CONVERSION OF NATURAL FOREST TO COCOA AGROFOREST IN LOWLAND HUMID GHANA: IMPACT ON PLANT BIOMASS PRODUCTION, ORGANIC CARBON AND NUTRIENT DYNAMICS

A Thesis submitted to the Department of Agroforestry, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY
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DECLARATION

I hereby declare that this work, submitted for the degree of PhD (Agroforestry) is the result of my own investigations conducted under supervision and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the university, except where due acknowledgement has been made in the thesis.

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Abstract

This study was conducted to assess the effects of forest conversion to shaded-cocoa system on plant biomass, nutrient fluxes and soil physico-chemical properties along a chronosequence (forest, 3, 15 and 30-year-old cocoa farms) in the Moist Semi-deciduous Forest Zone of the Ashanti Region, Ghana. It also explored farmer indigenous knowledge and perceptions of soils and soil fertility dynamic processes. Plant biomass and above-ground organic carbon and nutrient pools significantly declined following changes in land-use compared to soil pools. Tree biomass constituted the largest pool ranging from 12.7 ±1.6 Mg ha^{-1} for the 3-year-old cocoa system to 209.3±33.3 Mg ha^{-1} in the forest. Soil Organic Carbon (SOC) in 0-60 cm soil depth did not change significantly over a 30-year period and ranged from 49.0±2.3 to 67.4±1.1 Mg C ha^{-1} in 3 year-old shaded cocoa system and forest respectively. SOC significantly declined only in the top (0-10 cm) soil at 3 years after conversion but recovered at 15 years. Thirty-year-old shaded-cocoa systems yielded up to 151 Mg C ha^{-1} primarily stored in established trees (both cocoa and shade trees) and soil pools. Total N declined only in the 10-20 cm soil depth in 3 and 15 year-old treatments but remained stable in all other soil depths across the chronosequence while available P stocks declined significantly. Soil exchangeable Ca, K and Mg stocks remained relatively stable with a tendency to improve, and cation exchange capacity (CEC) and base saturation increased more or less along the chronosequence. Soil bulk density (gm cm^{-3}) increased significantly with increasing age of plantation only for the top 0-10 cm soil layer but did not differ among sites for similar depths. Despite the apparent stability of soil C stocks and nutrients (0-60 cm) along the chronosequence, soil quality declined under cocoa land-use at 3 years. Microbial biomass demonstrated a strong seasonal variation. However, conversion of forest did not result in a significant decline in microbial biomass.

Mean annual litterfall and stand litterstocks differed significantly among land-uses. Litterfall ranged from 5.0 Mg ha^{-1} in 3-year-old cocoa to 10.4 Mg ha^{-1} forest systems while stand litterstocks were from 3.6 to 5.9 Mg ha^{-1} in 3 and 15-year-old farms respectively. Annual decomposition coefficients (k_{L}) were similar in cocoa systems (0.221-0.227) but greater under forests (0.354). Estimated nutrient inputs from litterfall was 4 to 165 kg ha^{-1}yr^{-1} of P and Ca respectively in 15-year-old and forest plots respectively. Turnover of fine roots was 3,591, 1,427, 2,466 and 4,066 kg ha^{-1}yr^{-1} for forest, 3, 15 and 30-year-old plots respectively. Nutrient inputs through turnover of fine roots were estimated to be 16-31 kg N ha^{-1}year^{-1}, 2 -5 kg P ha^{-1}year^{-1}, 9-36 kg K ha^{-1} year^{-1}, 18-47 kg Ca ha^{-1}year^{-1} and 3-25 kg Mg ha^{-1}year^{-1} across the chronosequence.

There were significant differences in incident rainfall, throughfall and stemflow chemistry. Mean annual inputs of nutrients fluxes in incident rainfall were 5.7 kg N, 0.14 kg P, 13.6 kg K, 9.43 kg Ca and 5.6 kg Mg ha^{-1} yr^{-1}. Rainfall loading or net canopy exchange was negative for total N at all sites while concentrations of P and the basic cations increased in throughfall relative to incident rainfall. Throughfall on average constituted about 95% of the total solute inputs of rainfall origin to forest floor. The mean N and P input-output balances were negative showing the system's 'no external input' character.

Farmers in the study had a well-developed knowledge system of their soils and related fertility processes. They derived their knowledge from observable plant and soil characteristics namely; soil color, crop yield, water retention capacity, difficulty to work soil, type and abundance of indicator weeds, leaf color or deficiency symptoms observed on crops and presence and abundance of soil macro-fauna. The qualitative perceptions of farmers matched scientific assessment of fertile or infertile soils. The results suggest the integration of local and scientific knowledge to facilitate the processes for formulating

policies and development plans for agriculture truly participatory, gender sensitive and collaborative approaches. Enhancement farmers' capability to adopt improved farm management and land preparation methods is required to conserve the soil and sustain long-term productivity.

Key words: Litterfall, stand litterstocks, forest conversion, litter quality, nutrient fluxes, indigenous soil knowledge

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Finally, my affectionate thanks go to my wife Cecilia and our son Makafui who have made this achievement possible by their prayers and endured my long stay away from them. To them I dedicate this thesis.

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Abbreviations and symbols

AEO	Agric Extension Officer	
ANOVA	Analysis of variance	
COCOBOD	Ghana Cocoa Board	
CSD	Cocoa Services Division	
C/N ratio	Carbon to nitrogen ratio	
DBH	Diameter at breast height	cm
DI	Degradation index	
ECEC	Effective cation exchange capacity	mmol kg^{-1}
CEC	Cation Exchange Capacity	mmol kg^{-1}
FR	Fine roots	
FRB	Fine roots biomass	Mg ha^{-1}
FRP	Fine roots productivity	Mg $ha^{-1}yr^{-1}$
GDP	Gross Domestic Product	
Ha	Hectare	
HSD Test	Honestly Significant Difference Test	
IK	Indigenous Knowledge	
IN	Input	
k	Monthly decomposition coefficient	
k_L	Annual decomposition coefficient	
L	Litre	
LF	Litterfall	Mg ha^{-1}
L:N Ratio	Lignin to nitrogen ratio	
LS	Stand Litterstock	Mg ha^{-1}
LUC	Land-use chronosequence	
MBC	Microbial Biomass Carbon	mg kg^{-1}
MBN	Microbial Biomass Nitrogen	mg kg^{-1}
MBP	Microbial Biomass Phosphorus	mg kg^{-1}
Mg	Mega-gramm (ton)	
mg	milligram	
MoFA	Ministry of Food and Agriculture	
NUTMON	Nutrient monitoring----	
OUT	Output	
PP	Polyphenol	
PP:N ratio	Polyphenol to nitrogen ratio	
PVC	Poly vinyl carbon	
SD	Standard deviation	
SEM	Standard error of mean	
SOC	Soil organic carbon	
SOM	Soil organic matter	
SRI	Soil Research Institute	
UNDP	United Nations Development Programme	
USDA	United States Department of Agriculture	
VWM	Volumetric Weighted Mean	

CHAPTER 1

INTRODUCTION

1.1 The Agricultural Sector in Ghana

Ghana lies on the south-central coast of West Africa and covers a land area of approximately 239 million square kilometers of which agricultural land forms about 57 percent. Ghana is mainly an agricultural country and agriculture is the major occupation of about 47 percent of the economically active age group (Seini, 2002). The country's economy is therefore dominated by the agricultural sector in terms of its share of Gross Domestic Product (GDP), employment and foreign exchange earnings. The sector is often categorized into 5 sub-sectors namely: crops other than cocoa (61% of agricultural GDP), cocoa (14%), livestock (7%), fisheries (5%) and forestry (11%) (MoFA, 1997). In 2006, the sector contributed about 35.8 per cent to GDP and employed 55 per cent of the working population (UNDP, 2007). Although food crops are the most important contributor to agricultural output, cocoa production continues to dominate as an individual export crop, with cocoa exports constituting 27.2 per cent of total exports and earning the country over a billion dollars in 2006 (World Bank, 2007; FAOSTAT, 2008). Smallholder farmers with an average holding of less than one hectare account for about 80% of the agricultural production. Therefore, agriculture is a major economic driving force.

In recent times, changing trends can be observed in agricultural land-use systems in terms of technologies employed, crop emphasis, scale of operations and commercial orientation. Some of these trends include:

- Changing of crop emphasis in the case of the re-emergence of cocoa as a cash and export crop due to very attractive producer prices and assistance from central government mainly in the form of free spraying of farms and the provision of improved planting materials and,

- Increasing emphasis on the adoption of agro-production practices that promote climate change mitigation and environmental sustainability through the conservation of land resources to achieve sustainable rural and economic development goals.

In Ghana agricultural productivity is generally low (MoFA, 2003) and soil fertility degradation has been identified as the major constraint to sustainable agricultural production. Recent studies have indicated the prevalence of nutrient mining leading to negative nutrient balances in both annual and perennial cropping systems (Roy *et al.,* 2003; Stoorvogel and Smaling 1990). Most farmers do not apply chemical fertilizers due to high costs and farmers' principal means of maintaining soil fertility in both annual and perennial cropping systems is through nutrient recycling (MoFA, 1998). To design management systems with enhanced nutrient recycling calls for a good understanding of soil dynamic processes under prevailing land-use systems. This study uses the shaded cocoa as a typical farming system that captures dynamic fertility processes that prevail in cropping systems established after forest conversion.

1.2 Traditional soil fertility regeneration strategies

In the traditional farming system, land preparation involves slash and burning. There is nutrient release during slash burning: ash from burned biomass is incorporated into the soil resulting in an increase in soil fertility. Carbon (C) and nitrogen (N) are largely volatilized but phosphorus (P) and cations are transferred from the biomass to ash and then into the soil (Nye and Greenland, 1960; Giardina *et al.*, 2000). After cultivating the field for 1-3 years when yields begin to decline, the fields are abandoned and left under undisturbed fallow for several years to restore fertility to levels that prevailed initially before forest clearing. The longer the rest period, the higher the fertility regenerated. However, population pressure and the need to increase production have led to a shortening of the fallow periods (Ahn, 1993) resulting in reduced fertility and lower crop yields where nutrients are not applied.

1.3 Soil fertility dynamics under shaded-cocoa systems

In the perennial cash/tree cropping systems, soil fertility is maintained through the closed nutrient recycling system practiced. Cocoa cultivation has generally been dependent on cultivation of partly cleared forestland utilizing the 'forest rent' of newly cleared areas that is soil fertility built up in the forest soils. For cocoa established from virgin forests on relatively fertile soils, fertilizers may not be required for many years and farms have been shown to remain productive and environmentally sustainable for up to between 30-50 years, at a level comparable to long-term fallows or primary forests (MoFA, 1998; Dugumah *et. al.*, 2001). However, in recent years the prospects of this practice have diminished drastically in most areas due to dwindled forest areas. In the Ashanti Region for instance, the most common land-use prior to cocoa establishment is secondary forest fallow as there are no new virgin forests left to clear.

The fertility of soils under cocoa plantations with complete canopy formation can be sustained for a long time due to the ability of cocoa to recycle nutrients back into the soil through litterfall and litter decomposition. Nutrient content of this biomass helps sustain productivity through efficient recycling with only small amounts of nutrients leaking from the system (Brinkmann 1983; Herrera *et al.,* 1978). However, the continuous crop removal through harvested beans would result in the loss of nutrients from the soils over a period of time (Ahenkorah *et al.,* 1987; Appiah *et al.,* 1997).

1.4 Research problems, rationale and justification for the study.

1.4.1 Low inherent soil fertility

There has been an increasing interest in the effects of conversion of forest ecosystem into agro-ecosystems on nutrient cycling from perspectives of sustainability and in evaluating long-term agricultural and forest land-uses. Most of the soils of Ghana are old and generally of low inherent fertility (MoFA, 1998). In the Moist Semi-deciduous Forest Zone, the principal soils for agricultural development are the forest Ochrosols (Acrisols, Lixisols). These are strongly weathered and acidic soils which have been leached over a long period of time (Benneh *et al.,* 1990) and are dominated by low activity clays characterized by low organic matter content (about 1.5% in the A horizon), low cation exchange capacity (CEC) and low base saturation. Nutrient reserves are therefore generally low with total N concentrations and available P, K, Ca and Mg found in low amounts (MoFA, 1998). Soil fertility degradation and low soil fertility continue to be major causes of decline in yields, and the most important constraints to food and cash crop production on smallholder farms (Appiah *et al.,* 1997). Replenishment from other sources is crucial for proper plant growth. The challenge is to fully understand the long-term system-level nutrient sustainability and their dynamics as well as develop management strategies that minimize nutrient loss, enhance nutrient recycling and sustain productivity.

1.4.2 Limited information on nutrient flows and fluxes in cocoa systems.

Nutrient fluxes in agricultural systems comprise additions through wet and dry deposition, throughfall and stemflow, recycling through litterfall and fine roots turnover and losses through harvest exports and leaching. Though these are important nutrient flow pathways and their fluxes have repeatedly been measured in forests of the humid tropics (Brinkmann, 1983; Hölscher *et al.*, 1998), they have rarely been studied in agricultural and agroforestry systems (Leite and Valle, 1990; Opakunle, 1991). Indeed very few studies have comprehensively examined nutrient cycling through litterfall, throughfall, stemflow and fine roots turnover and their fluxes to provide insights to their functioning in cocoa systems at plot or farm level especially in humid lowlands of Ghana, and the patterns are still insufficiently understood. While nutrient accumulation in both soil and vegetation was seldom studied, research is also lacking on long-term system-level nutrient sustainability specifically in shaded cocoa systems. Moreover, of the limited number of studies focusing on ecosystem (soil, litter and plant) nutrient stocks (Jaiyebo and Moore, 1964), few assessed changes in nutrient stocks with time, via either chronosequences (Scott, 1977; Toky and Ramakrishnan, 1983) or the monitoring of long-term plots (Bebwa and Lejoly, 1993; Szott and Palm, 1996). Understanding the dynamics of nutrient cycling, the magnitudes of the fluxes and how balances can be improved is crucial for developing management recommendations to improve productivity of these tree-based farming systems (Schroth *et al.*, 2001; Gichuru *et al.*, 2003).

1.4.3 The need for environmentally viable agro production to mitigate climate change

In recent decades, the increase in atmospheric concentration of carbon dioxide has necessitated the identification of strategies for mitigating the threat of the attendant global warming under the framework of the Clean Development Mechanism of the Kyoto protocol including the possibility of land-use changes that lead to higher net carbon stocks. The net environmental consequences of land-use change will depend on the prior land-use, the type of land conversion process and the characteristics of the new land-use (Gockowski *et al.,* 2003). Farms created at the expense of forests will still result in significant emissions. Conversion of either short fallow or savannah lands, which have much lower stocks of carbon to tree-based cropping systems like shaded-cocoa will likely result in a net sequestration of carbon and thereby contribute to climate change mitigation. Despite its significance, C sequestration is a poorly assessed potential value of tree-based agro-ecosystems and few studies have assessed the C sink capacity of cocoa agroforestry systems in Ghana. The potential of shaded-cocoa agroforests to sequester carbon and thereby contribute to climate mitigation though widely acknowledged has been hardly studied in cocoa systems in Ghana.

1.4.4 Ex*clusion of farmer perspectives in agricultural research and planning*

Studies have shown that though farmers' perceptions, knowledge and perspectives are essential elements for the development and adoption of new technologies, farmers are commonly left out of the formal agricultural research and development process as sources of information and innovation (Murage *et al.,* 2000; Desbiez *et al.,* 2004). Their knowledge of soils, soil fertility and soil management practices plays an important role in developing more sustainable farming systems (Talawar and Rhoades, 1998; Chambers, 1983). In Ghana, over 60% of all cocoa produced is by smallholder farmers as a low external input venture with farmers using traditional technology with very little purchased inputs (Asenso-Okyere, 2001). To sustain nutrients in these systems calls for the introduction of efficient resource management practices. Designing diverse agroforestry systems that are adaptable and flexible to ecological as well as social conditions requires a full appreciation of farmer perspectives (Holling, 1986). While various current policies and research on agricultural sustainability depart from a top-down approach, local social conditions, particularly local knowledge, have entered into the development paradigm (Ingold, 2000). Several authors, amongst them Pretty and Chambers (1994) and Röling (1994) have advocated for interactive and collaborative approaches which consider farmers as equal partners in research and development, with a new role for researchers and extension agents as facilitators and catalysts. Integration of local and formal scientific knowledge is recurrently identified as an important component in sustainable development (Oudwater and Martin, 2003) and provides an important foundation for resource management (Becker and Ghimire, 2003; Moller *et al.*, 2004). Consequently, studies on local soil knowledge may provide a basis for integrative holistic methodologies (McIntosh *et al.*, 2000) for managing fertility especially in these low input farms and may facilitate a scaling up results from the farm to the landscape level.

1.5 Goal, specific objectives and research questions

1.5.1 Goal

Working on smallholder production systems and using an ethno-ecological approach, the overall goal of the study was to provide quantitative information on the effects of forest conversion to shaded-cocoa system on vegetation biomass and soil physico-chemical properties and to use this information to promote system sustainability. Insight from this study may contribute to developing principles and management strategies to enhance nutrient cycling in shaded-cocoa systems.

1.5. 2   Specific objectives

The specific objectives of the study were to:

(i) Investigate the effect of forest conversion to shaded-cocoa on above-ground plant biomass and above and below-ground carbon and nutrient stocks.

(ii) Estimate nutrient recycling through litterfall production and fine roots turnover in forest and shaded-cocoa land-use systems.

(iii) Estimate the magnitudes of nutrient fluxes in incident rainfall, throughfall and stemflow, and outputs through harvest exports and leaching in forest and shaded-cocoa land-use systems.

(iv) Assess farmers' local knowledge of soils and associated fertility processes in shaded-cocoa land-use systems.

1.5.3   Research questions

The questions that guided the study were:

1. Do soil organic carbon and nutrient stocks increase or decrease with time following forest conversion to shaded-cocoa land-use, and which pools are most affected?

2. Can shaded-cocoa systems be used as tools in the sequestration of carbon?

3. How much carbon is stored in the above-ground components (trees, leaf litter, pod husks, etc) of different aged shaded-cocoa systems?

4. Are nutrient outputs through crop harvests and leaching adequately compensated for by inputs through incident rainfall, throughfall and stemflow, and recycling through litterfall and fine roots turnover?

5. What are farmers' perceptions and understanding about their soils and fertility processes?

6. How do these perceptions and understanding influence their fertility management strategies?

1.5.4 Hypotheses

The study hypothesized that:

a) Carbon and nutrient pools as well as microbial biomass would decline significantly along the chronosequence following forest conversion to shaded-cocoa land-use.

b) Litter pools (stand litterstocks) and litterfall production in recently converted cocoa plantations will be low compared to forests or mature cocoa systems, and decomposition rates will correlate to litter quality in cocoa ecosystems.

c) Forest litter decomposition rates will be more rapid due to specific litter dominance of higher quality.

d) Nutrient outputs through crop harvests and leaching would be adequately compensated for by inputs from incident rainfall, throughfall and stemflow, and recycling through litterfall and fine roots turnover.

e) Collaboration among local farmers, scientists, policy makers and extension staff can result in a more complete understanding of local environments and the design of appropriate management strategies and more successful implementation of alternative management strategies.

1.6 Justification for choice of study district

In order to answer the research questions as well as validate the hypothesis or otherwise invalidate them, one administrative district was chosen. The Atwima Nwabiagya District was selected because of the convergence of several theoretical, conceptual and contextual factors.

First, districts are the basic development units that have planning and implementation powers on all issues related to the development of the country. This enables data collection and analysis to be focused and done within a meaningful framework, and ensures that recommendations can be implemented in a sustainable way (Inkoom, 1999). Secondly, the Atwima Nwabiagya District is one of the districts with a high proportion of old cocoa farms in Ghana faced with serious yield reduction and fertility degradation problems. The implementation of the Ashanti Cocoa Project in the area between 1976 and 1979 resulted in the rehabilitation of cocoa farms and the training of farmers in improved methods of cocoa production (Amoah, 1998). The district therefore provides opportunities for understanding the nature of cocoa production from various perspectives; historical factors and contact with research among others. Thirdly, resource issues of this nature demand micro-level study to capture all the necessary factors that account for the phenomenon under investigation (Inkoom, 1999). These allow for an in-depth and holistic approach to finding appropriate strategies for enhanced nutrient cycling and fertility management with the possibility of scaling-up to other areas.

CHAPTER 2

GENERAL METHODOLOGY

2.1 Description of study area

The study described in this thesis was conducted in small-holder farms in the Atwima Nwabiagya district of the Ashanti Region of Ghana (Figure 2.1). Atwima Nwabiagya District is one of the 21 political districts in the Ashanti Region. It is situated in the western part of the region and lies approximately on latitude 6^0 75' N and between longitudes 1^0 40' and 2^0 23' W. It covers an area of about 26,462 hectares (264.62 km^2), and has Nkawie as the district capital (Atwima Nwabiagya District Assembly, 2006). The population of the district stood at 139,174 based on the 2000 housing and population census with an annual growth rate of 3%. About 56,528 people (or 40.6% of the population) live in the rural settlements whilst 82,646 people (representing 59.4% of the population) live in the urban/peri-urban areas of the district. Major settlements in the district include Abuakwa, Nkawie-Toase, Asuofua and Barekese (Atwima Nwabiagya District Assembly, 2006).

2.2 Climate and vegetation

The district falls within the wet semi-equatorial rainforest climate zone. Mean annual rainfall is from 1,300-1,850 mm per annum with bi-modal distribution, with May - June and September - November as peaks (Figure 2.2). The dry season lasts from December to March, a period during which the desiccating harmattan winds blow over the area. Temperatures are uniformly high throughout the year. Average monthly temperatures range between 27^{o}C and 31^{o}C. The relative humidity is generally high throughout the year (Atwima Nwabiagya District Assembly, 2006).

