrification rate of  $13.8\text{ kg N ha}^{-1}\text{ 60 d}^{-1}$ , those in the 15-year-old treatment, a rate of  $21.4\text{ kg N ha}^{-1}\text{ 60 d}^{-1}$  and those in the 25-year-old treatment, a rate of  $25.9\text{ kg N ha}^{-1}\text{ 60 d}^{-1}$ . Plausibly, ammonium could have been immobilized during the incubation period, as well as possible denitrification losses due to potentially anaerobic conditions within the tubes following

Table 2. Nitrogen mineralization rates ( $\mu\text{g g}^{-1}\text{ soil d}^{-1}$ ), litterfall inputs ( $\text{Mg ha}^{-1}\text{ y}^{-1}$ ), C:N of litter material and decay rate ( $k$ ) values ( $\text{d}^{-1}$ ) for leaf decomposition at each treatment in a multistrata agroforestry system in the Sefwi Wiawso Region, Ghana.

Parameter	Treatment		
	2-year-old	15-year-old	25-year-old
Nitrogen mineralization ( $\mu\text{g g}^{-1}\text{ d}^{-1}$ )			
Ammonification	-0.37a	-0.35a	-0.40a
Nitrification	0.10a	0.20ab	0.32b
Net mineralization	-0.27a	-0.15a	-0.08a
Litterfall inputs ( $\text{Mg ha}^{-1}\text{ y}^{-1}$ )	3.2a	6.9b	10.4c
C:N of litter	49.2:1	45.2:1	47.3:1
$k$ -values ( $\text{d}^{-1}$ )	0.0258a	0.0178a	0.0167a

Values within a row followed by the same letter are not significantly different ( $p < 0.05$ , Tukey's test).

extreme rainfall events. Certain studies have also shown an immediate increase in mineralization after land change, with this flux stabilizing soon after land clearing (Mueller-Harvey et al. 1985), a process not confirmed in this study. This apparent lack of inorganic nitrogen production may also be a residual effect of the timing of the *in situ* incubation. Tubes were placed in the field after the beginning of the rainy season when the mineralization process was well under way and the key flush of inorganic nitrogen may have ended. However, significant nitrification rate increases in the chronosequence does suggest a strengthening of nitrogen fluxes as the agroforest matures.

A strong correlation was found between production of nitrates and aboveground biomass inputs ( $r = 0.99$ ). This relationship may explain the general trend towards increased nitrification rates as age of system increases. Long-term accumulation of organic matter enhances the size of the active nitrogen pool as a source of potentially mineralizable nitrogen within the soil.

#### *Litterfall*

The mass of material collected in litter traps showed a significant increase with time after land conversion (Table 2). Litterfall in the 25-year-old treatment was comparable to that found in undisturbed forests. Greenland et al. (1992) found the average litterfall in a humid forest to be approximately  $10,000 \text{ kg ha}^{-1} \text{ y}^{-1}$ . Vitousek and Sanford (1986) also observed aboveground inputs within a tropical forest to be between  $8,800$  and  $10,500 \text{ kg ha}^{-1} \text{ y}^{-1}$ . By 25 years, biomass inputs via litterfall had reached rates found in natural forests suggesting a sustained level of nutrient inputs.

#### *Decomposition*

Specific decay rate constants, on a  $\text{d}^{-1}$  basis, were not different between treatments (Table 2) and were in the range of previously measured decomposition rates in tropical agroforestry systems (Tian et al. 1992). As more light and higher temperatures were found in the younger agroforestry systems, it was expected that faster decomposition of material would occur at these sites. However, soil moisture was less prevalent in the younger systems and in all likelihood, this negated possible difference between sites. In addition, while tem-

peratures at 15 cm were ideal for decomposition processes, higher temperatures were found on the soil surface. As leaf material was not incorporated into the soil, leaves were exposed to temperatures, which may have been sufficiently extreme ( $> 30 \text{ }^\circ\text{C}$ ) to impede decay rates (Palm et al. 1996).

#### **Conclusions**

Trends in soil carbon in the top 15 cm, across the chronosequence, suggest a steady state has been reached at 15 years after land conversion. Higher soil carbon values before this point in time may be attributed to land preparation methods and may be a residual effect of the slash and burn process. The chronosequence results suggest that, by 25 years, aboveground biomass and the topsoil pool sequester, on average,  $3 \text{ Mg C ha}^{-1} \text{ y}^{-1}$  and the soil pool stores a total of  $18.2 \text{ Mg C ha}^{-1}$ . Total soil nitrogen does not differ over time. Low nitrogen levels ( $< 1.3 \text{ Mg N ha}^{-1}$ ) may be explained by minimal initial biomass inputs with a high carbon to nitrogen ratio, rapid mineralization during the first two years after land disturbance, and a potential loss of nitrogen from the system.

In several of the pools, fluxes and parameters measured in this chronosequence, no difference was found between the 15-year-old and 25-year-old treatments. Soil carbon, aboveground biomass and nitrification rates were not different in the older treatments of the chronosequence when compared to the younger treatment, indicating that long-term dynamics and biophysical interactions within this system become relatively stable after 15 years. By 25 years, results suggest that system-level attributes were progressing towards those of a natural system.

Further research is required to definitively respond to the long-term questions raised in this study. Expanding the chronosequence to encompass a primary forest or an older ( $> 80$  years) secondary forest, as well as a newly cleared site could offer more accurate explanations with respect to long-term carbon and nitrogen pools. As well, studies specifically on soil organic matter fractions within these agroforestry systems would enable researchers to focus on minute changes in soil carbon partitioning.

Although uncertainty remains with respect to the ability of an agroforest to develop sustained

pools of nutrients and soil organic matter, a steady state of soil carbon, and soil nitrogen, has been demonstrated. System fluxes exhibited little differences throughout the chronosequence, except for biomass inputs via litterfall, augmenting nutrient addition to the system. These agroecosystems, found extensively throughout west Africa, have the capability to sequester large amounts of carbon over their life cycles in both the above-ground biomass pool after 15 years and in the top soil pool in the early years of the chronosequence.

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