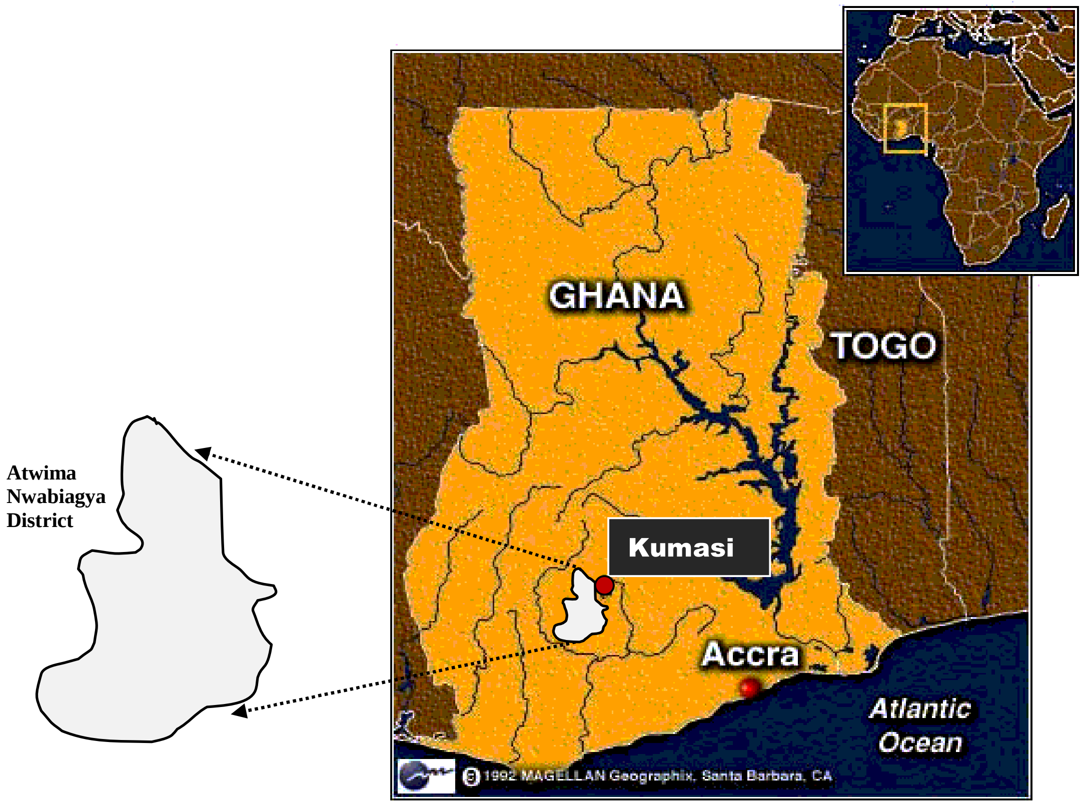

Figure 2.1 Location of study area in Ghana, West Africa

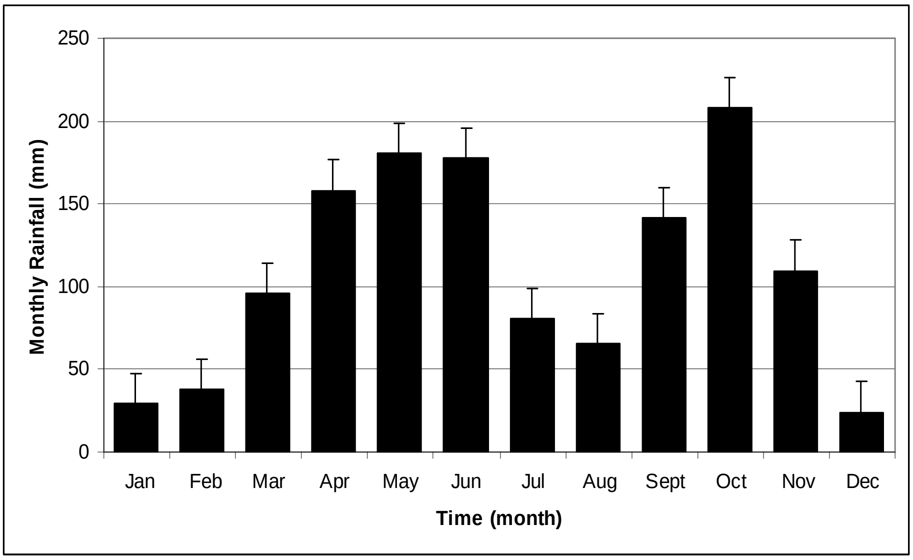

Figure 2.2 Mean monthly rainfall (mm) between 1998 and 2007. Data from Nkawie COCOBOD/MoFA Meteorological Data Station

The predominant vegetation in the district is the Moist Semi-deciduous Forest Type and consists of the *Celtis triplochiton* Floristic Association (Taylor 1960), where some of the trees in the upper and middle layers shed their leaves usually in the dry season. The type is characterized by several species including *Triplochiton scleroxylon*, *Celtis milbraedii*, *Baphia nitida* and *Groffornia simplicifolia*. Two species of *Sterculia*: *S. rhinipelata* and *S. Oblongata* might be considered as somewhat characteristic of the forest type. Heights often exceed 50 m and sometime 60 m. The upper canopy consists of a mixture of deciduous and evergreen species in varying proportions, but over the whole type, the two occur in about equal proportions – hence the term 'Semi-deciduous'. The understorey trees are sometimes gregarious (Hall and Swain, 1981). The district has one forest reserve, the Jimira Reserve covering 6,285 hectares of forests. (Atwima Nwabiagya District Assembly, 2006).

2.3 Soil Types

The soils of the study area are from weathered phyllites of the Lower Birimian geology (Adu, 1992). They consist mainly of Nzema soil series classified as Ferric Lixisols, and Kobeda series classified as Leptosols/Regosols (FAO/UNESCO, 1990). Ferric Lixisols which are most extensive in the landscape, are moderately good agricultural soils. They are deep and moderately well-drained with a subsoil texture ranging from silty-clay loam to silty-clay, which gives it a high moisture retention capacity. Rainfall within the moist semi-deciduous firest zone leads to leaching of nutrients than in types of lower rainfall. Base saturation is generally high (about 60 to 80%), providing a pH of about 5 - 6. Total exchangeable bases (TEB) are generally below 10 meq 100^{-1}g soil. The type as a whole has only a moderate elevation of 150 – 600 m, with higher elevations within the area carrying a forest of distinct type – Upland Evergreen (Hall and Swaine, 1981). The fertility status of soils on the site is thus generally low to medium with near-neutral to acid conditions. Most of the nutrients are concentrated in the topsoil. The soils of the Moist Semi-deciduous Forest Type are ideal for most of the forest zone crops, including cocoa. Tree crops e.g. cocoa, coffee, citrus, oil palm, avocado and mango, as well as food crops like cocoyam, yam, plantains, cassava and maize are best suited for these soils (MoFA, 1998).

2.4 Approach to the Study

Two approaches are often used in studying ecosystem dynamics. These are 'temporal monitoring' (where the dynamics of ecosystem components are examined over time at a single site) and the spatial analogue/chronosequence (which involves spatial sampling on sites that are subject to different land-uses but operating within a similar environment and on similar soil types) methods (Bhojvaid and Timmer, 1998; Lemenih *et al.,* 2005)**.** In this thesis, the chronosequence approach was adopted. An adjacent secondary forest (hereafter referred to as forest land-use) reference, and fields of cocoa farms aged 3, 15 and 30 years after forest conversion were selected. To assess nutrient stocks and litter dynamic processes along the chronosequence, soil samples (0-10, 10-20 and 20-60 cm soil depths) and plant tissue samples (leaves, stems, twigs and branches and fine roots) were collected from 35 m x 40 m plots established in forest and cocoa sites for chemical analysis using standard procedures. The trend of changes in plant biomass and soil properties are described and values in cocoa systems compared to forest values as standard reference. Details of the analytical methods used are described in the materials and methods sections of chapters 3, 4 and 5 of the thesis.

2.5 Outline of the thesis

This thesis is presented in eight chapters. **Chapter 1** introduces the study and presents the reader with general background information on the agricultural and cocoa sector, fertility management as a whole in Ghana and the justification for the study, while **Chapter 2** describes the general methodology adopted for the study. In **Chapter 3,** the literature is reviewed comprehensively. It covers the theories behind the concepts applied in the study, methodologies employed and major trends in organic carbon/nutrient dynamics and farmer perceptions to locate my research contributions within the ethno-ecological and cocoa agroforestry literature. **Chapter 4** reports on the effects of forest conversion on changes in above and below-ground nutrient stocks, while **Chapter 5** looks at the dynamics of litterfall and nutrient return through litter decomposition and fine roots turnover to the forest floor. **Chapter 6** gives a quantitative assessment of nutrient flows through the various input and output pathways. In **Chapter 7**, farmers' local knowledge of their soils and fertility processes as well as their fertility management strategies are explored. **Chapter 8** summarizes and synthesizes results of the entire study. It puts together the major findings, draws conclusions based on the findings and makes recommendations for enhancing nutrient cycling and improving balances in shaded-cocoa farming systems in the semi-deciduous forest zone of Ghana. Finally, recommendations and perspectives for future research are made.

CHAPTER 3

LITERATURE REVIEW

3.1 Nutrient cycling in forests and tree-based agro-ecosystems

The continual movement of nutrients between compartments within an ecosystem is referred to as nutrient cycling (Nair *et al.*, 1999; Kimmins, 1997). Since the seminal work Nye and Greenland (1960) on nutrient flows and pools in shifting cultivation systems, ecological research in nutrient cycling has made considerable progress. Young (1989) and Attiwill and Leeper (1987) provide details of the major pathways of nutrient cycling which consists of stores and flows as well as gains and losses within the system. Pools of nutrients are located both above-ground, in tree and crop biomass, and below-ground in plant residues, soil fauna, soil organic matter (both labile and stable fractions) and available nutrients in soil solution. Flows within the system (uptake and return or recycling) include the decomposition of plant residues and soil organic matter, and plant uptake. Gains and losses are external to the system. Gains into the system consist mainly of nitrogen fixation and fertilizer additions, rainfall and dry deposition while losses are attributed to leaching, erosion and product removal (Young, 1997). Nutrients in litterfall, fine roots turnover and prunings (unless added from off-site) represent recycled and not additions to the system.

3.2 Nutrient flux pathways

3.2.1 Litterfall and nutrient inputs

In tropical forest ecosystems where soils are highly weathered and nutrient-poor, litter production is a major process by which carbon and nutrients are transferred from vegetation to soil. Litter is a central nutrient resource and litterfall is an important pathway for the return and recycling of dead organic matter and nutrients from plants to soils (Lian and Zhang, 1998; Martius *et al.*, 2004).

The amount of nutrients annually transferred depends on the amount of litterfall and the nutrient concentration in the litterfall. Under cocoa agroforestry, Isaac *et al.* (2005) recorded litterfall rates of 2.9, 6.9 and 10.4 Mg ha^{-1} yr^{-1} respectively for 2, 15, and 25 year-old shaded-cocoa agroforests in a moist semi-deciduous forest in the Western Region of Ghana. Owusu-Sekyere *et al.* (2006) found that mean annual litter produced by primary and secondary semi-deciduous forests was both 7.9 Mg ha^{-1} while that for cocoa plantations was 6.9 Mg ha^{-1}. Opakunle (1989) reported an annual litterfall rate of 11.7 Mg ha^{-1} in a 22-year-old cocoa plantation in a lowland rainforest area in Ibadan, Nigeria. Hartemink (2005) reviewed the results of research on nutrient cycling in cocoa ecosystems and concluded that average annual litterfall in shaded-cocoa systems across all ages was 10 Mg $ha^{-1}yr^{-1}$.

3.2.2. Litter decomposition

Decomposition is a complex process regulated by the interactions between organisms (fauna and micro-organisms), physical environmental factors (particularly temperature and moisture), and resource quality usually defined by lignin, nitrogen and condensed and soluble polyphenol concentrations (Swift *et al.*, 1979).

Traditionally, mesh bags (litterbags) have been a valuable tool for measuring litter decomposition rates. Enclosing litter in mesh bags makes it possible to recover the experimental materials and defines the conditions under which the organism operates. However, the use of litterbags does have its problems. The litterbags and compaction of litter can create microclimate conditions different from conditions in unconfined litter under natural environment. The microclimate within litterbags tends to be moister than that of unbagged litter, and thus more favorable for microbial activity (Vossbrinck *et al.*, 1979). Litterbags with fine mesh sizes (1-2 mm) will exclude most macro-fauna and thus underestimate decomposition rates. Larger mesh sizes allow larger fragments to escape the bags thus overestimating decomposition. In most cases, litter bags probably underestimate actual breakdown rates. Nevertheless, their usefulness for comparative studies and for nutrient measurements makes them important tools (Coleman *et al.*, 2004).

Alternatives to litterbags and modifications to the standard approach have been reported. Quantitative decomposition rates can also be evaluated with the litter turnover rate method for unconfined litter (Nye, 1961; Olson, 1963). The rate of annual stand litter turnover (K_L) can be estimated as K_L=LF/LS where LF is the annual litterfall and LS the stand litter crop. The method's limitation is that it does not provide detailed information on the pattern of weight loss through time or the loss of nutrients in the litter. It also assumes a steady state of stand litter biomass, which probably changes over time. However when stand litter and litterfall measurements for the entire year are available, turnover/decomposition coefficient may be estimated relaxing the steady state assumption (Martius *et al.,* 2004).

Isaac *et al.* (2005) using the mesh-bag method measured leaf litter decomposition under cocoa in the Sefwi Wiawso District of Ghana and found that decomposition rates ranged from 0.484–0.784 month^{-1}. It would be interesting to know what decomposition rates would be using the litter turnover method for unconfined litter.

3.2.3 Nutrient inputs through dry deposition, incident rainfall, throughfall and stemflow

Dry Deposition

Dry deposition may be broadly defined as the transport of particulate and gaseous contaminants from the atmosphere onto surfaces in the absence of precipitation (Davidson and Wu, 1989). While it is an intermediate transport process responsible for the removal of pollutants from the atmosphere, it is a major pathway for the mobilization and transfer of elements in ecosystems. Traditionally, the atmosphere has been considered the main source of elements with gaseous phases such as N, and rock derived elements such as P and Ca for terrestrial and aquatic ecosystems (Morales-Bacquero *et al.*, 2006), as well as shaded-cocoa systems.

Dry deposition from the atmosphere may be an important additional nutrient source for plants. This is particularly true, when the soils are nutrient-poor as it is the case in the Semi-deciduous forest belt in Ghana. In this region, the deposition of nutrients from the atmosphere is enhanced by the frequent biomass burning that releases a large part of the nutrients stored in aboveground biomass to the atmosphere (Pivello and Coutinho, 1992; Kauffman *et al.*, 1994).

Currently, it is well established that the atmosphere can mobilize amazing quantities of dust from the arid areas of the world (Schlesinger, 1997), and the role of the atmosphere as a vehicle for rock-derived elements has been recently re-vindicated (Chadwik *et al.*, 1999). These authors found that the tropical ecosystems of Hawaii depend critically on phosphorus supplied by the atmosphere coming from the Central Asian Desert. At a global scale, the Sahara Desert is the largest arid area in the world and, consequently, it is the origin of the largest loads of dust to the atmosphere (D'Almeida, 1986). This dust is transported towards the Atlantic by the predominant westerly winds and towards the Mediterranean basin influenced by the presence of cyclones (Moulin *et al*., 1997). Saharan dust contains high quantities of particulate matter, soluble minerals and organic carbon (Talbot *et al*., 1986).

Wet deposition/incident rainfall inputs

In tropical forest ecosystems, important interactions occur between hydrological and nutrient cycles. Estimation of fluxes of elements in incident rainfall, throughfall and stemflow is a routine part of nutrient budget studies in forest and tree-based ecosystems. In Bahia Brazil, Liete and Valle (1990) found nutrient inputs in rainwater to the soil were greatest for N and Ca, with an annual means of 43 and 21 kg ha^{-1} respectively. Rainwater contribution of Mg and K were small both approximately 9 kg $ha^{-1}year^{-1}$ and those of P about 1 kg $ha^{-1}year^{-1}$. In cocoa systems in Ecuador and Ivory Coast respectively, rainfall nutrient fluxes were 8.1 and 7.2 kg $ha^{-1}yr^{-1}$ for Ca, and 6.1 and 2.1 respectively for P (Gerold, 2005). In the Central African rainforest, Chuyong *et al.*, (2004) recorded mean annual inputs of N, P, K, Mg and Ca in incident rainfall to be 1.50, 1.07, 7.77, 5.25 and 9.27 kg ha^{-1}, and total rain-based inputs to the forest floor were 5.0, 3.2, 123.4, 14.4 and 37.7 kg $ha^{-1}yr^{-1}$ respectively.

Throughfall and stemflow

Independent of the amounts of nutrients in the incident rainfall, significant amounts are added and transferred from above-ground plant parts to the forest floor as the rainwater passes through the canopy. The two routes are by throughfall (rain-wash) and by stemflow. Throughfall is that part of the incident rainfall, which passes through the forest canopy, either directly in gaps or in interacting with the vegetation (Hartemink, 2005; Bruijnzeel, 1989; Lloyd and Marques, 1988).

According to Hartemink (2005), large amounts of nutrients are transferred by throughfall in cocoa ecosystems. Though throughfall may be considered a transfer of nutrients (when certain nutrients notably the cations are leached from leaves), it can also become an addition if the leaves were covered with dust that has been transported from elsewhere (Asner *et al.*, 2001; Parker, 1983). The amount of nutrients transferred by throughfall is generally less than 8 kg ha^{-1} for N and P and for K varies from 38 to more than 100 kg ha^{-1}year^{-1}, which demonstrates the importance of throughfall for K nutrition of the cocoa. In a Brazilian cocoa ecosystem, Leite and Valle (1990) found that throughfall represented an important source of nutrients with recycling of K, Ca, Mg and P to the soil being in the order of 141, 28.4, 21, and 13 kg ha^{-1}year^{-1} respectively in unshaded plots, and 47, 21, 12.2 and 8 kg ha^{-1}year^{-1} respectively for the same nutrients in shaded cocoa plots.

Stemflow is the part of precipitation channeled by leaves and branches and eventually funneled down the trunks of the trees (Herwitz, 1986; Jordan, 1978). Stemflow is of hydro-ecological and biogeochemical importance in forested and agricultural ecosystems because it is a spatially localized point input of water and nutrients at the plant stem (Chang and Matzner, 2000; Levia and Herwitz, 2000). According to Johnson and Lehmann (2006), stemflow in general has higher nutrient concentrations than throughfall by up to an order of magnitude (Parker, 1983), which is in turn more greatly enriched than the incident precipitation. A longer canopy residence time for stemflow water than for throughfall, combined with greater leachability of bark tissue (Levia and Herwitz, 2000), contribute to a chemical concentration gradient of water fluxes in the order: stemflow > throughfall > precipitation (Johnson and Lehmann, 2006).

In a 22-year-old cocoa agro-ecosystem in Southeastern Nigeria, Opakunle (1989) reported that the contribution of stemflow to the total nutrients in rainfall (throughfall plus stemflow) on the plantation ranged from 1.9% for N to 11.4% for K. The quantities of nutrients returned to the soil annually through stemflow were 0.38, 0.12, 8.50, 1.64 and 0.36 kg $ha^{-1}year^{-1}$ for N, P, K, Ca and Mg respectively. Levia and Frost (2003) assert that there is no standard protocol as to the number and type of gauges necessary to adequately sample stemflow volume or chemistry. The lack of a standard protocol is, in part, likely the result of the diverse vegetation cover from which stemflow is collected and the differing objectives among stemflow studies. Stemflow drainage, however, is typically collected from forest trees using flexible tubing that is cut longitudinally and wrapped in an upward spiral around a tree trunk (Levia and Herwitz, 2000; Nakanishi *et al.*, 2001). The tubing is nailed or stapled to the tree trunk, and silicone sealant is applied to seal the collar to the trunk and to plug nail heads (Herwitz and Levia, 1997). The uncut section of each stemflow collar is connected to a collection bin. Levia and Frost (2003) have observed that, year-long studies are necessary to better understand the dynamics of stemflow generation for total nutrient inputs through stemflow to be expressed on a kg $ha^{-1}yr^{-1}$ basis. According to them total stemflow nutrient inputs based on extrapolations from a few months could be erroneous. The difference between the sum of these two fluxes and the incident rainfall gives the canopy interception (Carlyle-Moses and Price, 1999; Muoghalu and Oakhumen, 2000).

3.2.4 *Nutrient inputs through fine roots turnover*

Fine roots are constantly in flux, with death and replacement occurring simultaneously (Persson, 1983). Though root turnover plays a significant role in carbon budget and nutrient cycling of forest ecosystems (Eissenstat *et al.,* 2000), root production and nutrient cycling are difficult to study in forest and tree-based agro-ecosystems (Vitousek and Sanford, 1986). According to Fogel (1983), root turnover may have 4 to 5 times higher C returns than above-ground litter, this being the source of 30-60% of the organic soil pool (Heal *et al.,* 1997).

Apart from the pioneering works of Kummerow *et al.,* (1981, 1982), Alpizar *et al.*, (1986) and later Munoz and Beer (2001) very little information exists on fine root dynamics in cocoa systems. The earlier studies have mostly been limited to static inventory data; that is biomass at a given moment in time (Alpizar *et al.,* 1986; Beer *et al.*, 1990). On 16-year-old plantations, Munoz and Beer (2001) showed that fine root turnover was close to 1.0 in cocoa shaded with *Erythrina poeppigiana* or *Cordia alliodora* in Costa Rica and nutrient inputs from fine root turnover were estimated at 23-24 kg N, 2 kg P, and 14-16 kg K $ha^{-1}year^{-1}$. These amounts equaled about 6-13% of the total nutrient input in the cocoa shaded with *C. alliodora* and 3-6% in the cocoa shaded with *E. poeppigiana* (Munoz and Beer, 2001). Kummerow *et al.* (1982) also found that fine roots biomass in an 11-year-old cocoa plantation in Bahia Brazil was 400 kg ha^{-1}. Given the generally high turnover of fine roots in the tropics, their role in carbon and nutrient cycling under cocoa systems could be very important.

3.2.5 Methods for studying root growth and distribution

Although the importance of roots in net primary production and forest biogeochemical cycling is acknowledged, a lack of reliable information on root production and turnover has limited nutrient cycling studies (Aber and Melillo, 1991). There are several methods for sampling and studying roots, many of which have been reviewed by Böhm (1979). They are generally classified into two principal approaches: destructive or non-destructive. The method adopted depends on the nature and complexity of the information required.

By far the most popular destructive method for sampling and studying roots is extraction using cylindrical corers or augurs (Munoz and Beer, 2001) of specified core diameter (usually between 50-80 mm) to predetermined depths (e.g. 0-5, 5-10 cm soil depth), retrieving the roots by the wet sieving method as described by Böhm (1979), and separating the retrieved roots into required diameter classes for dry weight determination. A variation in the augur or core sampling method is the collection of soil monoliths (Visalakashi, 1994), from a specified area (e.g. 50x50cm area) to required depths and extracting the roots as described. Fine root productivity has been estimated using field incubated in-growth core method (Cuevas and Medina, 1988; Munoz and Beer, 2001) where in-growth bags made from plastic sacking with a minimum of 4 mm mesh are placed in augur-prepared holes and filled (in-situ) with root-free soil roughly to the bulk density of the surrounding soil. Roots are allowed to re-grow into the bags, which are harvested at various time intervals for total fine root biomass determination. The mini-rhizotron technique for the in situ observation and quantification of root growth involves installing a large glass plate in an observation gallery and then measuring the growth of roots against the glass over time (Anderson and Ingram, 1998). More sophisticated versions use a fiber optic system with a camera and flash light or miniaturized video system (Schroth, 2003; Guo *et. al.*, 2005).

Despite these advances, several of the methodological constraints require due consideration during root growth studies as these make comparisons at times difficult. Some important considerations include:

i) Different sampling and processing methods (including variations in coring depths, root isolation and washing techniques) to measure the same root parameter yielding significantly different results (Fogel, 1983; Hertel and Leuschner, 2002), and
ii) The lack of a standard definition for fine roots which has led to different studies classifying roots of different diameter classes as fine roots.

Fine roots biomass have been based on diameter classes < 1 mm, e.g. Burton *et al.* (2000) and Castellanos *et al.* (2001); < 2 mm, e.g. Vogt *et al.* (1986); < 3 mm, e.g. Melillo (1982); < 5 mm, e.g. Gower (1987); < 6 mm Klinge (1973) and <10 mm e.g. Deans *et al.* (1996). The fact that different diameter classes are considered as fine roots affects the estimation of fine roots biomass significantly and comparisons between studies are difficult (Millikin and Bledsoe, 1999).

3.3 Nutrient depletion and balances in agro-ecosystems

3.3.1 Nutrient budgets and balances

The distribution and cycling of elements in tropical forests and agro-ecosystems takes place within the context of inputs by means of precipitation, mineral weathering and gas absorption (including biological nitrogen fixation), and of outputs by means of solution losses (leaching), volatilization and the harvest and export of plant parts. In the short run, nutrient availability is regulated by processes releasing nutrients into available forms and those removing them; in the longer run, the nutrient status of the forest or agro-ecosystem is dependent on the balance between inputs and outputs of nutrients (Stoorvogel and Smaling, 1990; Vitousek and Sanford, 1986). A nutrient budget is a procedure that accounts for inputs and outputs of nutrients in a defined system, and the nutrient balance refers to the difference between the sum of inputs and outputs (Janssen, 1999). A nutrient balance is thus a land quality indicator that describes the rate at which soil fertility changes under actual management. The nutrient balance is calculated through the assessment of the major inputs and outputs of nutrients for the land-use systems. It can be calculated for different scales such as country, region, district, farm or plot and soil solution levels. By simply subtracting the nutrient inputs from the nutrient outputs one obtains a balance.

3.3.2 Nutrient Monitoring (NUTMON): Quantifying nutrient input and output pathways.

Since the pioneering works of Stoorvogel and Smaling (1990), nutrient flows and balances are increasingly being used as powerful tools for estimating nutrient depletion/accumulation. Several studies (e.g. van der Pol,1992; Krogh, 1997; van den Bosch *et al.,* 1998; Amare *et al.,* 2005; Kanmegne *et al.,* 2006) have used the nutrient monitoring (NUTMON) approach to assess nutrient input and output fluxes and their balances and to quantify subsoil nutrient depletion.

The NUTMON methodology involves the identification and quantification of relevant key nutrient input and output determinants. At the farm level which distinguishes between three types of units: crop activities, livestock activities and the homestead, the model identifies six inflows (IN1: mineral fertilizer, IN2: manure/organic fertilizer, IN3: atmospheric deposition (wet/dry deposition), IN4: biological nitrogen fixation, IN5: sedimentation and IN6: subsoil exploitation), and six outflows (OUT1: harvested products, OUT2: removal of crop residues, OUT3: leaching, OUT4: gaseous losses, OUT5: erosion and OUT 6: human faeces). Thus the nutrient depletion of an agro-ecosystem of spatial scale (S) at any given time (t) may be characterized by a balance, made up of a number of nutrient inputs that may exceed (Σ in - Σ out > 0), equal (Σ in - Σ out = 0), or be lower (Σ in - Σ out < 0) than the sum of outputs (Gichuru *et al.,* 2003). A negative balance implies that soil stocks of a certain element are decreasing. If the nutrient balance is negative, this does not necessarily constitute a constraint on production, although such a situation will not be sustainable in the long run. Nutrient balances should, therefore be assessed in relation to the stocks of available, or active soil nutrients (Defoer *et al.,* 2000).

Though questions have been raised as to whether nutrient budgets and balances give us the required information to understand the status and dynamics of soil fertility across farming systems, and whether such analysis may provide reliable directions and support to policy formulation on soil fertility management (Scoones and Toulmin, 1998), they are still widely used as they provide quick findings, based on a short time-frame exercise (Stoorvogel and Smaling, 1990).

3.3.3 Nutrient balances in cocoa systems

Hartemink (2005) reviewed research results on nutrient cycling in cocoa systems and calculated nutrient balances from experimental data from Malaysia, Venezuela, Costa Rica, Brazil and Cameroon. In the absence of inorganic fertilizers, he found the nutrient balance to be negative for all the essential nutrients. For instance the input and output balances of N, P and K respectively were -25, -4 and -15 kg $ha^{-1}year^{-1}$ for Malaysia, and -15.5, -2.8 and -44.0 kg $ha^{-1}year^{-1}$ for Cameroon. With fertilizer application the balances in Venezuela and Costa Rica were -14.0, 24.7 and 10.6 kg $ha^{-1}year^{-1}$ and 100.7, 14.4 and 7.1 kg $ha^{-1}year^{-1}$ respectively. It was found that in all cocoa systems, N removed by cocoa beans (yield) is lower than in the litterfall. For Cameroon, N in the litter is about twice the amount removed by the yield, whereas for Malaysia, this ratio is nearly 5. He concluded that if about 6000 kg N ha^{-1} is present in the topsoil, N removed by the yield is, on average, less than 0.5%. Addition of N by wet and dry deposition was found to be fairly high and ranged from one sixth to almost half of the yearly N removal (Hartemink, 2005).

3.4 Soil organic matter (SOM) dynamics

3.4.1 What is soil organic matter?

Baldock and Skjemstad (1999) defined SOM as “all organic materials found in soils irrespective of origin or state of decomposition”. Zech *et al.* (1997) defined SOM in a broad sense to include above and below ground macro-morphologically identifiable plant residues (primary resources), residues of soil animals and microorganisms (secondary resources), dissolved organic matter, root exudates and morphologically unstructured, macromolecular humic compounds. They stress that these pools are not stable but characterized by transformations because SOM is in a dynamic state.

Soil organic matter plays a number of essential roles in cropping systems and its dynamics merit special interest (Sanchez *et al.*, 1989). In low input tropical agriculture, soil productivity depends on the quantity, quality and dynamics of SOM (Sanchez *et al.*, 1989; Woomer *et al*., 1994). SOM contributes significantly to soil nutrient resilience and renders the physical environment of soil suitable for plant growth (Baldock and Skjemstad, 2000), increases water holding capacity, erosion resistance, cation exchange capacity, reduces leaching of plant nutrients (Young, 1997) and is a large reserve of geochemical carbon. SOM is a reservoir of various essential elements serving as an important source of inorganic nutrients for plant production in natural and managed ecosystems (Solomon *et al.*, 2002). SOM is one of the most important indicators of soil quality and its management is envisaged to maintain soil fertility and promote sustainable agriculture (Martin *et al.*, 1990; Katyal *et al.*, 2001).

3.4.2 Soil organic carbon (SOC) and nutrient changes under cocoa land-use

Several studies focusing on the effects of cocoa on soil organic carbon (SOC) have demonstrated that maintenance of SOC is the key to sustainable crop production (e.g. Guo and Gifford, 2002; Woomer *et. al.,* 1994). Beer *et al.* (1990) measured SOC in cocoa ecosystems shaded with *Erythrina poeppigiana* and *Cordia alliodora* on a Typic Humitropept in Turrialba, Costa Rica. They did not find any significant differences over 9 years in the 0-15 and 15-30 cm soil depths. On the contrary, after an initial decline in soil carbon stocks, percent organic matter in the 0-15 cm depth tended to increase with age in shaded-cocoa systems in Ghana (Isaac *et al.*, 2005).

Conflicting results exist in the case of basal nutrients and phosphorus. A number of trends can however be noted. Ahenkorah *et al.* (1987) reported increased soil phosphorus (P) status under shaded-cocoa on a Ghanaian Alfisol. Similarly, Ekanade (1987) found higher available P (9.4 mg kg^{-1}) under shaded-cocoa systems in comparison to mono-culture cocoa (5.2 mg kg^{-1}) on Alfisols in Nigeria. In general, low accumulation of P in biomass has been noted in cocoa ecosystems and is normally dependent on the availability of soil P stocks (Hartemink, 2005). While total N stocks varied greatly in the topsoil (4.8 to 18.8 Mg N ha^{-1}), high levels of N transfer through cycling and litter inputs are documented (Alpizar *et al.*, 1986). In mature cocoa ecosystems, K is a major nutrient and stocks of exchangeable K in the topsoil vary from 100 to 550 kg ha^{-1} (Hartemink, 2005). Again, Ekanade (1987) noted a significant decline in soil exchangeable K status from cocoa under shade to cocoa in monoculture (89 and 61 mg kg^{-1} respectively). Generally, cocoa ecosystem demonstrates high levels of nutrient transfer, providing evidence for nutrient use efficiency and nutrient cycling (Hartemink, 2005).

These studies provide insights into the differences and changes that may be expected when the natural forests are converted to perennial cropping systems like shade-cocoa. Thus although there is a large body of literature on ecological components of shaded-cocoa ecosystems, discrepancies in the literature are present, particularly indicating a need for more in-depth research into the mechanisms for improving soil fertility, increasing ecosystem services, and farm management strategies for enhanced nutrient cycling in these systems.

3.4.3 Carbon stocks in forest and agricultural ecosystems

Various carbon pools can be identified within forest and tree-based systems. These include the soil pool, the live wood pool in trees, the underground wood in roots, and the dead litter pool on the forest floor (Polzot, 2004). The quantity of carbon contained in each pool is referred to as the carbon-stock, and the total carbon-stock in an ecosystem is simply the sum of the carbon-stocks of the different pools. Carbon-stock is usually expressed in tonnes (t) or mega-grams (Mg) of carbon per hectare (C ha^{-1}). Tropical forests, accounting for about half of the world's forest area, store 46% of the world's living terrestrial carbon pool. No other biome stores as much carbon in the biota. However, tropical forests store only 11% of the world's soil carbon pool, whereas boreal forests, tundra, grasslands and peatlands store substantially larger amounts (Brown *et al*., 1982).

Forests store between 20 and 100 times more carbon per hectare than agricultural lands (Cairns and Meganck, 1994). Carbon is sequestered and stored in aboveground biomass, roots, litter and soil. Most of this carbon is lost when forests are removed and replaced by other land-uses. Brown *et al.,* (1984) report that stocks of carbon tropical moist forests average between 155 and 187 MgC ha^{-1} (aboveground), whereas tropical dry forests average between 27 and 63 Mg C ha^{-1}, depending on location. Table 2.1 presents the carbon storage potential of various ecosystems and illustrates the significant impact that tropical forests have on the global carbon cycle.

Table 2.1 Mean carbon storage of various ecosystems

Ecosystem	Carbon Storage (Mg C ha^{-1})
Tropical forest	220
Temperate forest	150
Boreal forest	90
Grassland/savanna	15
Agriculture	5

(Source: Cairns *et al*., 1994)

The amount of biomass accumulated through forest tree-growth gradually decreases as forest age increases; it follows that the carbon sequestration potential of forests also decreases over time. Nonetheless, Kyrlund (1990) reports that undisturbed tropical moist forests show net growth, and thus net carbon sequestration, for 100 years after establishment. Therefore, although other forest-based systems, such as young plantations, can sequester carbon at a higher rate than mature forests, primary forests conserve much more carbon per hectare, thereby conserving the terrestrial carbon pool and preventing carbon release into the atmosphere (Kyrlund, 1990). Moreover, although fire and oxidation contribute to CO_2 emission, forest gaps created by these events allow additional carbon to be sequestered, if natural regeneration takes place.

3.5 Approaches of studying ecosystem dynamics

Two approaches are often used in studying ecosystem dynamics. The first and ideal type of approach is ‘temporal monitoring’, where the dynamics of ecosystem components (for example soil, plant, etc.) are examined over time at a single site. This is feasible where long term data are available and changes in ecosystem components over time can be directly measured. Unfortunately, such long-term data are rarely available in the tropical countries (Sanchez *et al*., 1985; McDonagh *et al*., 2001) like Ghana. According to McDonagh *et al*. (2001), even where available, such data usually come from on-station experiments that do not reflect the environment and management conditions of farmers' fields. Therefore, it is rarely possible to follow this approach especially under on-farm situations (Bhojvaid and Timmer, 1998).

The alternative approach is to use the spatial analogue and chronosequence methods (Young, 1991; Bhojvaid and Timmer, 1998). The spatial analogue method involves spatial sampling on sites that are subject to different land uses but operating within a similar environment and on similar soil types. The chronosequence method is a synchronized spatial sampling from neighboring sites of different ages managed on similar soils, under similar climatic conditions and management practices (Young, 1991; Hartemink, 1998). These approaches have been widely used in several studies such as to (a) assess long-term effects of global climate change (Tate, 1992); (b) assess long-term changes in soil productivity (Martin *et al*., 1990); (c) evaluate effects of deforestation and subsequent cultivation (Sanchez *et al*., 1985; McDonagh *et al*., 2001); (d) assess soil carbon dynamics due to long-term land uses (Dominy *et al*., 2002) and (e) study nutrient dynamics and carbon storage changes (Garten, 2002). Chronosequence and spatial analogue methods have the danger of confounding time with possible spatial variability and assume that all measured differences reflect the effects of time or management and not inherent spatial variability. These have been and still are widely used in studying different aspects of ecosystem dynamics (Marques and Ranger, 1997; Bhojvaid and

Timmer, 1998; McDonagh *et al*., 2001)**.** A major advantage of these techniques is that they provide data on long-term changes in soil, plant or other ecosystem components within a reasonable time. In situations such as Ghana where data on long-term experiments are very rare, the chronosequence and spatial sampling approaches are valuable alternatives to study ecosystem dynamics in a temporal perspective.

A necessary assumption in using the chronosequence approach to studying soil nutrient dynamics is that soil conditions or other parameters of interest for all the sites studied should be similar before changes in the land-use have been introduced. This is because observed differences in present soil conditions or other parameters can be interpreted as being caused by the present land-use practices only if the conditions were assumed comparable prior to the introduction of the new land management. Similarity in particle size distributions in the sub-surface (those parts of the soils that are little affected by the changing land management) particularly the clay fraction at all depths supports the assumption that soil conditions prior to the shifts in land management were more or less similar (Sanchez *et al.*, 1985; Lilienfein *et al.*, 2000).

3.6 Shaded-cocoa systems and C sequestration

Carbon sequestration is a poorly assessed potential value of shade trees in cocoa agroforests (Newmark, 1998). Some work (Gockowski *et al.*, 1998) found mature (40-year-old) cocoa agroforestry systems in Cameroon to be fixing carbon at around 154 Mg C ha^{-1}, while cocoa systems in place for 15 and 25 years show average carbon amounts of 111 and 132 Mg C ha^{-1} respectively. Although these recorded values are less than that for primary forest (308 Mg C ha^{-1}) in Camerouns (Koto-Same *et al.*, 1997), they are generally greater than for annual crops.

In Turrialba, Costa Rica, Koskela *et al.* (2000) compared labile and perennial C stocks in cocoa systems shaded with *Erythrina poeppigiana*, a nitrogen-fixing tree and *Cordia alliodora,* non-nitrogen-fixing tree as shade trees. In both systems, soil C stocks increased through time. Carbon sequestration in perennial plant biomass was similar for both systems: an average of 4.28 Mg C $ha^{-1}yr^{-1}$ for the cocoa-*Cordia* system, and 3.08 Mg C $ha^{-1}yr^{-1}$ in the cocoa-*Erythrina* system (Beer *et al.*, 1990).

Whether agroforestry systems can be a sink or a source of C depends on the land-use systems that they replace (Montagnini and Nair, 2004). If they replace primary or secondary forests, they will accumulate comparatively lower biomass and C, but if they are established on degraded or otherwise treeless lands, their C sequestration value is considerably increased.

3.7 Cocoa (*Theobroma cacao*) in Ghana

3.7.1 Cocoa ecology and production systems

The cocoa industry in Ghana is dominated by a large number of peasant farmers who cultivate small farms of about 0.5 to 5.0 hectares and who lack the resources to expand or improve their farms. About 66% of farms are within the size range of 0.5 - 8 hectares owned by 332,244 peasant farmers, with only 18.9% of the farms larger than 20 ha (Cocoa Services Division, unpublished data). Although cocoa is native to South America, it is now grown pan-tropically, between latitudes of 10ºN and 10ºS. Optimal climatic conditions for cocoa growth are in temperature ranges from 18 - 23°C with detrimental effects on growth under long periods below 10 °C or above 30°C. Cocoa is a drought intolerant species, showing most favorable growth in regions with rainfall ranging from 1,150 mm to 2,500 mm (Willson, 1999). Ideal soil pH range for cocoa growth is 5.0-7.5 in the topsoil. Soil pH below 4 may invoke aluminum toxicity. However, a relatively low percent base saturation of 35% is ideal (Willson, 1999). Coarser soils with a mix of sand and clay are optimal for cocoa root growth as large particle size allows for root penetration. Although the cocoa tree root zone consists of a thick tap root, a mat of lateral roots (80-85%) are found predominantly in the top 0 - 30 cm of the soil, functioning as the major channel for moisture and nutrients (Wood and Lass, 1985; Leite and Valle, 1990).

Land preparation for cocoa cultivation involves farmers selectively clearing and burning small parts of the primary/secondary forest to open up new land for planting cocoa. After clearing, cocoa is planted normally as seedlings and intercropped with maize, yams, plantains and cassava to provide initial shade (Amoah, 1995). Typically, the shaded-cocoa systems are mostly mixed stands of cocoa with variable proportions of shade trees. At a spacing of 2.4 x 2.4 m to 3.6 x 3.6 m, cocoa tree density ranges from 900-1,300 trees ha^{-1} with about 10-15 medium sized shade trees per hectare. Upper canopy/shade trees found on farms include *Terminalia superba* Engl. & Diels, *Newbouldia laevis* (Beauv.) Seem. Ex Bureau and *Ceiba pentandra* L.). Fruit trees such as orange (*Citrus sinensis* (L.) Osbeck), avocado (*Persea americana*) and mango (*Mangifera indica* L.) may also be planted for shade, food and other purposes (Padi and Owusu, 1998).

Mature cocoa trees can reach between 4 and 8 m tall with lateral upright shoots originating at a height of 1-1.5 m (Willson, 1999). Pod production is dependent on pollinations of cauliflorous flowers by midges or aphids, with fruiting normally occurring after 3 to 5 years after planting. During early growth, weed control, typically through manual labor, is highly important for successful cocoa growth. It has been shown that weed suppression usually enhances plant vigour thus resulting in greater tree performance as the tree matures (Jones and Maliphant, 1958; Willson, 1999). However, tree performance may decline with common fungal e.g. black pod disease (Danquah, 1995). Most farmers do not apply fertilizers. Average cocoa yields in Ghana are about 300 kg ha^{-1}, compared with the potential yield of 1.0 to 1.5 Mg ha^{-1} (MoFA, 2003). Without fertilization, yields decrease after about 20 years, but production is possible for up to 50 years (Amoah, 1995; Duguma *et al.*, 2001).

3.7.2 Eco-physiology of cocoa

Solar radiation and shade

Cocoa is one of the most important perennial crops in the world with an estimated output of 3.5 million tons in 2006 (ICCO, 2007). It is commercially exploited for seed output mainly destined for chocolate manufacturing. The most important determinant parameters of cocoa yield are related to (i) light interception, photosynthesis and capacity of distributing photoassimilate, (ii) maintenance respiration and (iii) pod morphology (Zuidema *et al.*, 2005). Comprehensibly, these three parameters are crucial to seed yield and have been examined by Yapp and Hadley, (1994) who showed that seed production is light limited. Heavy shade not only reduces seed yield, because of low photosynthate production (Ng, 1982), but also increases the incidence of diseases (Alvim, 1977). On the other hand, cocoa is a shade tolerant species in which appropriate shading could lead to adequate photosynthetic rates, growth and seed yield (de Almeida and Valle, 2007).

Cocoa has a low light saturation point (LSP) of 400 μE $m^{-2} s^{-1}$ and a low maximum photosynthetic rate (7 mg dm^{-1} h^{-1}) at light saturation (Hutcheon 1981). The photosynthetic rate of the crop decreases if the photosynthetic apparatus is exposed to light intensities exceeding 60% of full sunlight that is 1800 μmol $m^{-2} s^{-1}$ (Galyuon *et al.*, 1996), while prolonged exposure to high light intensities damages the photosynthetic mechanism of the leaves (Raja Harun and Hardwick, 1988). Low light intensities however suppress flower production with light levels less than 1800 hours $year^{-1}$, having a considerable depressing effect on production (Asomaning *et al.*, 1971).

It is well established that, in general, where soil nutrients, water and temperature are not limiting and losses from pests and diseases can be avoided, crop growth and yield are dependent on the total solar radiation intercepted during the growing season (Monteith, 1978). Consequently, there is a positive correlation between cacao yields and light, as has been shown by Bonaparte (1975) and Ahenkorah *et al.,* (1987). Vernon (1967) concluded that the relationship between cocoa yield and available light was approximately linear from 30 to 60% full sunlight. However, when modeled from zero to 100 %, a quadratic model showed better adjustment than the simple linear model, suggesting that some degree of shading is desirable.

Trials in West Africa have shown that potential yields of cocoa can be doubled by removing permanent shading (intercepting 30-50 % incident radiation) provided fertilizers are applied (de Almeida and Valle, 2007 citing Lechenaud and Mossu, 1985). The comprehensive work of Ahenkorah *et al.*, (1987) sheds light on the importance of appropriate fertilization in unshaded cocoa plantations. Cunningham and Burridge (1960), by submitting cocoa seedlings to full sunlight and heavy shading (85%) showed that water and mineral nutrients were the most crucial factors for growth promotion at full sun exposure. The higher production of non-shaded cocoa implies in a smaller productive lifespan, a larger demand for fertilizers (Owusu, 1978), a decrease in the incidence of cherelle wilt (Asomaning *et al.*, 1971) and larger investments (Ahenkorah *et al.*, 1987).

Temperature

Closely related to radiation is temperature. Cocoa as a tropical crop can only be profitably grown under temperatures varying between 30-32 ^{o}C mean maximum and 18-21 ^{o}C mean minimum and absolute minimum of 10 ^{o}C (Wood and Lass 1985). Temperature has been related to light use efficiency with temperatures below 24 ^{o}C having a decreasing effect on the light saturated photosynthesis rate (Hutcheon, 1977). Temperatures below 10 ^{o}C caused severe inhibition of the photosynthesis rate. The stomata of chilled leaves never opened as wide as stomata of non-chilled plants. Leaf temperature affects stomatal resistance, decreasing the resistance upon increasing temperatures. However, since the increases in temperature may often go together with higher vapour pressure deficits (VPD), the effect of VPD may override the effect of temperature (Raja-Harun and Hardwick, 1986). In Ghana, the period of high temperatures when the widest range in the maximum and minimum temperature occurs have been noted to coincide with flushing (Hurd and Cunningham, 1961; Asomaning *et al.*, 1971).

3.8 Hi-Tech Cocoa Production in Ghana

In a bid to replenish soil fertility and to improve on the productivity of the cocoa tree, the Government through COCOBOD initiated the Cocoa 'Hi-Tech' Programme. The programme involves the application of fertilizers, the provision of improved planting materials and the application of insecticides and fungicides on cocoa farms. The scheme enables the farmers to receive inputs as credit in the form of fertilizers, agro-chemicals and farm equipment and tools and farm provision of farm services like weeding, pruning, and the application of the chemicals and fertilizers. In its first year, 50,000 farmers benefited from this programme, a number that increased to 100,000 one year later. The adoption of the Hi Tech Programme has helped to increase the productivity of most cocoa farms (Dormon *et al.*, 2004)

Following the successes of the Hi-tech programme, a private fertilizer company, Wienco (Gh) Limited, convinced about the agronomic package under the programme has established a scheme for cocoa farmers called *Cocoa Abrabopa*. *Cocoa Abrabopa* is an association of cocoa farmers who desire to raise the productivity of their farms and have signed on as members to receive a package of hi-tech cocoa inputs sufficient to cover two acres of mature cocoa farm on credit with the promise to repay the total amount of the credit facility after harvest. The *Abrabopa* package consists of 6 bags of 590 kg *Asaase Wura* Special Cocoa Fertilizer, agrochemicals (16 bottles of 30 ml Confidor 200 SL, 48 sachets of Nordox and 48 sachets of Ridomil) and a Matabi Pneumatic Sprayer, supported by extension education all valued at Gh¢318.10 and equivalence of \$ 212.00 (Quartey, 2007)

3.9 Indigenous Knowledge

3.9.1 The meaning and status of indigenous knowledge in agriculture

There is no standard definition of indigenous knowledge (IK). However, there is a general, understanding as to what constitutes IK. According to Haverkort and de Zeeuw (1992), IK is the actual knowledge of a given population that reflects their experiences based on traditions and includes more recent experiences with modern technologies. IK has evolved through "unintended experimentation", fortuitous mistakes and natural selection by farmers, and arises from the practical judgment and skill needed to survive in a fragile soil system (Aina, 1998) by a number of environmental challenges (Adedipe, 1983; Adedipe, 1984). Though based on experience passed from one generation to the next, it nevertheless, changes, adapts and assimilates new ideas. It can be quite specific to location and may vary between individuals from different social groups according to the differentiating factors such as age, gender, wealth, ethnicity and occupation. It includes cultural, as well as technical knowledge and is interlinked with social and political knowledge and skills (Oudwater and Martin, 2003).

3.9.2 Ethnopedology: Farmers' local knowledge of soils and soil fertility processes.

Ethnopedology is a part of ethno-ecology, the study of indigenous environmental knowledge (Toledo, 1992; 2000). It is a hybrid discipline structured from the combination of natural and social sciences, such as soil science and geo-pedological survey, social anthropology, rural geography, agronomy and agro-ecology (Barrera-

Bassols and Zinck, 1998). Often, terms such as traditional, folk, local, indigenous, farmers' and peoples' soil knowledge systems are used interchangeably to refer to ethnopedology, although they are not strictly synonymous (WinklerPrins, 1999; Talawar and Rhoades, 1998). Ideally, ethnopedology encompasses all empirical soil and land knowledge systems of rural populations, from the most traditional to the modern ones.

Farmers' conception of soil fertility

The ethnographic record shows that farmers' idea of soil fertility in most instances differs from that of scientists (Talawar and Rhoades, 1998). Scientists generally consider the nutrient status of soil apart from its physical condition in evaluating soil fertility levels. Typically, soil fertility tests are carried out to identify the deficiency of soil nutrients so that they could be rectified by applying fertilizers and soil amendments in general.

In Benin *Adja* farmers for example, identify soil depletion as a result of cultivation of soils over a number of years, and regard soil fertility as a "limited good" that is, if it is taken away, it must be put back again before use (Brouwers, 1993). In other settings, farmers correlate soil fertility to "soil moisture" (Amanor, 1991). Amanor (1991) found that among the farmers of Upper *Manya Krobo* District of southeast Ghana the word for "blessed" and "soft" are one and the same, a blessed or fertile soil being soft and moist. Based on the symbolic analysis of crop production decisions by the farmers of *Indus* basin, Kurin (1983) indicated that farmers preferred to plant wheat crops in light textured soil (perceived to be cool and dry), which they fertilized with manure, or Di-Ammonium phosphate as a second choice, instead of urea, which was perceived to be hot and dry.

Talawar and Rhoads (1998) indicated that farmers in semi-arid regions of southern India considered comparatively less fertile sandy soil as “rich” (fertile) soil because of its quality of high water permeability not because of micronutrients or minerals. Factors considered for rating certain soils as “fertile” include: sustainable productivity, high permeability, and water holding capacity, few tillage operations, ease of operation and low requirement of composted manure (Talawar and Rhoads, 1998).

Tamang (1993) identified that the predominant idea of soil fertility among farmers in the hills of Nepal was the overall improvement of “soil structure.” As soil structure is highly influenced by the textural properties of the soil it is clearly one of the main criteria for classifying soils as fertile or infertile among many farming communities. Colour, crop suitability, geographical location, and consistency are some of the other criteria farmers in Burkina Faso, Benin and Zambia use (Brouwers, 1993; Dialla, 1993). Soil texture influences crop production through other properties such as water permeability, water holding capacity, drainage, and other physico-chemical properties of soil.

3.9.3 Methodological approaches to studying ethnopedology

A review of ethno-pedological information sources reveals three main research approaches: ethnographic, comparative and integrated (Barrera-Bassols and Zinck, 1998; WinklerPrins, 1999).

Ethnographic approach: In the ethnographic approach, field data analysis and ethnopedological knowledge acquisition are the main objectives in recognizing farmers’ environmental rationality from a cultural perspective (Malinowski, 1935; Conklin, 1957).

In this type of study, the ethno-pedological information is not compared with scientific soil information.

Comparative approach: The comparative approach aims to establish similarities and differences between local knowledge and scientific information. This type of study intends to identify possible correlations between different soil and land classifications and management systems. The analysis does not take into consideration the socio-cultural contexts from which perception, beliefs, cognition and practices are derived (Thrupp, 1989; Sillitoe, 1998).

Integrated approach: The integrated approach identifies and mobilizes the relationship between cultural and scientific information in order to elaborate natural resource management schemes according to local social, cultural, economic and ecological contexts. Its main goal is to link soil and land wisdom and knowledge in order to promote feasible and sustained local endogenous development in an interdisciplinary perspective (Barrera-Bassols and Zinck, 2003).

CHAPTER 4

IMPACT OF FOREST CONVERSION TO SHADED-COCOA SYSTEM ON PLANT BIOMASS AND NUTRIENT STOCKS IN A HUMID SEMI-DECIDUOUS FOREST IN GHANA

Abstract

Changes in vegetation biomass, carbon (C) and nutrient stocks, and responses of soil physico-chemical property to land-use change from forest to shade-cocoa agroforestry was investigated along a chronosequence of farm fields on a ferric lixisol in the Ashanti Region of Ghana. Total standing tree biomass declined significantly ($F_{3,\ 131}$ =11.22, P =0.0031) from 209 to 13 Mg ha^{-1} in forest and 3-year-old plots respectively. There were significant differences in stand litterstocks ($F_{3,\ 71}$=4.62, P=0.047), under-storey vegetation ($F_{3,\ 35}$=61.4, P=0.000) and biomass of fine roots (($F_{3,\ 35}$ = 9.58, P=0.0001) Soil bulk density increased significantly ($F_{3,\ 35}$ = 18.5, P= 0.0006) only in the top 0-10 cm soil layer. Total stocks of soil organic C decreased significantly ($F_{3,\ 35}$=4.46; P=0.0404) in the top 0-10 cm soil depth but were similar ($F_{3,\ 35}$ =1.05, P=0.4224) for the 0-60 cm soil depths in both forest and cocoa systems. By 30 years after forest conversion, cocoa system had re-accumulated up to 151 Mg C ha^{-1} at rate of 3.6 Mg C $ha^{-1}yr^{-1}$. Total soil quality declined 3 years after conversion to below pre-conversion levels. Available P stocks declined ($F_{3,\ 11}$=3.12, P=0.038) while soil exchangeable Ca, K and Mg stocks as well as cation exchange capacity (CEC) and base saturation remained more or less stable with a tendency to improve. The inclusion of trees in the cropping system and enhancement of farmer capability in improved farm management is required to maintain high C and nutrient base minimize soil quality degradation during plantation development phase and sustain long-term productivity.

Key words: Carbon and nutrient stocks, carbon sequestration, biomass accumulation, forest conversion, soil degradation.

4.1 Introduction

Conversion of forests to agricultural land-use strongly impact soil nutrients and microbial biomass depending on the new land-use and the post conversion management practices (Sharma *et al.*, 2004). Forest clearing for annual crops (e.g. maize) removes the major source of litter and therefore reduces the supply of organic material to the soil while soil organic matter stock continues to decompose possibly at a higher rate, as the removal of forest cover leads to higher soil temperatures (Davidson and Ackerman, 1993; Guo and Gifford, 2002). Declining soil organic C may lead to a reduced effective cation exchange capacity (ECEC) and reduced N stocks while reduced ECEC may make cations more vulnerable to leaching (Dechert, 2003).

In contrast, forest conversion to land-use systems characterized by perennial crops, which provide litter and shading to the soil especially during the maturity phase may improve stocks of nutrients and other soil fertility parameters to levels capable of sustaining crop productivity (Beer *et al.*, 1998). In the Cameroon for instance, shaded-cocoa systems are reputed to remain productive and environmentally sustainable for up to 50 years at levels comparable to long-term fallows or primary forests (Duguma *et al.*, 2001), most probably because the continuous vegetation cover which provides shading, litter, organic matter and plant nutrients to the soil (Dechert and Veldkamp, 2003).

The effects of land-use change on soil carbon and nutrient storage are of great interest in the context of international policy on greenhouse emission mitigations (Kanmegne *et al.*, 2006). For instance cocoa farms created at the expense of natural forests will still result in significant emissions, while the conversion of either short fallow or savannah land, which have much lower stocks of carbon to perennial tree crop systems will likely result in a net sequestration of carbon and thereby contribute to climate change mitigation.

While nutrient accumulation in both soil and vegetation was seldom studied, research is also lacking on long-term system level nutrient sustainability specifically in shaded cocoa systems (Szott *et al.,* 1999; Isaac *et al.,* 2005). Few studies have assessed changes in carbon and nutrient stocks with time, either via chronosequences (Toky and Ramakrishnan, 1983) or the monitoring of long-term plots (Bebwa and Lejoly, 1993; Szott and Palm, 1996). Soil organic carbon represents a key indicator for soil quality. It is the main determinant of biological activity and has a major influence on the physical and chemical properties of soils (Robert, 2001). Its dynamics are still not well understood under perennial cropping systems like cocoa. While some studies (e.g. Koto-Same *et al.,* 1997; Kauffman *et al.,* 1998) did not find significant declines in soil carbon following forest conversion to perennial cropping systems, several others (e.g. Houghton *et al.,* 1991; van Noorwijk *et al.,* 1997; Schroth *et al.,* 2002; Isaac *et al.,* 2005) have reported significant declines after conversion. Therefore, studies are needed for understanding the trends, magnitudes, and rates of soil quality changes especially-for designing management options for sustainable agricultural productivity in perennial cropping systems.

Specific objectives of the study are to:

(i) Quantify the effects of forest conversion on plant biomass accumulation in shaded-cocoa systems.

(ii) Quantify total C and macro-nutrient stocks in vegetation and soil compartments in shaded-cocoa systems.

(iii) Quantify the degree to which shaded-cocoa systems may act as C sinks in the semi-deciduous humid lowlands in Ghana, West Africa.

(iv) Quantify the magnitude of soil quality degradation along the chronosequence following forest conversion to shaded-cocoa systems.

The chosen durations after forest conversion represent distinct phases of the development in a cocoa farm, specifically the planting and developing phase (3 years), the productive phase (15 years) and the mature phase (30 years) (Isaac *et al,*. 2005). It was expected that carbon and nutrient pools as well as microbial biomass would decline significantly along the chronosequence following forest conversion to shaded-cocoa land-use.

4.2 Materials and methods

4.2.1 Description of study sites

A general description of the study sites including climate, vegetation and dominant soil types and the approach adopted for the study are in sections 2.1, 2.2, 2.3 and 2.4 of the general methodology in Chapter 2.

4.2.2 Selection of sites and establishment of treatment plots

A reconnaissance survey of 16 farming communities in the district was conducted in October 2005. Following the survey, five communities namely Seidi, Kobeng, Apaahkrom, Nkonteng and Amankyia were selected based on the availability of the required plot ages of cocoa fields. Sites of the different land-uses, i.e., natural forest, 3, 15 and 30-year old cocoa farms replicated three times were selected. Owners were interviewed on site about the age of the site since land was brought under cultivation, land preparation methods, management practices and cropping history. Subsequently 12 experimental plots with sizes ranging from 35 m x 35 m to 35 m x 40 m depending on the farm size were established. None of the sites had received any fertilizer amendments since they were brought under cultivation.

4.2.3 Parameters measured

Biomass of standing trees

In each of 12 experimental plots, a subplot of 5 m x 20 m (Koto-Same *et al.*, 1997) was randomly established. The diameter at breast height (DBH in cm) was recorded for all trees with diameter > 2.5 cm falling within the 100 m^2 subplots, using a diameter tape. Species-specific biomass equations were not available in the literature, so the biomass (Y in kg tree^{-1}) was estimated from the following generalized tree biomass allometric equation involving the tree diameter at breast height (DBH) developed for specific precipitation zone, the moist tropical forest with rainfall between 1500 - 4000 mm (Brown, 1997):

$$Y = \exp[-2.134+2.530 \ln(DBH)];\ (R^2 = 0.97) \qquad (4.1)$$

where y = dry above-ground biomass (kg) and DBH = diameter at breast height (cm). This equation is considered suitable for estimating total above-ground tree biomass of individuals with <150 cm DBH in relatively dense stands (Brown, 1997). It is recommended for above-ground biomass estimation where destructive sampling cannot be conducted (Anderson and Ingram, 1998), as in on-farm situations like in the present study due to farmer set restrictions. Necromass of felled but unburned logs were not measured as it was considered to be beyond the scope of objectives of this study.

Estimation of biomass of under-storey vegetation

Biomass of under-storey vegetation that is trees with DBH < 2.5 cm were determined from three 1m x 1m sub-plots assigned at random within each sampling plot by cutting all under-storey vegetation at ground level (Woomer and Palm, 1998). These were air dried (to halt biological transformations while waiting for access to oven), weighed, sub-sampled, oven-dried for 24 hrs at 65^{o}C, corrected for moisture content and analyzed for total carbon and major nutrients N, P, K, Ca and Mg in duplicates.

Estimation of standing litterstocks

Surface litter was collected by randomly throwing 20 cm x 20 cm (400 cm^2) wooden quadrat, manually cutting through and collecting all litter inside the wooden frame. Ten such samples were collected per site every month. Steps were taken to ensure that no area of the forest/cocoa floor was sampled twice by tagging all previously sampled points with colored polythene strips. The collected surface litter was oven-dried at 65°C for 24 hours for dry weight determination. The material from one sampling event every 4 months was manually cleaned from adhering soil particles and analyzed for major nutrient in duplicates.

Estimation of pod husks biomass under productive cocoa systems

Biomass of cocoa pod husks produced per hectare on productive farms was determined by establishing a pod husk: seed weight ratio (on dry weight basis) using 50 randomly harvested cocoa pods from 15 different farms in the district. This ratio was multiplied by cocoa beans seed yield for the project district to estimate the weight of pod husks that housed beans harvested from a hectare of farmland.

Estimation of fine root biomass production

The standing stock of fine roots (≤ 5 mm diameter) was sampled every month for 12 months to determine biomass production of fine roots. On each occasion, fifteen randomly located soil cores or five cores (height 30 cm; 5.6 cm diameter; internal volume 739 cm^3) per plot were collected from each 35 m x 35 m / 35 m x 40 m plot at 0 - 30 cm soil depth. Fine roots were separated from the soil using the wet sieving (0.5 mm grid) method within 48 hours of sampling (Böhm, 1979), or samples were stored in a refrigerator (4^0C) until they could be processed, usually within one week. All roots were washed to ensure the removal of all sand particles. Non-root organic material and roots with diameter > 5 mm were removed manually with forceps and the separated fine roots were then dried (65^0C; 48 h). Results were expressed as values for total fine roots (FR) biomass per treatment (sum of live plus dead for both upper and cocoa canopy trees). A correction factor for the soil adhering to the FR was determined for each sampling date by incinerating (450^0C; 8 h) three sub-samples (0.3 g) from the bulked sample of all FR recovered from each treatment. Weights of all root samples were taken using an (Ogawa Seiki Fx-300, d=0.001) electronic balance.

Stem-wood sampling

Stem-wood samples were taken at 1.3 m height (from both upper and lower storey trees on cocoa farms, and from trees in the natural forest) using increment borers inserted into the centre of each selected trunk to ensure that the entire bole including bark was represented by each sample. Three samples were taken from each of 15 randomly selected trees from each plot. Samples from similar plots were pooled together, oven-dried at 65^oC for 48hrs.

Chemical analysis of plant tissues

Oven-dried (65^oC to a constant weight for 48 hrs) plant tissue samples (fine roots, leaf and stem-wood tissues, leaf litter and under-storey vegetation) were separately ground in a stainless steel mill to pass through a 0.5 mm mesh sieve and analyzed for total C, N, P, K, Ca and Mg concentrations in duplicates.

Organic carbon content was determined using the wet oxidation by acidified potassium dichromate (Walkley and Black, 1934) method by adding 10 ml concentrated H_2SO_4, 10 ml 0.5N $K_2Cr_2O_7$ and 10 ml orthophosphoric acid and back titrating the solution with 1.0 M $FeSO_4$ solution with diphenylamine indicator.

Total N concentration was determined using the standard micro-Kjeldahl method by digesting 0.5 g samples in 10 ml concentrated sulphuric acid using a catalyst mixture of ($CuSO_4$, K_2SO_4 and selenium powder) and distillation with colorimetric determination by spectrophotometer.

Basic cations and Phosphorus: Calcium (Ca), Mg and K were analyzed by atomic absorption spectrophotometry. Total P in digested plant tissue sample was determined using ammonium molybdate method. Analytic procedures followed those of Anderson and Ingram (1998). Carbon and nutrient stocks in the different fractions of plant biomass was calculated by multiplying the dry biomass per hectare of each component by its respective C and nutrient concentration. All analyses were carried out at the Soil Research Institute in Kumasi, Ashanti Region.

Soil sampling

From each of the 12 plots, soil samples were taken from twelve spots (along an S-shaped transect starting from one of the diagonals) on each of 30 m x 40 m plots by auguring at three depths; 0-10, 10-20, and 20-60 cm (i. e. 12 samples x 3 replicates x 1 treatment or 36 samples for each soil depth for each treatment/plot age). Soil samples were air-dried for 2 days, roots removed, hand-milled with a roller and homogenized to pass through a 2-mm sieve. For each treatment, soil samples from the same depth were thoroughly mixed and 2 subsamples per soil depth taken for chemical analysis in duplicates.

Chemical analysis of soil samples

Total N: Samples were analyzed for total N using the standard micro-Kjeldahl method by wet-digesting 0.5 g samples in 5.0 ml concentrated H_2SO_4 using a catalyst mixture

(K_2SO_4 and selenium powder) and distillation with colorimetric determination by spectrophotometer.

Soil organic carbon: Soil organic carbon was determined using a modified Walkley and Black wet oxidation method as described by Nelson and Sommers (1982). The procedure involves wet combustion of the organic matter with a mixture of acidified potassium dichromate and titrating excess dichromate after reaction against 1.0 M ferrous sulphate using diphenylamine as indicator.

Available P and cations: Available P was extracted with an HCl: NH_4 mixture using the Bray's No. 1 method as described by Bray and Kurtz (1945). Phosphorus in the extract was subsequently determined on a spectronic 21D spectrophotometer by blue ammonium molybdate method with ascorbic acid as reducing agent.

Exchangeable bases: Potassium (K), Ca and Mg were determined by extraction with 250 ml of buffered 1M ammonium acetate at pH 7 followed by flame photometric determination. Effective cation exchange capacity was calculated as the sum of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and exchangeable acidity (Al^{3+} + H^+).

Soil pH: Soil pH was determined in a 1:2.5 suspension of soil and water using an HI 9017 Micro-processor pH meter after calibrating the pH meter with buffer solutions at pH 4.0 and 7.0. The pH was read by immersing the electrode into the upper part of the suspension.

Bulk density: Soil bulk density at (0-10, 10-20 and 20-60 c m) was determined for each treatment block in duplicates by driving a thin-walled metal cylinder of known volume

($V=100cm^3$) and weight W_1 into the vertical face in each plot with a wooden mallet. Soil samples were dried at 105°C for 48 hours and weighed again (W_2). The bulk density (D) was calculated as: D ($gm\ cm^{-2}$) = W_2-W_1/V.

Texture and particle size distribution: Soil particle size distribution was determined for each land-use by the pipette method. Soil samples were dispersed using chemical dispersant (sodium pyrophosphate solution), pouring the soil suspension on to a 0.05 mm fine sieve for separating out the sand fraction, and washing the clay and silt fractions into a sedimentation cylinder. The clay content was subsequently determined by drying a constant volume suspension extracted with a pipette and textural categories established from the USDA soil triangle.

Carbon stocks

Total soil organic C stocks in ($kg\ ha^{-1}$) in the soil of each land-use type were calculated from % SOC contents of samples, soil layer thickness (*z meters*), and bulk density ($\rho\ kg/m^3$), of the samples by the following equation from Solomon *et al.,* (2002):

$$\text{Total SOC } (kg\ ha^{-1}) = SOC/100 \text{ X } (\rho\ kgm^{-3} \text{ X } z \text{ meters X } 10{,}000\ m^2) \qquad (4.2)$$

Forest clearing and cultivation usually causes compaction and consequently the bulk density of the cultivated soils increases with time. Since the bulk density has an important effect on C-balance calculations, such differences in soil bulk density between the natural forest and other sites (the cocoa fields/plantations) needs to be accounted for. In the present study, the thickness (z meters) of the soil layer under cocoa land-use was corrected ($z_{corrected}$) following the methods of Solomon *et al.,* (2002) assuming that the bulk density and depth of the cultivated soils were originally the same as those of the corresponding forest soils:

$$Z_{corrected} = (\rho_{forest} / \rho_{cocoa\ fields})\ x\ Z \qquad (4.3)$$

where ρ = bulk density (kg m^{-3}) and z = thickness of the soil depth (m)

The stocks of carbon in each layer (0-10, 10-20 and 20-60cm depths) were summed up to give an overall soil stock in the 0-60 cm layer.

Nutrient stocks

Stocks of extractable P, K, Ca, Mg, and total N in each soil depth were calculated by multiplying the concentrations of the respective elements by bulk density and the thickness of each soil horizon, then summing the quantities in each layer to give an overall soil nutrient stock in the 0-60 cm soil layer. Nutrient accumulation in the different fractions of plant biomass was calculated by multiplying the dry mass per hectare with the nutrient content of the samples.

Soil Degradation index

Following Lemenih (2004), soil degradation indices (DIs) were calculated as the difference between mean values of individual soil properties from the cocoa land-use chronosequences and the baseline values of similar soil properties under the natural forest land-use expressed as a percentage of the values under the natural forest (Islam and Weil, 2000). These percentage changes were summed across all soil properties to compute an index of soil degradation or improvement. Values of pH, C/N ratio and exchangeable Na were not included in this calculation because the criterion of 'more is better' (i.e. higher value means higher fertility level) is uncertain over the range of values in this study for these soil properties (Islam and Weil, 2000).

Soil microbial biomass carbon, nitrogen and phosphorus

Soil samples were randomly taken from 12 spots along an S-shaped transect from each of 30 x 40m plots by auguring at 0-10 cm depth. Samples from each plot were thoroughly mixed and three composite samples taken for analysis in triplicates at the laboratories of the Soil Research Institute (SRI) of Ghana, Kumasi. The microbial biomass C, N and P for each land-use was estimated by chloroform fumigation-extraction method (Vance *et al.,* 1987; Brookes *et al.,* 1985). Microbial biomass carbon (MBC) was calculated as: MBC = $k\Delta C$, where ΔC is the difference between organic C extracted from fumigated soils and organic C extracted from non-fumigated soils and $k = 2.64$ (Vance *et al.,* 1987). Microbial biomass nitrogen (MBN) was calculated as: MBN = $k\Delta N$, where ΔN is the difference between total N extracted from fumigated soils and total N extracted from non-fumigated soils, and $k = 1.46$, and microbial biomass phosphorus (MBP) was calculated as: MBP=$k\Delta P$, where ΔP is the difference between total P extracted from fumigated soils and total P extracted from non-fumigated soils and k=2.5 (Anderson and Ingram, 1998). Samples were collected every three months over a period of 2 years (2005-2006 and 2006-2007) and marked as dry or wet season samples.

4.2.4 Data processing and statistical analysis

A completely randomized design with four treatments: Forest land-use (pre-conversion period), and cocoa farms established 3, 15, and 30 years after conversion of forest. Each treatment had three replicates. Biomass and nutrient concentrations in the different above-ground, and below-ground fractions (fine roots) and nutrient concentrations and stocks at different soil depths were used as the dependent variables. For each variable normal distribution was tested using the Shapiro-Wilks W-test for homogeneity of variances. Variables that conformed to normal distribution were analyzed using one-way analysis of variance (ANOVA) using the software package Statistix 7.0 (Analytical Software, 2000). Separation of means was done using Tukey's Honestly Significant Difference (HSD) test to test for significant effects at 5% probability level. Concentrations of soil nutrients at the various depths did not meet the assumptions for an ANOVA even when transformed so Kruskal-Wallis Tests were used and differences in nutrient concentrations between sites were assessed with an ANOVA on the mean ranks. Regressions and correlations were also employed as tools for statistical tests and to establish trends and relationships between parameters. Pearson's product moment correlation coefficients were calculated to investigate the degree of association between selected variables.

4.3 Results

4.3.1 Soil physical parameters

Mean values (± SEM) of particle size distribution and soil bulk density, along the chronosequence for respective depths (0-10, 10-20 and 20-60 cm) and the entire studied depth (0-60 cm) are in Table 4.1. For the 0-60 cm soil depth, there were no differences in percentage silt ($F_{3,\ 35}$ = 2.28, P=0.0985) and in percentage clay ($F_{3,\ 35\ =}$ 3.04. P=0.0432) contents, though there was significant difference among land-uses in percentage sand ($F_{3,\ 35}$ =8.63, P=0.0009). Across the different land-uses, particle sizes were similar for corresponding depths except for the 20-60 cm soil depth where % sand was significantly higher in the 3 and 30-year-old plots compared to forest and 15-year-old cocoa plots. Using the USDA Soil Textural Triangle for assigning soil texture classification (Anderson and Ingram, 1998), overall soil texture for the 0-60 cm soil profile was similar across the different land-uses and soils could be classified as silty loam.

Bulk density (0-60 cm depth) did not differ significantly between land-uses ($F_{3,\ 35\ =}$ 2.41; P=0.0848). Differences between land-uses were significant ($F_{3,35}$ = 18.5, P= 0.0006) only for the top 0-10 cm. For 10-20 ($F_{3,\ 11}$ = 0.23; P=0.8717) and 20-60 ($F_{3,\ 11}$ = 5.57; P=0.0233) soil depths, bulk densities did not differ among land-uses for similar depths (Table 4.1).

4.3.2 Soil carbon, nitrogen and nutrient concentrations

Concentrations of soil C, N and elemental nutrients along the chronosequence for the three soil depths 0-10, 10-20 and 20-60 cm are in Table 4.2. Total C concentration in the top 0-10 cm soil depth was significantly different ($F_{3,\ 11}$ = 0.53; P=0.0296) among land-

Table 4.1 Mean values (±SEM) for particle size distribution (%) and bulk density (gm/cm^3) of 0-10, 10-20 and 20-60 cm soil depths forest and cocoa systems

Soil physical parameters	Depth (cm)	Land-use			
		Forest	Cocoa 3 years	Cocoa 15years	Cocoa 30 years
Sand (%)	0-10	20.8 (±2.4)^a	24.0 (±1.3)^a	19.7 (±2.7)^a	21.8 (±1.90)^a
	10-20	20.3 (±1.1)^a	28.6 (±2.4)^a	19.5 (±2.6)^a	22.7 (±1.3)^a
	20-60	19.5 (±0.6)^a	32.9 (±4.5)^b	19.7 (±2.8)^a	27.7 (±0.4)^{ab}
Mean	**0-60**	**20.2 (±0.8)^a**	**28.5 (±1.9)^b**	**19.6 (±1.4)^a**	**24.1 (±1.1)^{ab}**
Silt (%)	0-10	68.2 (±2.5)^a	64.5 (±0.3)^a	68.6 (±2.1)^a	63.9 (±3.6)^a
	10-20	62.2 (±2.1)^a	59.8 (±1.8)^a	60.2 (±2.1)^a	54.8 (±0.4)^a
	20-60	55.3 (±3.0)^a	48.2 (±8.4)^a	55.2 (±4.0)^a	48.0 (±1.1)^a
Mean	**0-60**	**61.9 (±2.3)^a**	**57.5 (±4.1)^a**	**61.4 (±2.4)^a**	**55.6 (±2.54)^a**
Clay (%)	0-10	11.0 (±1.5)^a	11.6 (±1.4)^a	11.6 (±0.7)^a	14.4 (±3.6)^a
	10-20	17.5 (±1.3)^a	11.6 (±0.7)^b	20.3 (±1.0)^a	22.5 (±1.3)^a
	20-60	25.2 (±2.8)^a	18.9 (±4.7)^a	25.1 (±1.5)^a	24.3 (±5.7)^a
Mean	**0-60**	**17.9 (±2.3)^a**	**14.0 (±1.9)^a**	**19.0 (±2.0)^a**	**20.4 (±1.92)^a**
Bulk	0-10	1.01(±0.03)^a	1.19 (±0.03)^b	1.26 (±0.04)^b	1.31 (±0.02)^b
density	10-20	1.40(±0.04)^a	1.45 (±0.05)^a	1.40 (±0.09)^a	1.45 (±0.02)^a
(gm/cm^3)	20-60	1.34 (±.08)^a	1.63 (±0.04)^a	1.59 (±0.06)^a	1 .63(±0.05)^a
Mean	**0-60**	**1.25(±0.03)^a**	**1.42 (±0.14)^a**	**1.42 (±0.14)^a**	**1.46 (±0.15)^a**
Texture	Silty Loam	Silty Loam	Silty Loam	Silty Loam	Silty Loam

Figures in the same column followed by the same superscript for different land-uses are not significantly different at $P < 0.05$ level using Tukey's HSD range test.

Table 4.2 Soil chemical properties (±SEM) at different depths for forest and cocoa land-use systems in the Ashanti Region, Ghana.

Soil Chemical properties	Depth (cm)	Land-use			
		Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
C (%)	0-10	2.95 (±0.7) [a]	2.12 (±0.5) [b]	2.50 (±0.7) [ab]	2.55 (±0.5) [ab]
	10-20	1.11 (±0.3) [a]	0.70 (±0.01) [b]	0.80 (±0.01) [a]	0.78 (±0.08) [a]
	20-60	0.40 (±0.01) [a]	0.30 (±0.05) [b]	0.40 (±0.001) [a]	0.44 (±0.01) [a]
N (%)	0-10	0.30 (±0.01) [a]	0.18 (±0.03) [b]	0.20 (±0.01) [b]	0.18 (±0.01) [b]
	10-20	0.07 (±0.01) [a]	0.07 (±0.01) [b]	0.07 (±0.01) [b]	0.07 (±0.01) [b]
	20-60	0.13 (±0.03) [a]	0.03 (±0.01) [a]	0.03 (±0.01) [a]	0.05 (±0.01) [a]
Available Bray's P (mg/kg)	0-10	2.07 (±0.53) [a]	2.32 (±0.33) [a]	2.18 (±0.23) [a]	1.29 (±0.21) [a]
	10-20	2.00 (±0.13) [a]	1.26 (±0.14) [a]	0.86 (±0.03) [b]	0.52 (±0.05) [ab]
	20-60	1.16 (±0.11) [a]	0.93 (±0.04) [b]	0.50 (±0.05) [b]	0.10 (±0.01) [b]
Exchangeable K (cmol kg^{-1})	0-10	0.40 (±0.04) [a]	0.62 (±0.05) [a]	0.46 (±0.03) [a]	0.67 (±0.04) [a]
	10-20	0.30 (±0.04) [a]	0.26 (±0.01) [a]	0.26 (±0.01) [a]	0.29 (±0.01) [a]
	20-60	0.23 (±0.02) [a]	0.22 (±0.02) [b]	0.18 (±0.01) [b]	0.30(±0.04) [a]
Exchangeable Ca (cmol kg^{-1})	0-10	9.04(±2.2) [a]	7.83(±1.53) [a]	10.4 (±2.31) [a]	10.3 (±2.31)[a]
	10-20	5.08 (±1.1) [a]	5.3 (±1.1) [b]	4.36 (±1.1) [a]	5.03 (±1.1) [a]
	20-60	3.39(±0.9) [a]	4.18 (±1.3) [b]	3.38 (±0.7) [a]	3.87(±1.1) [a]
Exchangeable Mg (cmol kg^{-1})	0-10	3.48 (±1.1) [a]	4.28(±1.1) [a]	6.00 (±1.4) [a]	7.52(±2.1) [a]
	10-20	1.11(±0.7) [b]	2.73 (±1.1) [a]	2.67 (±1.0) [a]	1.91(±0.7) [b]
	20-60	1.05(±0.7) [a]	1.29 (±0.7) [a]	2.58 (±0.9) [b]	1.73 (±0.7) [a]
CEC (cmol kg^{-1})	0-10	13.3(±1.0) [a]	13.0(±1.0) [a]	17.3(±2.7.0) [a]	19.1(±3.0) [a]
	10-20	6.85(±1.0) [a]	8.78(±1.0) [b]	7.72 (±1.0) [a]	7.82(±2.1) [a]
	20-60	5.28(±1.0) [a]	5.98(±1.0) [b]	6.60(±1.0) [a]	7.54(±0.9) [a]
Base Saturation (%)	0-10	98.5 (±1.0) [a]	99.2(±1.0) [a]	98.9 (±1.1) [a]	98.0 (±1.5) [a]
	10-20	97.4 (±1.0) [a]	94.7(±1.0) [a]	68.8 (±5.0) [a]	93.4 (±2.2) [a]
	20-60	92.9 (±3.2) [a]	97.2 (±1.0) [a]	94.9 (±1.8) [a]	92.8 (±4.0) [a]

Values for a particular chemical property followed by the same letter for different land-uses are not different at the same depth (Kruskal-Wallis ANOVA mean on the ranks, p=0.05).

use systems. In both 10-20 and 20-60 cm depths, differences between land-uses were not significant.

Largest total concentrations of N were observed in the forest land-use at all depths. In the top 0-10cm soil depth, concentration of N was similar ($F_{3,\ 11}$ = 0.82, P=0.5165) for all land-uses. Concentrations of N for the 10-20 cm depth was greater ($F_{3,\ 11}$ = 19.4, P= 0.0072) in forest but similar in all cocoa plots.

The different land-uses had similar or smaller concentrations of available P compared to forest soil at all corresponding depths. In the top 0-10 cm depth, available P was similar among land-uses ($F_{3,\ 11}$=0.12, P=0.948). In the 10-20 and 20-60 cm soil depths, concentrations of P differed ($F_{3,\ 11}$=3.12, P=0.038) between land-uses with the greater level occurring in the forest. Concentrations of exchangeable K in the 0-10 and 10-20 cm soil layers were similar among the land-uses. Differences were however significant ($F_{3,\ 11}$ = 20.5, P= 0.0044) in the 20-60 cm soil depth (Table 4.2). Concentration of Mg was similar ($F_{3,\ 11}$ =1.88, P = 0.211) in the 0-10 cm and ($F_{3,\ 11}$ = 0.67, P=0.593) in the 10-20 cm soil depths. Cation exchange capacity (CEC) and base saturation was similar ($F_{3,\ 11}$ = 0.22, P = 0.438) in topsoil of converted sites but differed in the subsoil.

Pearson’s product moment correlation coefficients calculated to relate selected mean soil parameters to one another are in Table 4.3. Whereas clay content of soils was positively correlated with organic C stocks and bulk density, it was negatively correlated with sand %. Bulk density was negatively correlated with organic carbon and total N stocks, and soil depth was negatively correlated with soil pH, available P and total nitrogen concentration. Cation exchange capacity (CEC) was significantly (P < 0.05) positively correlated with concentration of organic carbon and soil pH, and concentration of organic carbon was positively correlated with concentration of nitrogen.

Table 4.3 Pearson's correlation coefficients between selected soil physical and chemical parameters in the 0-60 cm soil depth.

X	Y	R	P
CEC	Organic C %	0.87*	<0.001
Clay %	Organic C (Mg ha^{-1})	0.06	0.728
Clay %	Sand %	-0.03	0.859
Clay %	Bulk density	0.56*	<0.001
Bulk Density	Organic C (Mg ha^{-1})	-0.26	0.133
Bulk Density	Total N (%)	-0.03	0.862
Depth	Total N (%)	-0.54*	0.001
Total N %	Organic C (%)	0.45	0.638
CEC	pH	0.30	0.079
Depth	pH	-0.34	0.400
Depth	Available P	-0.45*	0.006

*Correlation Significant (P<0.05); P = Probability Level

4.3.3 Standing trees and above-ground biomass fractions

Standing trees and under-storey vegetation

Stand density, above-ground tree biomass, under-storey vegetation biomass, standing litterstocks, pod husk and fine roots biomass changes along the chronosequence are shown in Table 4.4. Total standing tree biomass (i.e. cocoa plus upper-storey canopy strata) declined significantly ($F_{3,\ 131}$ =11.22, P =0.0031) after forest conversion to cocoa system (Table 4.4). For the upper-storey trees, differences were significant (F =7.99, P=0.002) between land-uses. Under-storey vegetation biomass differed ($F_{3,\ 35}$=61.4, P=0.000) between the forest land-use on the one hand and all the cocoa land-uses on the other (Table 4.4).

Stand litter and cocoa pod husks biomass

Standing litterstocks (i.e. sum of leaf litter, twigs and branches and miscellaneous litter) were significantly smaller ($F_{3,\ 71}$ = 4.62, P = 0.0047) in 3-year-old-plots compared to forest, 15 and 30-year-old cocoa systems while biomass of cocoa pod husks accumulated on productive/mature (15 and 30-year-old) cocoa farms averaged 540 kg ha^{-1} (Table 4.4).

4.3.4 Below-ground (fine roots) biomass

Biomass of fine roots (diameter $\leq$ 5mm) under each land-use showed significant growth ($F_{3,\ 35}$ = 9.58, P = 0.0001) with increasing chronosequence age (Table 4.4). The forest and 15-year-old land-uses recorded comparable mean fine root biomass.

4.3.5 Carbon and nutrient pools in standing trees, above-ground fractions & fine roots

The comparative contributions of the various components (tree biomass, standing litter, under-storey vegetation, fine roots and cocoa pod husks) to nutrient pools under each land-use are in Table 4.5. Generally, pools of C and element nutrients declined from forest values to their smallest values 3 years after forest conversion. For example, C storage in tree biomass (cocoa and upper storey) was 94 Mg ha^{-1} in the forest and 5.7 Mg ha^{-1} in the 3-year- old cocoa farms. The trend was the same for total N and other nutrients, with total stocks increasing along the chronosequence from 3 to 30-year-old plots (Table 4.5). Among the different pools, nutrient stocks ranked in the order trees (shade and cocoa) > surface litter > fine roots. Under-storey vegetation had the least stock of all nutrients across the chronosequence. Phosphorus was the element with the smallest stocks in the different pools. In litter layer, Ca was the element with the largest stock and varied from 80.7 to 55.7 kg ha^{-1} (Table 4.5)

Table 4.4 Tree density, above-ground tree and under-storey vegetative biomass for upper storey and cocoa canopies for forest and cocoa systems in the Ashanti Region, Ghana.

Parameter	Land-use			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Cocoa Canopy				
Number of trees ha^{-1}	-	1,500	1,100	900
Biomass (Mg ha^{-1})	-	5.0^{b} (±0.31)	43.8^{a} (±5.0)	57.5^{a} (±5.21)
Upper-storey				
Number of trees ha^{-1}	900	16	35	26
Total Biomass (Mg ha^{-1})	209.3^{a} (±33.3)	7.65^{c} (±2.4)	91.2^{b} (±38.6)	127.7^{b} (±38.6)
Cocoa and upper storey canopies				
Total tree biomass (Mg ha^{-1})	209.3^{a} (±33.3)	12.7^{b} (±1.6)	135.0^{a} (±43.7)	185.2^{a} (±27.3)
Under-storey vegetation Total Biomass (Mg ha^{-1})	1.74^{a} (±0.15)	0.57^{b} (±0.04)	0.26^{b} (±0.08)	0.49^{b} (±0.07)
Stand litterstock (Mg ha^{-1})	4.56^{ab} (±0.30)	3.57^{b} (±0.42)	5.78^{a} (±0.63)	5.89^{a} (±0.61)
[1]Cocoa pod husks (Mg ha^{-1})	-	-	0.54	0.54
Fine roots biomass (Mg ha^{-1})	3.3^{b} (±0.27)	2.3^{c} (±0.13)	3.3^{b} (±0.29	4.4^{a} (±0.34)

Values in the same row followed by the same letters for the different land-uses are not significantly different at P < 0.05 level using Tukey's HSD range test. Numbers in parenthesis are the standard error of the means (SEM).

[1]Biomass of pod husks are estimates from seed: pod weight ratios. Seed weight was from district yield data assumed to be the same for productive (15 and 30-year-old) farms.

Table 4.5 Distribution of [1]Carbon and nutrient stocks (kg ha^{-1}) among biomass fractions (trees, surface litter, under-storey vegetation, cocoa pod husks and fine roots) in forest and cocoa land-uses in the Ashanti Region, Ghana

Land-use/nutrient pool	Mg ha^{-1}	Nutrient stocks (kg ha^{-1})				
	C	N	P	K	Ca	Mg
Forest						
Trees	94.0	2,236	167.4	1,360	1,643	1005
Surface litter	1.44	71.1	3.65	17.8	80.7	22.8
Under-storey vegetation	0.74	18.6	2.09	19.5	15.7	9.40
Fine roots	1.44	17.8	4.63	33.0	43.2	19.5
Cocoa 3 years						
Cocoa trees	2.25	32.5	3.50	40.5	51.0	23.0
Shade trees	3.43	56.6	5.40	61.2	72.7	37.5
Surface litter	1.25	48.2	2.86	7.85	55.7	17.5
Under-storey vegetation	0.25	6.3	0.63	6.95	6.56	3.65
Fine roots	0.92	18.6	3.45	11.0	25.3	5.06
Cocoa 15 years						
Cocoa trees	19.6	289.1	30.7	420.5	499.3	262.8
Shade trees	40.8	629.1	54.7	757.0	1,021	538.1
Surface litter	2.21	59.3	5.13	16.5	96.6	29.6
Under-storey vegetation	0.11	2.39	0.29	4.65	4.42	1.69
Fine roots	1.49	33.0	3.63	19.8	23.8	13.2
[2]Pod husks	0.24	6.2	0.54	18.3	4.3	2.0
Cocoa 30 years						
Cocoa trees	25.8	448.5	37.4	552	621.0	299.0
Shade trees	57.2	983.3	102.2	1,085	1,430	485.3
Surface litter	2.39	76.0	6.48	31.2	97.1	27.1
Under-storey vegetation	0.21	4.75	0.50	9.16	8.48	2.99
Fine roots	1.98	34.7	5.39	20.7	40.9	27.9
[2]Pod husks	0.24	6.20	0.54	18.3	4.3	2.0

[1]Quantities of respective nutrient pools in each biomass fraction were obtained by multiplying average nutrient concentrations in those components by their respective biomass.

[2]This is the mean value per hectare of pod husk biomass from productive (15 and 30-year-old) farms in the district

4.3.6 Changes in soil carbon and nutrient stocks

Soil carbon and nitrogen changes with depth

Differences in C and nutrient stocks in corresponding soil depths (0-10, 10-20 and 20-60 cm) along the chronosequence are in Table 4.6. The carbon stock (±SE) differed significantly ($F_{3,35}$=4.46; P=0.0404) among land-uses for the 0-10 cm soil depth. Differences in C stocks in the 10-20 cm soil depth were not significant ($F_{3, 35}$=0.59; P =0.6387). Total N stocks in the 10-20 cm soil depths were significantly s in 3 and 15-year-old plots compared to forest and 30-year-old plots. Apart from Mg in the 20-60 cm soil depth where stocks differed significantly ($F_{3, 35}$=5.0; P =0.0306), for all other soil depths available P, and extractable K, Ca and Mg stocks did not differ significantly between land-uses for similar or corresponding soil depths.

Changes in total soil C, N and nutrient stocks with time

Changes in total stocks of C, N and nutrients within the 0-60 cm soil depth are in Table 4.7. Soil carbon stocks did not differ significantly ($F_{3, 35}$ =1.05, P=0.4224) between forest and cocoa land-use over time. Similarly total soil nitrogen stocks did not differ ($F_{3, 35}$ =2.69, P =0.1166) between the land-uses. Stocks of available P in forest, 3 and 15-year-old plots were similar but differed significantly ($F_{3, 35}$ =9.02; P=0.006) from stocks in the 30-year-old plot. Stocks of total extractable K were similar ($F_{3, 35}$=0.42; P=0.742) in forest and cocoa systems. Calcium was the element with the largest total stocks. Differences were significant ($F_{3, 35}$ =7.30; P= 0.0112) with 30-year-old plots having significantly greater stocks than forest and 15-year-old plots. Mg stocks did not differ ($F_{3, 35}$ =2.97; P=0.097) between land-uses. The quadratic relationships between total stocks of C and N, Ca, Mg, P, K and duration after forest conversion are depicted in Table 4.8.

Table 4.6 Quantities of carbon and nitrogen (Mg ha^{-1} ± SEM), and elemental nutrient stocks (kg ha^{-1} ± SEM) at the different depths of the soil profile in forest and cocoa land-use systems.

	Depth (cm)	Land-use: Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
C	0-10	29.8 (±0.40)^{a}	21.6 (±0.51)^{b}	25.5 (±1.77)^{ab}	26.0 (±2.56)^{ab}
Mg ha^{-1}	10-20	15.8 (±5.10)^{a}	10.4 (±4.53)^{a}	9.29 (±0.73)^{a}	12.8 (±2.97)^{a}
	20-60	21.8 (±4.99)^{a}	17.0 (±1.35)^{a}	22.5 (±1.08)^{a}	24.8 (±5.00)^{a}
N	0-10	2.97 (±0.84)^{a}	1.73 (±0.20)^{a}	2.10 (±0.18)^{a}	1.87 (±0.18)^{a}
Mg ha^{-1}	10-20	3.88 (±1.88)^{a}	1.04 (±0.51)^{b}	1.09 (±0.13)^{b}	2.18 (±0.32)^{a}
	20-60	1.51 (±0.29)^{a}	1.70 (±0.33)^{a}	1.86 (±0.19)^{a}	2.33 (±1.00)^{a}
P	0-10	2.09 (±1.00)^{a}	2.46 (±1.08)^{a}	2.23(±0.26)^{a}	2.31 (±0.24)^{a}
kg ha^{-1}	10-20	3.02 (±1.24)^{a}	1.86 (±0.72)^{a}	1. 46 (±0.78)^{a}	0.75 (±0.16)^{a}
	20-60	6.38 (±3.42)^{a}	5.30 (±1.80)^{a}	2.62 (±2.02)^{a}	0.44 (±0.55)^{b}
K	0-10	158.7 (±25.9)^{a}	247.3 (±75.8)^{a}	184.8 (±21.7)^{a}	268.6 (±61.0)^{a}
kg ha^{-1}	10-20	170.6 (±30.4)^{a}	148.5 (±70.4)^{a}	150.5 (±12.0)^{a}	165.9 (±40.1)^{a}
	20-60	485.9 (±181)^{a}	414.5 (±245)^{a}	392.4 (±19.6)^{a}	666.3 (±141)^{a}
Ca	0-10	1,849 (±87.5)^{a}	1,812 (±341.9)^{a}	2,115 (±291)^{a}	2,097 (±223.3)^{a}
kg ha^{-1}	10-20	1,397 (±338)^{a}	1,568 (±618.1)^{a}	1,292 (±13.8)^{a}	1,487 (±221.9)^{a}
	20-60	3,561 (±384)^{a}	4,729 (±765.0)^{a}	3,844 (±306)^{a}	5,411 (±783.1)^{a}
Mg	0-10	423.6 (±213)^{a}	523.4 (±161)^{a}	735.1 (±127)^{a}	920.3 (±130)^{a}
kg ha^{-1}	10-20	190.0 (±59.5)^{a}	485.4 (±316)^{a}	474.2 (±59.9)^{a}	339.9 (±43.8)^{a}
	20-60	494.8 (±210)^{b}	879.3 (±236)^{ab}	1,759 (±225)^{a}	1,182 (±240)^{ab}

Figures in the same row followed by the same superscript for different land-uses are not statistically different at $P < 0.05$ level using Tukey's HSD range test.

Table 4.7 Total stocks of carbon (Mg $ha^{-1} \pm$ SE), and nitrogen and elemental nutrients (kg ha^{-1} ± SEM) at the 0-60 cm soil depths in forest and cocoa land-use chronosequence

Land-use	Mg ha^{-1}	Nutrient stocks (kg ha^{-1})				
	C	N	P	K	Ca	Mg
Forest	67.4[a] (±1.1)	8,365[a] (±1,367)	11.5[a] (±1.44)	815.3[a] (±225.9)	6,807 [a] (±254.2)	1,108[a] (±426.5)
Cocoa 3 years	49.0[a] (±2.33)	4,474[a] (±182.4)	9.6[a] (±1.61)	810.3[a] (±387.6)	8,128 [ab] (±682.6)	1,888[b] (±597)
Cocoa 15 years	57.3[a] (±0.23)	5,053[a] (±290.3)	6.3[ab] (±0.96)	727.6[a] (±22.7)	7,251 [a] (±153.1)	2,968[b] (±269.2)
Cocoa 30 years	63.6[a] (±1.1)	6,380[a] (±153.7)	3.5[b] (±0.45)	1,101[a] (±223.6)	8,996 [b] (±933.3)	2,441[b] (±334.3)

Figures in the same column followed by the same superscript for different land-uses are not different at $P < 0.05$ level using Tukey's HSD range test.

Table 4.8 Quadratic regressions ($y = ax^2 + bx + c$) showing the relationship between the number of years after forest conversion (x) and total stocks organic C, total N, K, Ca, Mg (Mg ha^{-1}) and available P (kg ha^{-1}) in the 0-60 cm soil depth in shaded-cocoa systems in the Ashanti Region, Ghana.

Nutrient stock	*a*	*b*	*c*	R^2
Organic C (Mg ha^{-1})	0.038	-1.025	60.84	0.293
Total N (Mg ha^{-1})	0.012	-0.370	7.18	0.542
Available P (kg ha^{-1})	0.005	-0.481	11.2	0.992
Total K (Mg ha^{-1})	0.001	-0.021	0.84	0.982
Total Ca (Mg ha^{-1})	0.002	-0.032	7.432	0.650
Total Mg (Mg ha^{-1})	0.005	0.207	1.195	0.984

Except for P, all fitted functions returned to near zero deviation from the original values over the 30-year time span. The fitted functions explained in general 54 to 99% of variations in N, P, K, Ca, and Mg dynamics with time for the studied soil depth (0-60 cm soil depth). For organic C (only 30% is explained).

4.3.7 Microbial biomass C, N, and P

Mean annual microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and microbial biomass phosphorus (MBP) in the different land-uses are in Table 4.9. Analysis of variance showed no significant differences: MBC ($F_{3,\ 23}$ = 2.43; P= 0.125), MBN ($F_{3,\ 23}$ = 1.64; P= 0.232) and MBP ($F_{3,\ 23}$ = 2.24; p=0.135) among land-uses. Microbial biomass C and N in the land-use systems differed significantly between the rainy and dry seasons. MBP did not differ significantly between seasons across the chronosequence ($F_{3,}$

Table 4.9 Soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and microbial biomass phosphorus (MBP) in the 0-10 cm soil depth in forest and different stages of cocoa land-use systems.

Land-use	MBC (mg kg^{-1})	MBN (mg kg^{-1})	MBC/MBN	MBP (mg kg^{-1})
Forest	109.8^{a} (±18.5)	52.0^{a} (±23.5)	2.1^{a} (±1.49)	12.6^{a} (±1.8)
Cocoa 3years	48.5a (±5.7)	10.0^{a} (±2.9)	4.8^{b} (±0.89)	8.2^{a} (±1.1)
Cocoa 15 years	157.5^{a} (±31.6)	27.3^{a} (±7.1)	5.5^{b} (±0.77)	9.8^{a} (±1.0)
Cocoa 30 years	105.0^{a} (±45.1)	23.8^{a} (±11.7)	5.4^{b} (±0.82)	13.4^{a} (±2.3)

Figures in the same column followed by the same letter are not significantly different at P < 0.05 level using Tukey's HSD range test. Numbers in parenthesis are standard errors of means.

Table 4.10 Seasonal variation in soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and microbial biomass phosphorus (MBP) in forest and different stages of cocoa land-use systems

Microbial property /land-use	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
MBC (mg kg^{-1})				
Rainy season	141.4 (±6.5)a	58.0 (±4.0)a	210.4 (±3.2)a	182.1 (±2.5)a
Dry Season	78.2 (±4.4)b	39.0 (±0.17)b	104.6 (±19.9)b	73.4 (±27.5)b
MBN (mg kg^{-1})				
Rainy season	92.1(±9.2)a	13.8 (±4.6)a	36.9 (±9.3)a	41.5 (±13.8)a
Dry season	11.9 (±0.56)b	6.1 (±0.00)b	17.7(±6.0)b	6.12 (±2.3)b
MBP (mg kg^{-1})				
Rainy season	14.6 (±3.1)a	6.9 (±2.07)a	9.4 (±1.04)a	12.2 (±7.0)a
Dry season	10.5 (±1.2)a	9.4 (±0.26)a	10.2 (±1.2)a	9.6 (±0.14)a

Figures in the same column followed by the same letter are not significantly different at P < 0.05 level using Tukey's HSD range test. Numbers in parenthesis are standard errors of means

$_{23}$ = 13.24; p= 0.231) (Table 4.10). The nutrient ratios of microbial C: N were similar in all cocoa systems ($F_{3, 23}$ = 2.43; P= 0.125), but lower in the forest. Microbial biomass C, N and P were significantly correlated (r = 0.964, r = 0.972 and r = 0.983 respectively, P<0.05) to organic carbon. Additionally, MBC and MBP were significantly correlated (r = 0.961). While MBN was significantly positively correlated (r =0.974) to total nitrogen, it was significantly negatively correlated (r = - 0.896) to available P (Table 4.11).

Table 4.11 Pearson's correlation coefficients among soil properties for the 0-10 cm soil depth. (MBC= microbial biomass carbon, MBN = microbial biomass nitrogen and MBP = microbial biomass phosphorus)

Soil/microbial property	Land-use	Organic C	MBC	MBN	MBP	Total N
Organic C	-0.0547					
MBC	0.2136	0.9637*				
MBN	-0.2846	0.9717*	0.8753			
MBP	0.0079	0.9828*	0.9614*	0.9339		
Total N	-0.4943	0.8947	0.7436	0.9740*	0.8477	
Available P	0.1660	-0.9627*	0.9006	-0.8964*	-0.8964	-0.9176

* Significant at the 0.05 level

4.3.8 Total system carbon and nutrient pools

Changes in C, N, P and basic nutrients held in above-ground pools (tree biomass, surface litter, cocoa pod husks and under-storey vegetation) and below-ground (fine roots and 0-

60 cm soil matrix) pools along the chronosequence are shown together in Figures 4.1 and 4.2 respectively. The high above-ground C, N and nutrient pools originally present decreased to their minimum values 3 years after conversion of the forest, thereafter pools increased with increasing duration after forest conversion. Nitrogen (N), Ca and Mg were more in below-ground than in the above-ground pools. In cocoa fields, calcium followed by potassium were the nutrient elements with the largest stocks in above-ground pools. Calcium pools ranged from 107 to 988 kg ha^{-1} in the order 30 years > forest >15 years > 3 years, while potassium ranged from 56 to 961 kg ha^{-1} also increasing in the order 30 years > forest >15 years > 3 years.

The greatest loss in total system C stocks resulted from land preparation prior to first cultivation with an average of 108 Mg C ha^{-1} (or 65% of original forest values) being lost from the system. By 15 years after conversion of the forest, combined C pools had gone up to 121.8 Mg C ha^{-1} (or 73.7% of original value), and 30 years after conversion of forest, total system carbon had built up to 151.4 Mg C ha^{-1} (91.6% of forest values). These increments are equivalent to system-carbon fixation rates of 5.4 Mg C $ha^{-1}yr^{-1}$ between 3 and 15 years, and 2.0 Mg C $ha^{-1}yr^{-1}$ between 15 and 30 years after conversion. Thus between 3 and 30 years after conversion, the cocoa system on the average fixed 3.6 Mg C $ha^{-1}yr^{-1}$.

Total pools of nitrogen ranged from 4,644 to 10,742 kg ha^{-1} with maximum loss of the system total N being about 57% of original forest values predictably occurring 3 years after

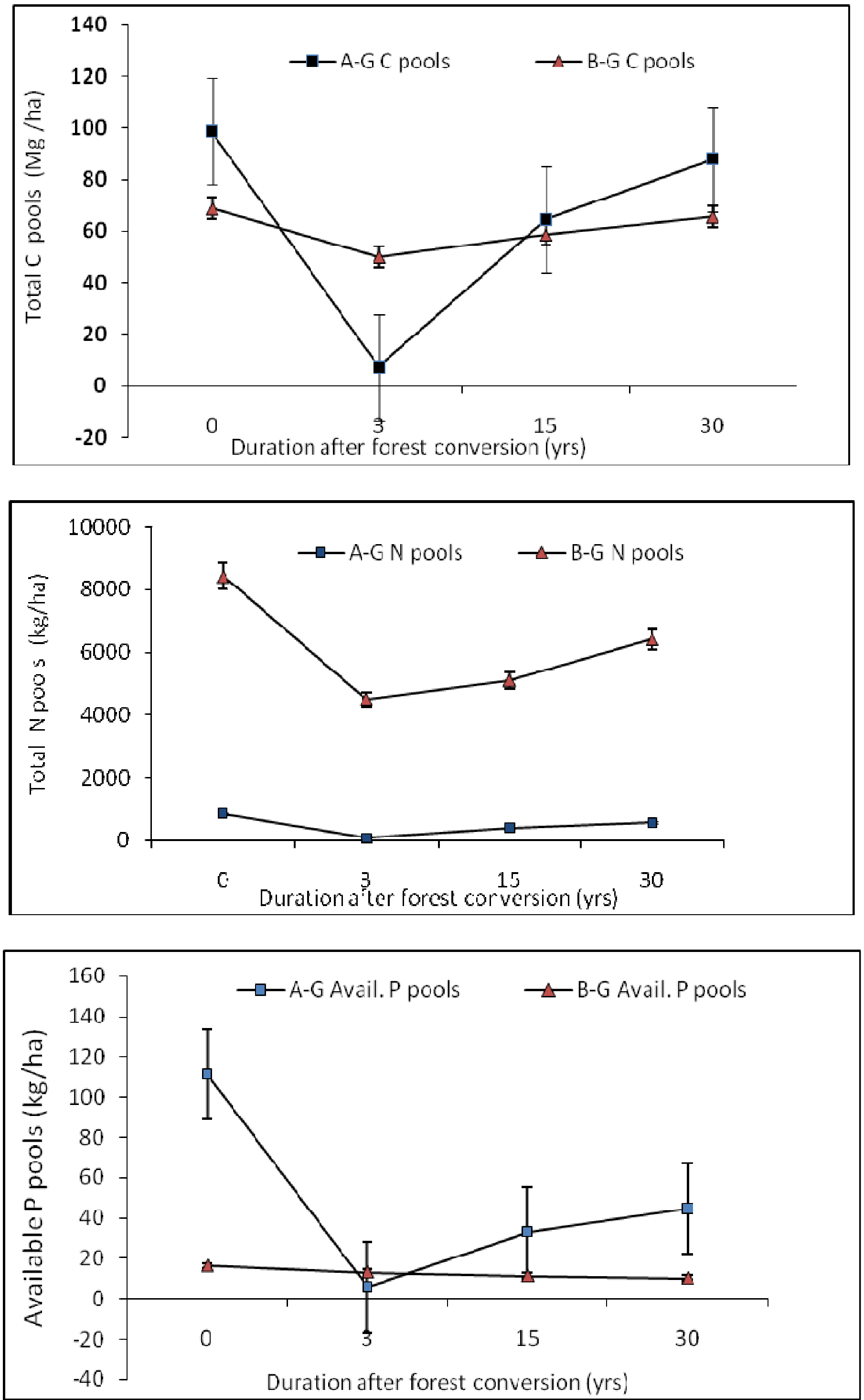

Figure 4.1 Changes in above-ground and below-ground (0- 60 cm soil matrix) pools of organic C, total N and available P along a chronosequence of cocoa fields converted from forest land-use. (A-G = above-ground; B-G = below-ground)

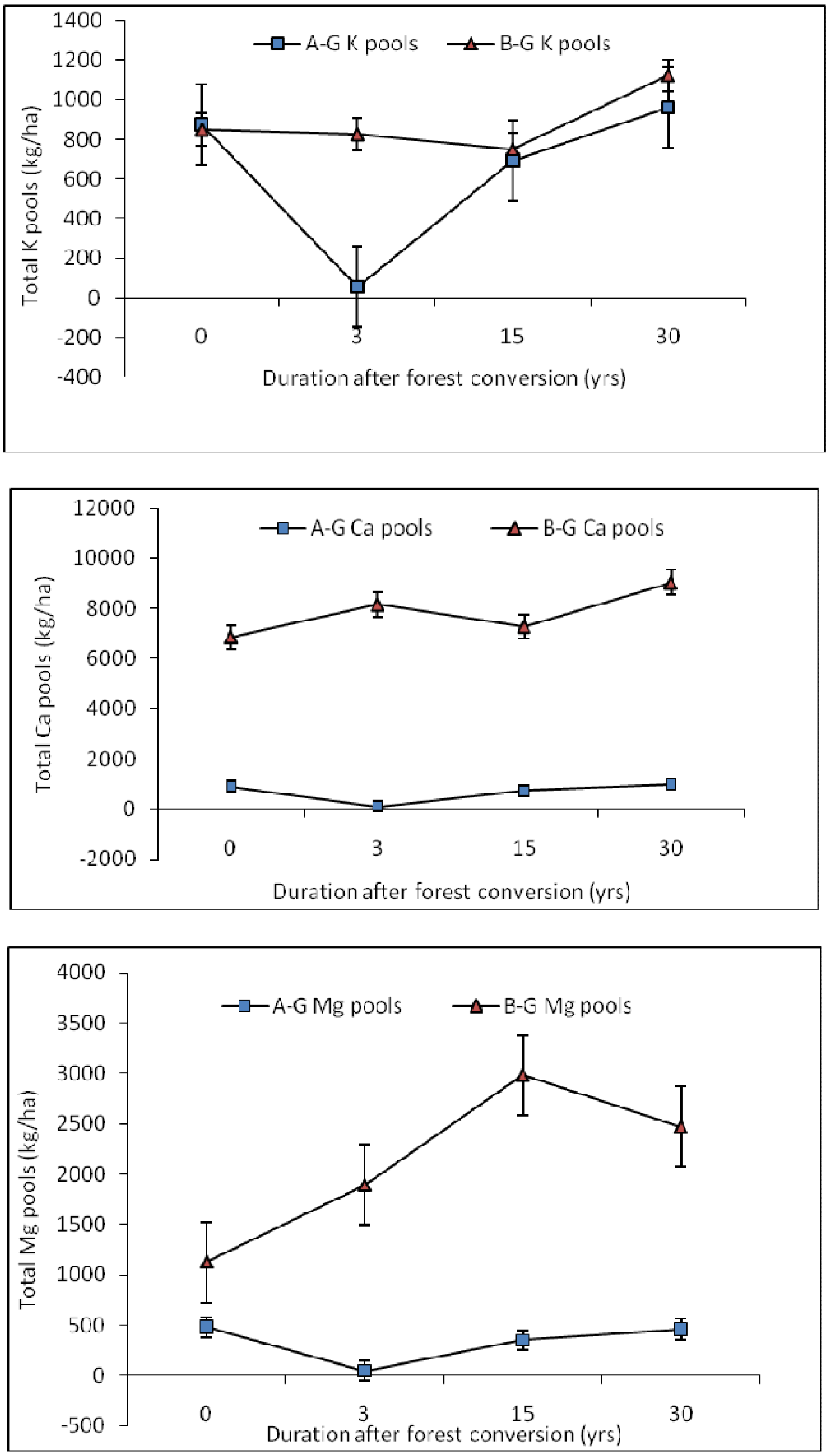

Figure 4.2 Changes in above-ground and below-ground (0- 60 cm soil matrix) pools of total K, total Ca and total Mg along a chronosequence of cocoa fields converted from forest land-use. (A-G = above-ground; B-G = below-ground)

clearing of forest. The trend was the same for P and K. Smallest pools of C, N, P and K were recorded three years after clearing the forest with pools increasing with age. Under cocoa system, Ca is the element with the largest pool and total stocks decreased in the order Ca > N > Mg > K > P while for forest land-use the trend was N > Ca > K > Mg > P.

4.3.9 Land-use change and soil degradation

Extent of total soil quality degradation along the chronosequence is in Figure 4.3. Each DI was calculated as the sum of the percentage deviation of bulk density, soil C, total N, CEC, BS%, available and exchangeable base cations except Na of the upper 0-60 cm soil depth from their respective values under forest land-use. Indices of degradation were -4.85, 75 and 86.8 respectively for the 3, 15 and 30 year old plots measured against forest as the standard reference with an index of zero.

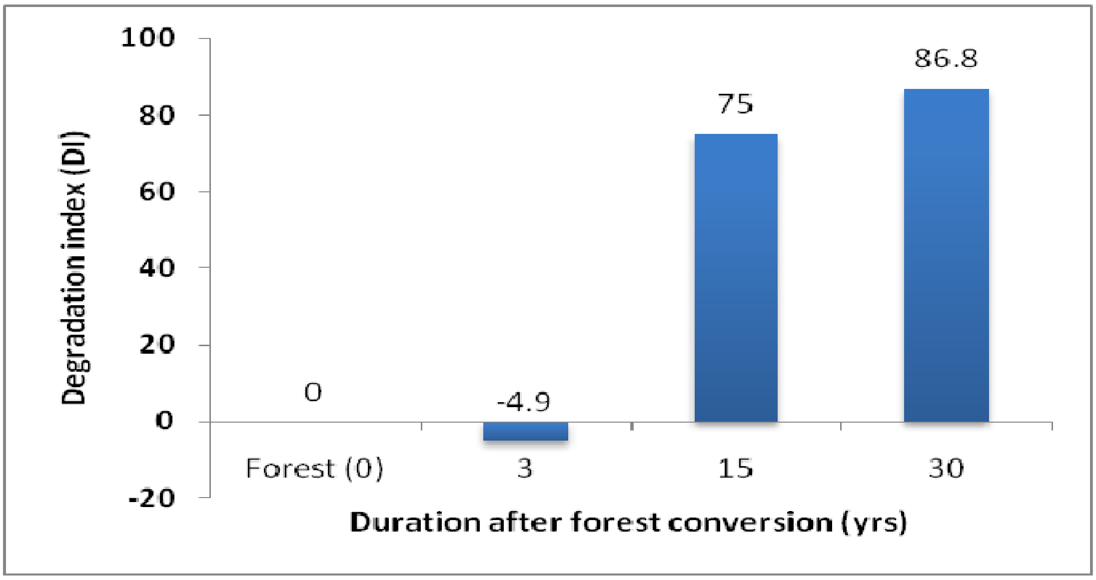

Figure 4.3 Degradation indices of forest soils along a chronosequence of cocoa fields at 3, 15 and 30 years of cultivation following conversion of forest.

4.4 Discussions

4.4.1 Effect of land-use system on soil physical parameters

Perennial cocoa systems created at the end of annual cropping cycles can be considered as the beginning of a controlled forest fallow with cocoa trees as the main tree layer. Farm management includes cutting back of some of the shade trees and the brushing of weeds between the crop plants in canopy gaps at least once a year. This activity seems to have a strong influence on bulk density especially in the top 0-10 cm layer, which was significantly greater under cocoa at 3 years than the primary forest soil probably due to the human traffic associated with these plantation management operations.

There were no differences in percentage silt contents between the land-uses though sand and clay percentages differed. However overall, soil texture was similar across the different land-uses. Using the USDA triangular soil classification chart (Anderson and Ingram, 1998), soils on all sites are similar and were classified as silty loam. The similarity in textural composition of the soils under the various plot ages clearly indicates that the soils were formed from similar parent materials under uniform environmental conditions and was used to justify comparability between two or more spatially sampled soils and allowed for further evaluation and comparison of other characteristics of interest in this chronosequence study.

4.4.2 Effect of forest conversion on standing tree and vegetation biomass

The total above-ground tree biomass of 209 Mg ha^{-1} recorded in the forest reference treatment was smaller than the 355 Mg ha^{-1} reported by Greenland and Kowal (1960) and the 350 - 560 Mg ha^{-1} reported by van Reuler and Jassen (1993) in similar semi-deciduous forest types in Ghana and the Cote d'Ivoire respectively. However the forests in these two studies had undergone very little disturbance compared to the forest in the present study thus accounting for the lower biomass. Andriesse and Schelhaas (1987) reported tree biomass of 475 Mg ha^{-1} for a Malaysian rainforest, while Kotto-Same *et al.*, (1997) reported standing biomass of more than 700 Mg ha^{-1} in southern Cameroon. The standing biomass of cocoa canopy tree recorded in this study was 43.8 and 57.5 Mg ha^{-1} in 15 and 30-year-old cocoa systems respectively. These values appear to be slightly lower than the 61.6 Mg ha^{-1} reported by Opakunle (1989) in a 22-year old cocoa agro-ecosystem in the semi-deciduous forest zone of south western Nigeria, but within reported biomass ranges in a 25-year-old cocoa agro-ecosystem in Ghana (Isaac *et al.*, 2005). Comparing forest biomass to biomass in cocoa systems reveals that, conversion of forests affects above-ground biomass significantly and is the major cause of above-ground biomass losses.

4.4.3 Effect of forest conversion on above-ground tree carbon

Conversion of forest to cocoa land-use resulted in a loss of 94% of initial forest tree carbon within the first three years. The 27% loss of soil carbon is small by comparison with above-ground carbon losses. This indicates that above-ground carbon pool is more vulnerable to losses when forests are converted to agro-systems compared to soil pools. Similar findings have been reported by Kauffman *et al.*, (1995) in Brazil when an Amazonian forest was converted to pasture, Toky and Ramakrishnan (1983) in secondary succession studies following slash-and-burn in North-eastern India and by Ewel *et al.*, (1981) in Costa Rica. To stem this tide of high carbon loss following forest conversion and to speed up carbon sequestration it is imperative that the establishment of new cocoa farms should be accompanied by the planting and introduction of more trees including indigenous timber tree species to serve as shade trees, which are important for the establishment of productive cocoa farms.

4.4.4 Effect of forest conversion on stand litter biomass, carbon and nutrients

The litterstocks on the forest floor are a dynamic component of carbon and nutrient cycling in the forest ecosystem (Currie, 1999). According to several authors (e.g. Swift *et al., 1981;* Anderson *et al.,* 1983; Spain, 1984) the litter standing crop in tropical and sub-tropical forest is often small owing to its high decomposition rate. However, numerous studies in tropical tree plantations also show a large accumulation of litter standing crop, especially when the planted species is exotic (Kadeba and Aduayi, 1985; Lugo, 1992; Bernhard-Reversat, 1993).

Litterstocks on forest floors have not been extensively studied. Very few studies exist for comparing our litterstocks with especially for shaded-cocoa systems. In this study, stand litter constituted 2.3, 27.8, 4.3 and 3.2 per cent of total above-ground biomass in forest, 3, 15 and 30-year-old land-uses respectively. Though often neglected, stand litter constitutes an important biomass pool in forest and cocoa ecosystems. Measured litterstocks in this study are well within the ranges reported by Spain (1984) for tropical and subtropical forests that ranged from 2.1-12.5 Mg ha^{-1}, but well below the stocks reported by Martius *et al.,* (2004) in rainforest and agroforestry sites in Amazonia. This could most probably be explained by the fact that, litterstocks in their study included large wood litter, which was not included in the present study. If they had been included especially under the forest land-use, total stand litter biomass would have been higher. It needs also to be mentioned that there was not much large wood litter in shaded cocoa plots as most had been exploited for fuel wood. It appears that litterstocks are controlled by a combination of factors such as litter production, stand-age linked to litter accumulation with time, stand density, and leaf area index that interact to affect litter layer build up (Yang *et al.*, 2005). The surface litter C pools showed relatively small differences varying from 1.25 - 2.39 Mg C ha^{-1} between plot ages. Surface litter is an important carbon pool and may contribute to carbon sequestration in forest and cocoa ecosystems.

4.4.5 Pod husks biomass, carbon and nutrients

Productive cocoa farms produced about 534 kg ha^{-1} of cocoa pod husks annually. These are piled at the pod breaking bays on all productive cocoa farms and constitute an important pool of carbon and nutrients in cocoa systems. Lack of management strategies to facilitate their effective recycling and even distribution over entire cocoa fields means that most of the cocoa tress are not benefitting from this nutrient pool and may be considered as lost nutrients. There is the need to develop management interventions that would ensure better utilization of pod husks as soil amendments. The biomass of pod husks produced in the systems under study is smaller than those reported by Opakunle (1989) in south-west Nigeria where husk production was 810 kg ha^{-1}. The greater pod husk production in SW Nigeria correlates with the greater bean yields (640 kg ha^{-1}) obtained from this on-station field study. This is twice what farmers get in the Nwabiagya District. Pools of nutrient in pod husks averaged 240 kg C, 6.2 kg N, 0.5 kg P, 18.3 kg K, 4.3 kg Ca and 2.0 kg Mg ha^{-1}.

4.4.6 Effects of forest conversion on fine roots biomass and carbon

Biomass of fine roots (diameter $\leq$ 5mm) expressed as root weight on a per hectare basis showed significant growth with increasing age of land-use. Between forest and 3-year old cocoa land-use, 30% of fine root biomass had disappeared. However, by 15 years after conversion to shaded-cocoa system, biomass of fine roots had recovered to initial forest levels. Whereas the recorded biomass of fine root for the different plots in this study appear not to differ (especially when compared to the lower age bracket) from the 2.6 Mg ha^{-1} reported for cocoa -*C. alliodora* system at 5 years, the values are smaller than the 6.1 Mg ha^{-1} recorded by Beer *et al.,* (1990) at 10 years. The principal reason for this difference could be that no correction was made for soil adhering to fine roots in the study by Beer and his co-researchers. The present values are however greater than the maximum values of 1.9 and 1.2 Mg ha^{-1} reported by Munoz and Beer (2001) in 16-year-old cocoa plantations in Costa Rica. This difference should be expected as fine roots in their study referred to fine roots $\leq$ 2mm and not $\leq$ 5mm as defined in the present study. Similarly fine roots biomass (≤ 2 mm; 0–10cm depth) of cocoa age 11 years shaded by *Erythrina glauca* was reported as 0.8 Mg ha^{-1} (Kummerow *et al.,* 1981) and 0.4 Mg ha^{-1} (≤ 1 mm) (Kummerow *et al.,* 1982). Results from this study, would therefore infer that production of fine roots and consequently nutrient contribution under cocoa increase with age, if we assume that there is no nutrient retranslocation before root senescence. As to whether nutrient contribution by fine roots significantly improves after forest conversion will depend on the composition of trees in the forest, their nutrient content, mortality and decomposition of fine roots (Idol *et al.*, 2000).

4.4.7 Effect of forest conversion on soil carbon and nitrogen

Soil organic carbon (SOC) and nitrogen concentrations were greater in surface soils than deeper in the profile across all the land-uses (Table 4.1), and is consistent with the majority of SOC and N being returned to the soil in above-ground litterfall and through turnover of fine roots, which are predominantly in surface soil (Guo *et al.,* 2004; Yang *et al.,* 2005). Carbon stocks in the 0-10 cm soil depth declined significantly 3 years after clearing. This is in agreement with previous reports (Juo and Kang 1989; Houghton *et al.,* 1991; van Noorwijk *et al.,* 1997; Schroth et *al.,* 2002; Isaac *et al.,* 2005) which indicate significant changes in soil carbon content over time in the top 0-15 cm soil depths. Andriesse and Schelhaas (1987) also reported soil carbon losses as large as 21 Mg C ha^{-1} in Thailand and 15 Mg C ha^{-1} in Sri Lanka following slash-and-burn forest conversion. Similarly, Guo and Gifford (2002), who conducted a meta-analysis covering 74 publications studying the conversion of forest to cropland found significant declines of soil C in the range of 40-50%.

Contrary to the above findings, other reports (e.g. Ewel *et al.,* 1981; Koto-Same *et al.,* 1997; Kauffman *et al.,* 1998) have emphasized that soil carbon pools remain approximately constant during most land conversion practices in the tropics. These and other mixed reports of soil organic matter stability during slash and burn illustrate the difficulty in generalizations about soil organic matter, and may well be further complicated by erosion subsequent to land clearing (Palm *et al.,* 1996; Nye and Greenland, 1960). It appears that the stability of soil organic matter in lands undergoing conversion by slash and burn is by no means universal. According to Koto-Same *et al.,* (1997), the magnitude and direction of change is likely to depend on the soil type and initial C content, the history of land-use, the new land-use system and the sampled depth. Carbon stock changes (0-60 cm) in this study were not significant probably because the standard reference is a secondary forest fallow and not an undisturbed natural forest. It is likely that if comparisons had been made with a natural forest, differences would have been significant for the studied depth. Significant reductions in concentrations of organic C and N and levels in the surface soil layers (0-10 and 10-20 cm depths) could be due to rapid mineralization during the first two-three years after land disturbance as a result of increased surface temperature.

Though C stocks (0-60 cm depth) remained relatively stable in this study, the general trend towards an increase in total carbon, albeit, insignificantly does suggest that with time, the system may accumulate more soil carbon. For organic C the fitted functions explained only 30% of the variation with time. Much of the remaining unexplained variability is probably due to local soil differences, sampling and laboratory errors. The stability of organic C fractions in converted forests may be due to the C stocks in soils being physically protected from massive loss during felling and burning and may increase due to entry of incompletely combusted particulates depending on the intensity of the burn (Andriesse and Schelhaas, 1987). Furthermore, decaying roots from felled and burned forest vegetation may contribute to soil organic matter following conversion to agriculture under annual and plantation crops.

Total soil nitrogen stocks of 8.4, 4.5, 5.1 and 7.3 Mg ha^{-1} recorded for the forest, 3, 15 and 30 year-old plots respectively and is comparable to the 7.6 Mg ha^{-1} (0-60 cm soil depth) in a 22-year-old cocoa system reported by Opakunle (1989) in a similar forest zone in South Western Nigeria. Total concentration of N (0-10 cm depth) declined significantly at 3 years probably due to mineralization followed by leaching after forest clearance and subsequent reduction in shade. Total stocks (0-60 cm) however did not differ between land-uses when bulk density of the different layers was taken into account. No differences in total stocks between land-uses were expected. Although large amounts of biomass residue are being added to the system as it matures (Isaac *et al.,* 2005), and rainfall can potentially add nitrogen to the soil, several pathways of nitrogen loss exist within agroforestry systems (Santana and Cabala-Rosand, 1982). 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 and subsequent reduction in shade intensity. According to Ofori-Frimpong *et al.,* (2007), significantly higher nutrients particularly N and P are found in soils under shaded-farms compared to unshaded farms probably because of efficient nutrient cycling prosess under shaded farms.

4.4.8 *Effect of forest conversion on soil phosphorus and base cation stocks*

Measured P stocks in the 0-60 cm soil depth remained relatively stable up to 15 years but had declined significantly by 30 years. This can be attributed to nutrient exports through harvest and P fixation (immobilization) in insoluble forms as organo-mineral complexes (Walker and Seyers, 1976). While soil stocks decreased, stocks in plant biomass appeared to increase. This may be attributed to relocation from below to above-ground pools. Greater stocks in surface layers can be explained by the release of organically bound P after burning especially at 3 years and release from decomposing litter. Organic matter normally accounts for up to 50% of the total phosphorus in the surface horizons of tropical soils and may represent 60-80% of the total soil phosphorus in highly weathered Oxisols, Ultisols, and Alfisols (Sanchez, 1976). Organic phosphorus circulates rapidly between plant and soil via the litter, and its release through decomposition can be an important regulator of productivity (Hedley *et al.*, 1982). Ahenkorah *et al.* (1987) observed that available P dropped to 68 per cent of their initial values on acrisols in the Eastern region of Ghana. Phosphorus is the primary limiting nutrient for crop production in weathered tropical soils, because of sorption of phosphate onto Al- and Fe-hydroxides where it is potentially, but not readily available to plants (Cardoso *et al.*, 2003).

Measured K, Ca and Mg stocks in the 0-60 cm soil depth along the chronosequence indicated that on the average base cations either remained stable as in the case of K or showed the tendency to increase as in the case of Ca and Mg. Ahenkorah *et al.* (1974) have noted that cocoa growing soils were well buffered against K depletion. Total stocks of base cations Ca and Mg in the entire studied depth at 3 years after conversion were greater compared to forest. This pattern was most likely as a result of the initial burning of above-ground biomass during land preparation, resulting in high input of bases through ashes in the early years after conversion. Increases in extractable K, Ca and Mg caused by the addition of plant ash after burning in shifting agriculture in Eastern Amazonia has also been reported by Hölscher *et al.*, (1997). However, this high base cation stock along the chronosequence in older cocoa farms (15 and 30 years) cannot be explained by ash input through burning alone because in shaded-cocoa farms burning is not part of the management on established farms. The sustained high levels with time seem to be the result of an on-going process. One hypothesis that may explain this is the "nutrient pumping" effect of deep rooting cocoa and shade trees in the cocoa system:

decomposition of leaf litter from litterfall and the frequent brushing and subsequent decomposition of understory vegetation brings nutrient that were taken from deeper soil layers by tree roots to the top soil layers. Dechert (2003) and Ahenkorah *et al.* (1987) observed that there were no appreciable changes in exchangeable Ca and Mg after 20 years of cropping on an Acrisol in the Eastern Region of Ghana.

4.4.9 Effect on total system carbon and nitrogen stocks

The total system (above and below-ground including fine roots) C stock of the original forests averaged across three sites was 165 Mg C ha^{-1} with 97 Mg C ha^{-1} contained in above-ground (tree biomass, surface litter and under-storey vegetation) pools. The greatest loss in system C stocks resulted from land preparation prior to first cultivation with an average of 65 per cent of total stocks being lost from the system. Most of this loss is attributable to the destruction of natural vegetation. However, by 30 years after forest conversion, cocoa system had re-accumulated up to 151 Mg C ha^{-1} primarily stored in established trees (both cocoa and shade trees) and soil pools. The carbon pool most vulnerable to loss when forests are converted to cocoa land-use is above-ground biomass as 92% of above-ground C was lost three years after conversion of the forest. These results illustrate the tremendous impact that shaded-cocoa systems have on C re-accumulation and the importance of minimizing forest conversion to less complex systems. Annually, between 3 and 15 years after land conversion, the entire cocoa system had a carbon fixation rate of 5.4 Mg C $ha^{-1}y^{-1}$ and between 15 and 30 years, the carbon fixation rate was reduced to 2.0 Mg C $ha^{-1}y^{-1}$.

Although reductions in above-ground N pools during conversion of forests to cocoa land-use were substantial (94%), the fractions of total system N losses were relatively smaller (approximately 57%) compared to C losses within 3 years after conversion of forest. This was because the vast majority of N pool was located in soils and was not significantly altered by land-use change compared to the above-ground pool. Along the chronosequence below-ground N pools were consistently larger than above-ground pools. The observed dynamics of C and N pools are similar to findings of other studies that demonstrated that changes in ecosystem pools are primarily driven by losses of above-ground biomass while soil pools of elements are affected to a smaller degree (Kauffman *et al.,* 1995, 1998; Trumbore *et al.*, 1995).

4.4.10 Effect of forest conversion on microbial biomass C, N, and P.

Mean annual microbial biomass carbon C, N and P did not show any significant variations between the different land-uses. This was rather contrary to what was expected especially when organic carbon in the 0-10 cm soil depth differed between treatments. According to Sharma and Sharma (2004), land transformations that lead to reduced plant biomass and organic carbon may lead to reduced microbial biomass. The non-significant differences in microbial biomass recorded could most probably be due to the high variability between individual microbial biomass values (rainy and dry season values) from which the annual averages were computed. Nutrient ratio of microbial biomass C:N ranged from 2.1 in forest to 5.8 in 15-year-old cocoa systems respectively.

The microbial C:N ratio is often used to describe the structure and the state of the microbial community (Singh and Yadava, 2006). Jenkinson & Ladd (1981) reported that fungi and bacteria have considerably different microbial C:N ratio i.e. ratio of the fungal hyphae is often 10-12 and that of bacteria usually between 3-5. A high microbial C:N ratio indicates that the microbial biomass contains a higher proportion of fungi, whereas low value suggested that bacteria predominate in the microbial population (Campbell *et al*. 1991). In the present study, the mean microbial biomass C : N ratios of 2.1, 4.8, 5.5 and 5.4 in forest, 3, 15 and 30-year-old cocoa systems respectively indicate that bacterial population predominates in the 0-10 cm soil depths on all sites. Conversion form forest to cocoa system did not impact on the composition of microbial community.

The microbial biomass C, N and P pools in the different land-uses were significantly affected by the rainy and dry seasons. Microbial biomass was higher in the rainy season compared to the dry season. This contrasts with several other studies (e. g. Singh and Yadava 2006; Sharma and Sharma 2004; Barbhuiya *et al.*, 2004) which reported higher microbial biomass C, N and P for dry winter seasons and lower values during the rainy season. Explanations offered for this trend include possible run-off losses of microbial propagules along with the plant materials due to heavy rainfall (Shukla *et al.*, 1989) and strong demand for these nutrients by the plants that grow vigorously during the rainy period (Singh and Yadava 2006; Sharma and Sharma 2004). It appears from the present result that, the early weeks preceding the peak of the rainy season generally experience increased microbial biomass. Lodge *et al.*, (1994), citing from the works of Luizao *et al.*, (1992) emphasized that rewetting of seasonally dry Amazonian forest soil resulted either in immobilization of nutrients or large pulse of nutrient, particularly N mineralization. It is here hypothesized that, increase in microbial biomass may be attributed to microbial nutrient flush at the start of the rainy season. It is very likely that, microbial biomass would reduce during the peak of the rainy season when plant growth would optimal and nutrient demands would be strong. Seasonality therefore plays an important role in microbial C, N and P turnover (Wagai *et al.,* 1998). This indicates the dynamic nature of C and N circulation on the forest floor and the importance of microbial populations for nutrient conservation, regeneration and management. Li *et al.* (2005) similarly found that in secondary forests and pine plantations, microbial biomass was greater in the wet season compared to the dry season. The observed responses of the soil microbial biomass to the start of the rainy season in the forests under study have important consequences for nutrient cycling in these seasonal ecosystems. Microbial biomass reflects the degree of immobilization of carbon and nitrogen. A decrease in soil microbial biomass could result in mineralizing of nutrients, while an increase in microbial biomass may lead to immobilization of nutrients (McGill *et al.,* 1986).

Highly significant correlationships ($P < 0.05$) between microbial biomass C, N and P and soil organic carbon in the 0-10 cm soil depth show that microbial biomass is highly influenced by soil organic nutrient (Singh and Yadava, 2006) in both forest and cocoa ecosystems, and that the successional dynamics of these elements were closely interlinked in nutrient-poor tropical soils and that microbial immobilization and mineralization have a close relationship with carbon and nitrogen in soil. It further suggests that organic matter is an important factor in the build-up and development of soil microbial biomass carbon and nitrogen. Consequently, a close relationship has also been reported between soil fertility and microbial biomass (Arunachalam, 2003; Hofman *et al.,* 2004), because the high level of organic matter supplied enough carbon, nitrogen and energy source to microbial growth. There is no reported work from cocoa systems that the present results can be compared with. Positive relationship between microbial C, N and P and soil organic C, total N and P in grassland and agroecosystem have however been reported by Singh and Singh (1995), Ghoshal and Singh (1994) and Moore *et al.*, (2000).

4.4.11 Effect of land-use change on soil degradation along the chronosequence

Despite the apparent stability of stocks of soil C and nutrients (0-60 cm) along the chronosequence, results of this study showed that clearing of lixisols for cocoa cultivation in the semi-deciduous forests of Ghana results in some land quality decline prior to canopy closure at 3 years. Analysis of total soil quality at each stage of the chronosequence using degradation indices (DIs) which incorporated other parameters like bulk density, CEC and base saturation %, revealed that overall, soil quality declined to levels below the condition of forest soils 3 years after conversion of forest. This is caused by forest clearing and land preparation methods followed by crop harvesting activities, brushing of undergrowth that may have strong influence on pH, bulk density and organic matter, which remain significantly greater in forest soil throughout the duration plantation. Deterioration in soil physical properties such as bulk density and pore space particularly in the surface horizons is due to the frequent human traffic associated with farm management practices has been cited as contributing to the deterioration (Lemenih *et al.,* 2005). It is important to mention that the land-use system in the area is not only spatially but also temporally dynamic. Numerous small adjustments are continuously being made to the production processes. Though slowly and with limited success, these farmers are able to adapt their production system to different socio-economic and biophysical circumstances. Conscious efforts need to be made at this stage to adopt practices that would minimize soil quality degradation. For instance burning could be limited to only woody and such components as would hinder farmer access to land at planting. As much as possible, leaf litter and other biomass fractions that do not hinder farmer access to land should not be burnt.

4.5 Summary and conclusions

This study has quantified the effect of land-use change from forest to cocoa system on biomass, carbon and nutrients, and pools in above and below-ground compartments.

Biomass, carbon and nutrients in tree biomass, under-storey vegetation, surface litter and biomass of fine roots significantly declined immediately after conversion of the forest. Above-ground biomass and carbon is the larger pool and is more vulnerable to losses when forests are converted to agro-systems compared to soil stocks.

Soil pools in the entire studied depth (0-60 cm) remained relatively stable across the chronosequence. The role of cocoa shaded-cocoa systems in carbon sequestration is demonstrated under a changing climate. Between 3 and 30 years after conversion, the cocoa system (above ground and soil pools) can sequester about of 3.6 Mg C $ha^{-1}yr^{-1}$. By 30 years after forest conversion, cocoa system could store 95% of carbon and 76% of nitrogen in the secondary forest system.

Soil exchangeable Ca, K and Mg stocks remained more or less stable with a tendency to improve presumably because of “nutrient pumping” effect of deep rooting cocoa and shade trees in the cocoa system and the addition of nutrients to the soil surface through decomposition of leaf litter (Dechert, 2005). Significant decline in available P stocks at 30 years imply that levels of this nutrient shift from sufficient at early growth to insufficient as cocoa system ages, suggesting that these systems do not meet P requirements over time. Microbial biomass C, N and P demonstrated a strong seasonal variation but conversion of forest did not result in a significant decline across the chronosequence.

Cocoa pod husks constitute an important under-utilized nutrient pool in cocoa systems. If redistributed appropriately, could be useful in marginally increasing stocks of available plant nutrients especially N and K.

The study has also shown that soils in the semi-deciduous forest zone cleared for shaded-cocoa cultivation go through a degradation stage during the plantation development phase. This might affect the long-term productivity of the system. Management strategies adopted at this stage should be geared towards minimizing adverse effects that may lead to degradation in soil quality. The adoption of conservation-oriented land preparation strategies are required if degradation of soil quality during plantation development phase is to be minimized.

To design appropriate and cost-effective management options to stabilize nutrient stocks in perennial cropping systems like cocoa, there is the need to understand also the dynamics of nutrient flows between compartments in the system. In the literature, many nutrient flow exercises treat soil dynamic processes as a 'black box', a not-too-satisfactory approach (Gichuru *et al.,* 2003). In this approach, nutrient depletion or enrichment of the system is simply assessed taking into consideration the nutrient inputs (i.e., mineral fertilizer, organic inputs, deposition, biological fixation, sedimentation) and outputs (i.e., harvest exports, leaching, gaseous losses, erosion, etc) without paying attention to the processes within the box: internal recycling. In the next chapter, I examine the processes within the 'box' by investigating dynamics of nutrient recycling through litterfall and turnover of fine roots, as well as factors driving the recycling process.

CHAPTER 5

LITTERFALL AND LITTER NUTRIENT DYNAMICS UNDER SHADED-COCOA SYSTEMS IN A HUMID SEMI-DECIDUOUS FOREST IN GHANA

Abstract

Few studies have assessed changing processes occurring in forest floor litter following conversion to plantation crops such as cocoa. Using litter traps and sampling quadrats, this study investigated litterfall production, standing litter changes, gross litter decomposition and nutrient return through turnover of fine roots along a chronosequence (natural forest, 3, 15 and 30-year-old shaded-cocoa) in a moist semi-deciduous forest in the Ashanti Region. Mean annual litterfall production differed significantly among land-uses and ranged from 5.0 to 10.4 Mg DM ha^{-1}. Similarly, standing litter differed significantly between land-uses. Estimated inputs from litterfall production was 4 – 165 kg $ha^{-1}yr^{-1}$ for P and Ca in 15-year-old and forest plots respectively while inputs from turnover of fine roots varied from 2 kg P to 47 kg Ca $ha^{-1}yr^{-1}$ in 3 and 30-year-old shaded-cocoa systems respectively. There were significant differences in quality between litter from forest and litter from cocoa plantations. Litterfall from forests had greater concentrations of nitrogen and smaller concentration of soluble polyphenols and lignin compared to litter from cocoa systems. Monthly decomposition coefficients (*k)* were estimated as $k = (A - (L_1\text{-}L_0))/ ((L_1+L_0)/2)$, where A is litterfall production during the month, L_0 is the standing litterstock at the beginning of the month and L_1 is the standing litterstock at the end of the month. Annual decomposition coefficients (k_L) were similar in cocoa systems (0.221-0.227) but higher under secondary forests (0.354). Correlations between litter quality parameters and the decomposition coefficient showed N and lignin concentrations as well as ratios that include N are the best predictors of decomposition for the litters studied. The results support the hypothesis that decomposition decreases following forest conversion to shaded-cocoa systems because of litter quality changes.

The study also showed that standing litter pools and litterfall production in recently converted cocoa plantations are low compared to secondary forests or mature cocoa systems. Management strategies involving the introduction of upper canopy species during plantation development with corresponding replacement of tree mortality with diverse fast growing species will provide high quality and quantity litter resources.

Key words: Cocoa, litterfall production, standing litterstocks, decomposition.

5.1 Introduction

Litterfall and litter decomposition and subsequent nutrient release represent major biological pathways for element transfer from vegetation to soils, and play an important role in regulating nutrient cycling, and in maintaining soil fertility in forest and agro-ecosystems (Yang *et al*,. 2003). Forest litter acts as an input-output system of nutrients and the rates at which forest litter falls contribute to the regulation of nutrient cycling, fertility sustenance and primary productivity in forest and tree-based ecosystems (Ranger *et al*,. 2003; Berg, 2000). In Ghana, cocoa has re-emerged as an important export and cash crop. For majority of farmers, fertility of soils under cocoa plantations is maintained through the recycling of nutrients back through leaf fall and decomposition of leaf litter (ISSER 2004; Appiah *et al.,* 2006). The decomposition process is influenced by a number of factors. These are: (1) microclimate, mainly temperature and humidity, (2) litter quality, (3) soil nutrient content and (4) the qualitative and quantitative compositions of decomposer communities. (Anderson and Swift, 1983). These factors interact to determine the rates of decomposition.

Despite many studies carried out on litterfall and decomposition dynamics, in both tropical and temperate forests (Isaac *et al.,* 2005; Martius *et al.,* 2004; Ranger *et al.,* 2003; Berg 2000), few attempts have been made to assess ecological processes in standing litter under shaded-cocoa systems. In shaded cocoa systems, no study to date has assessed parameters of litter dynamics along a chronosequence with forest as a reference. Thus, it is vital to understand the nutrient dynamics of litter in these ecosystems (Isaac *et al*, 2005; Appiah *et al.,* 2006; Schroth, 2003) to advice small farmers who depend on natural nutrient recycling for fertility sustenance. The present study was carried out to measure comparatively litterfall, litterstock, litter decomposition and turnover of fine roots and how they influence nutrient cycling in shaded-cocoa systems as the plantations age.

It was hypothesized that litter pools (stand litterstocks) and litterfall production in recently converted cocoa plantations will be low compared to forests or mature cocoa systems, and decomposition rates will correlate to litter quality in cocoa ecosystems. It was also expected that forest litter decomposition rates would be more rapid due to specific litter dominance of higher quality.

The specific objectives were to:

(i) Measure the production and accumulation of litter in forest and cocoa ecosystems.

(ii) Quantify potential nutrient return through litterfall under forest and cocoa land-use.

(iii) Compare decomposition of litter under forest and shaded-cocoa ecosystems and

(iv) Estimate production of fine roots and nutrient contribution through turnover of fine roots.

5.2 Materials and methods

5.2.1 *Site Description*

A description of the study sites including climate, vegetation and dominant soil types and the approach adopted for the study are in sections 2.1, 2.2, 2.3 and 2.4 of the general methodology in Chapter 2.

5.2.2 Litterfall sampling

Litterfall was collected monthly by pooling together fortnightly samples using 0.25m^2 litter traps (Anderson and Ingram, 1993). Litter traps consisted of 50 cm x 50 cm wooden-framed open boxes, 30 cm high with 1mm nylon screen mesh base. Each trap was raised on four preservative-treated wooden stands 10 cm above the forest litter floor to prevent decay (Plate 5.1). Four litter traps were established in each plot at three replicates for four land-use chronosequence ages giving a total of 48 litter traps or 12 litter traps per chronosequence age. To improve representativeness of plot means, the litter traps were distributed randomly within the experimental plots and their positions changed from time to time (Schroth, 2003) throughout the study period. The collected litter was manually separated into different fractions; leaves, twigs and branches and floral parts (flowers and seeds), weighed and then oven-dried at 65°C for 48hours for dry weight determination. Monthly values of litterfall for each land-use were summed up to obtain the annual litterfall at each site. Sampled material from each treatment plot was returned to the laboratory every 4 months for nutrient analysis.

5.2.3 Stand litter decomposition coefficients

The decomposition coefficient can be estimated from the annual litterfall and the stand litterstock on the forest floor (determined in chapter 4, section 4.2.3). The monthly decomposition coefficient k for each land-use was calculated as:

$$k = (LF - (LS_1 - LS_0)) / ((LS_1 + LS_0)/2) \qquad (5.1)$$

(formula simplified after Olson, 1963)

where LF is litterfall during the month, LS_0 is the stand litterstock at the beginning of the month; LS_1 is the litterstock at the end of the month (Bernhard-Reversat, 1993). Monthly values of (k) for each land-use were summed up to obtain the annual decomposition coefficient (k_L) at each site.

5.2.4 Measurement of fine roots productivity

Sampling holes approximately 10 cm in diameter and 30 cm deep were carefully dug using a 25 cm long digging chisel. In-growth tubes/cylinders (PVC pipes 30 cm tall; 8.5 cm diameter and 5 mm grid/mesh size) were inserted into the sampling holes and then filled with root-free soil collected from the same depth and packed to an approximate bulk density of 1.0 g cm^{-3} (Plate 5.2). Instead of installing all the in-growth tubes at the beginning of the study and extracting subsets at sequential time intervals, twelve in-growth tubes at one per plot or 3 tubes per land-use chronosequence were buried in the top 30 cm of soil at random locations at the beginning of each time period and extracted at the end of pre-determined period. A time-period of 30-45 days was chosen to reduce the possible overestimation of short-term fine root growth rates and to minimize the likelihood of death and decomposition of any fine roots that grew into the in-growth cores (Idol *et al.,* 2000). Fine roots were separated from the soil using the wet sieving (0.5 mm grid) method (Böhm, 1979). A correction factor for the soil adhering to the fine roots (FR) was determined for each sampling date by incinerating (650^{o}C; 8 h) three sub-samples (0.3 g) from the bulked sample of all FR recovered from each treatment. Annual fine root productivity in the top 30 cm of soil was estimated by multiplying the mean daily mass of roots that grew inside the cores at each sampling by 365 days.

5.2.5 Light transmission and canopy cover measurement

Estimates for percent canopy closure/light transmission under the cocoa strata were based on image analysis. Canopy closure was measured using a hemispherical lens (180-degree equidistant fisheye lens) attached to a digital camera (Nikon Cool Pix 950) mounted onto a tripod set approximately at DBH. The camera was oriented in a north-south direction for each photo. For each plot, ten (10) shots were taken at random points about 5.0 meters from each other along a diagonal transect across the plot. The hemispherical photographs were analyzed with gap light analysis software (Gap Light Analyzer, Version 2.0 1999).

5.2.6 Chemical analysis

All samples were oven-dried (65^{o}C, 48 hours) and ground to pass through 0.5 mm mesh. Composite samples of litterfall and fine root samples from each land-use were analyzed for carbon and major nutrients (N, P, K, Ca and Mg) in triplicate. Carbon was determined by wet oxidation method (Walkley and Black 1934), total N using the standard micro-digestion method (Kjeldahl) with colorimetric determination by spectrophotometer, P by the Bray and Kurtz (1945) method, and Ca, Mg and K were analyzed by atomic absorption spectrophotometry. Lignin content of 1 g ground dried (60^{0}C) litterfall material was determined by alcohol extraction after acid digestion (72% H_2SO_4) and correction for ash following the acid detergent fiber method of Van Soest (1963). Total soluble polyphenols (PP) was determined according to Anderson and Ingram (1998) after extracting with 20 ml methanol.

5.2.7 Data Processing and analysis

The analysis of variance (ANOVA) was used to test for significant effects of land-use on total litterfall, litterstocks, microbial biomass, litter quality and turnover of rates of fine roots using STATISTIX 7.0 (Analytical Software, 2000). Multiple comparisons were determined with the Tukeys HSD test at a significance level of 0.05. Monthly variations in litterfall, litterstocks and litter turnover coefficients with time were portrayed graphically. Regressions and correlations were also employed as tools for statistical tests to establish trends and relationships between parameters. The monthly potential nutrient input to the forest floor through each litter fraction was computed by multiplying monthly values of each fraction mass with its corresponding mean nutrient concentrations. Annual potential nutrient input was the sum of monthly nutrient inputs based on 12 monthly estimations. Fine roots turnover rate or renewal was calculated as (FR productivity/FR biomass) for each treatment (Cavelier 1989, cited by Muñoz and Beer, 2001). Turnover rates of fine roots (kg $ha^{-1}year^{-1}$) was estimated as the product of the turnover rate and productivity. Nutrient inputs from fine roots were estimated on an annual basis by multiplying annual FR turnover by corresponding FR nutrient concentrations from each land-use.

Plate 5.1 Collection of litterfall using 50 cm x 50 cm x 30 cm litter boxes.

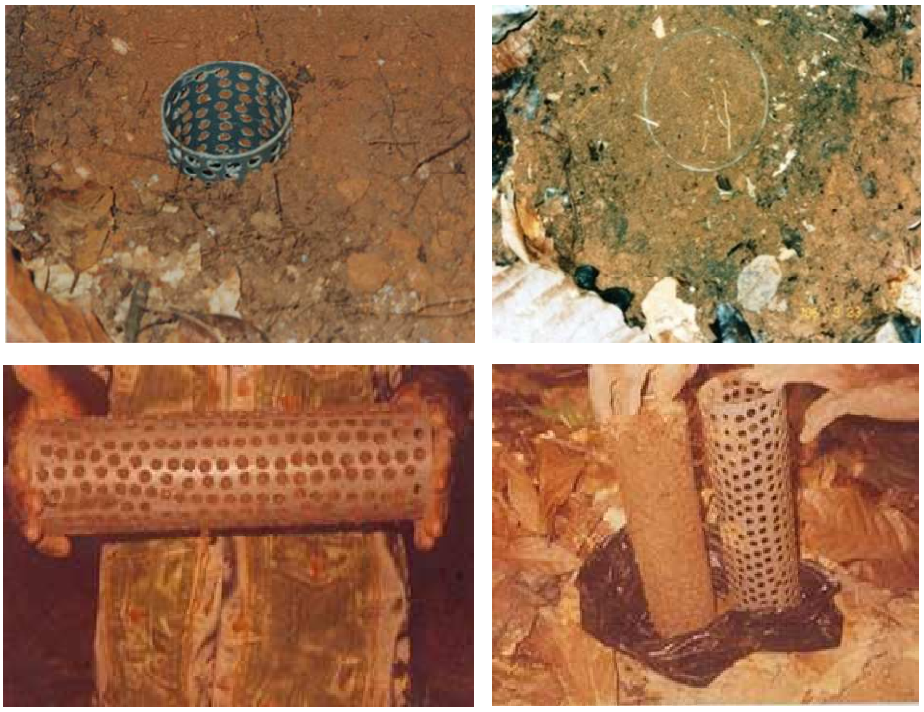

Plate 5.2 Installation and extraction of PVC in-growth tubes for the determination of fine roots productivity and turnover using the modified in-growth bag technique.

5.3 Results

5.3.1 Litterfall production

Monthly patterns of litterfall were similar among the treatments with peaks during the dry period (Nov-Feb), and dips during the rainy period (May –July and Sept Oct) (Figure 4.1). Differences in total annual litterfall were significant ($F_{3, 95} = 20.41$, $P < 0.001$) among land-use types. Annual litterfall was largest in forest and 30-year-old cocoa systems compared to the 3 and 15-year-old cocoa systems. Litterfall exhibited monthly/temporal patterns indicating greater rates of litterfall during the dry season (Fig. 5.1). Mean seasonal litterfall differed significantly ($F_{3, 47} = 6.48$, $P=0.0291$) between the rainy and dry periods.

Litterfall composition

There were significant differences in leaf litter ($F_{3, 71} =12.34$, $P < 0.001$), twigs and small branches ($F_{3, 71} = 9.8$, $P < 0.001$) and floral/ reproductive parts ($F_{3, 71} =27.21$, $P < 0.001$) among the land-uses. Leaves always represented the largest fraction in both forest and cocoa systems (Table 5.1). Three-year-old land-use produced the least litter for all the litter fractions.

5.3.2 Litter decomposition coefficient

Monthly decomposition coefficients among land-uses ranged from 0.022-0.685 (Figure 5.1). The average annual decomposition coefficients differed significantly ($F_{3, 23}=12.67$, $P=0.003$) between land-uses with coefficients in the cocoa systems being significantly smaller than in

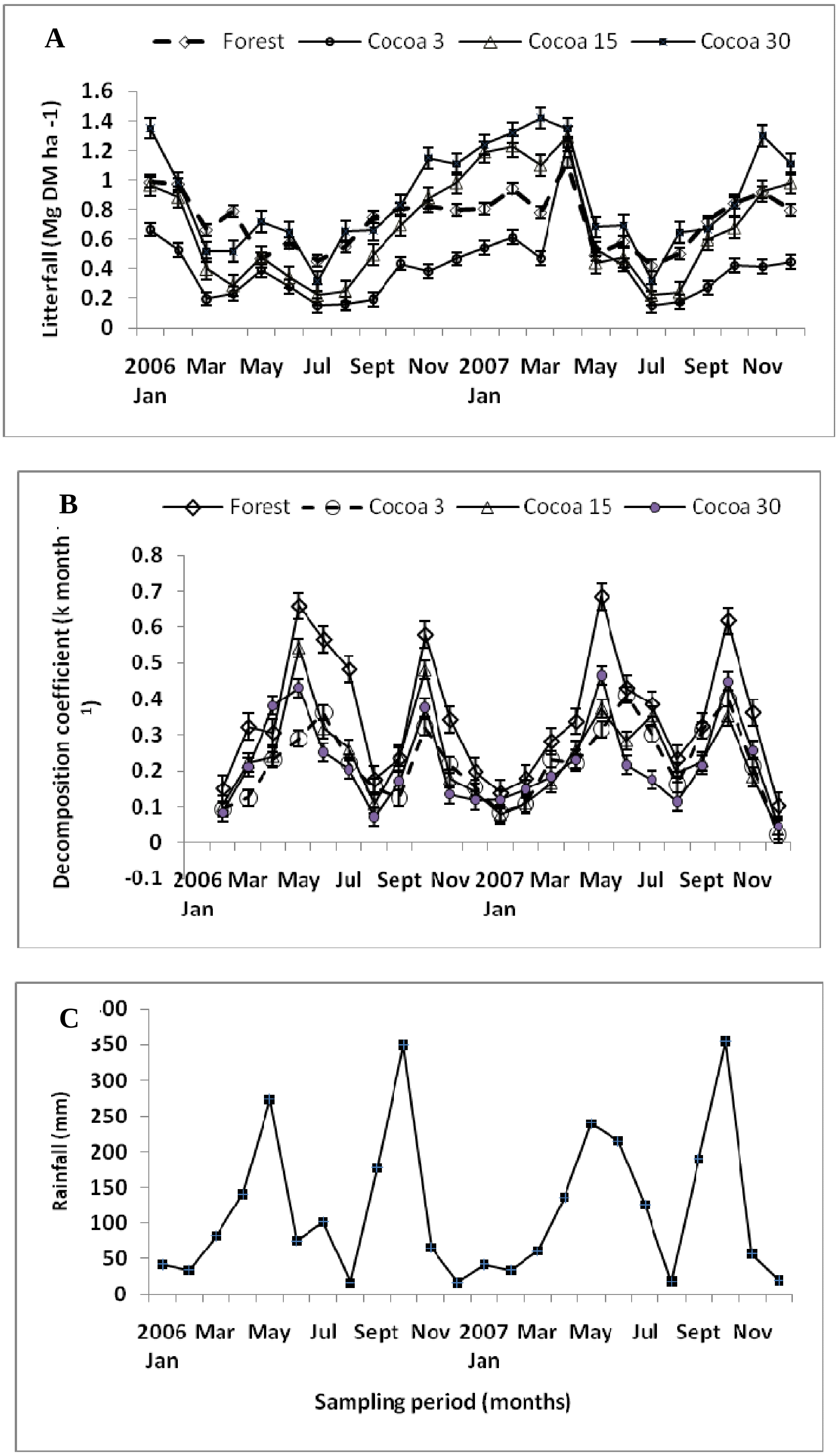

Figure 5.1 (A) Monthly litterfall production (Mg ha^{-1}), (B) decomposition coefficients (k) and (C) rainfall (mm) for study sites.

Table 5.1 Quantity (Mg $ha^{-1}yr^{-1}$ ± SEM) and composition (%, in parenthesis) of litterfall fractions in forest and cocoa land-use systems in the Nwabiagya District, Ashanti Region, Ghana

Land-use	Leaf	Twigs & small branches	Reproductive parts	TOTAL
Forest	6.9 ±0.32^{ab} (78.4)	0.9 ±0.12^{a} (10.2)	1.0± 0.09^{a} (11.4)	8.8 ±0.36^{ab} (100)
Cocoa 3 years	4.6± 0.37^{c} (92.0)	0.06± 0.04^{b} (1.2)	0.3± 0.03^{b} (6.0)	5.0(± 0.39^{c} (100)
Cocoa 15 years	6.7± 0.53^{b} (81.7)	0.7± 0.11^{a} (8.5)	0.8± 0.07^{c} (9.8)	8.2(± 0.61^{b} (100)
Cocoa 30 years	8.4± 0.46^{a} (80.5)	1.0± 0.16^{a} (9.0)	1.0± 0.09^{a} (10.5)	10.4± 0.58^{a} (100)

Mean parameters for the different land-uses with the same superscript are not significantly different at $P < 0.05$ level using Tukey's HSD range test.

Table 5.2 Estimated standing litterstock (Mg DM ha^{-1} ± SE), decomposition coefficient, residence time and canopy openness in forest and cocoa land-use systems in the Nwabiagya District, Ashanti Region, Ghana.

Parameter	Land-use			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Litter standing crop (LS) (Mg DM ha^{-1})	4.6^{a} (± 0.63)	3.6^{b} (± 0.31)	5.8^{a} (± 0.46)	5.9^{a} (±0.42)
Annual decomposition coefficient (k_L yr^{-1})	0.354^{a} (± 0.07)	0.217^{b} (± 0.03)	0.237^{b} (± 0.03)	0.221^{b} (± 0.02)
Mean residence time (MRT) ($1/k_L$ years)	(2.8)	(4.6)	(4.2)	(4.5)
Canopy openness (%)	12.7^{a} (±2.34)	14.8^{b} (±1.88)	9.7^{c} (±1.58)	12.3^{a} (±1.95)

Mean parameters for the different land-uses with the same superscript are not significantly different at $P < 0.05$ level using Tukey's HSD range test.

the forest systems (Table 5.2). Openness of canopy differed significantly ($F_{3,\ 11}$=4.08, P=0.032) among treatments and was largest in 3-year-old cocoa plots.

5.3.3 *Initial chemical composition of leaf litter and litter quality*

Polyphenol (PP) concentrations were similar in cocoa systems but significantly greater ($F_{3, 31}$ =11.15; P=0.0009) than in forests (Table 5.3). Lignin (L) concentration was similar in 3, 25 and 30-year-old plots but significantly greater ($F_{3, 31}$=10.22; P=0.0013) compared to the forest plot. Initial leaf litter N concentrations differed significantly among the four land-uses ($F_{3, 31}$ = 26.92; P < 0.0001) (Table 5.5). While L:N ratios were significantly greater ($F_{3, 31}$ =43.78; P < 0.0001) in 3 and 15-year-old shaded-cocoa systems compared to forest and 30-year-old shaded-cocoa system, PP:N and PP+N:N ratios were similar in all shaded-cocoa systems though there was a clear trend towards decreasing ratios with increasing age of stand. C:N ratios were similar in 3 and 15-year-old shaded-cocoa systems but significantly greater ($F_{3, 31}$ = 30.68; P = 0.000) than in both forest and 30-year-old shaded-cocoa systems. Most of the litter quality parameters were correlated with the decomposition coefficient with significant positive correlations for N and significant negative correlations for C:N, L, L:N, PP:N and PP+N: N ratios (Table 5.4).

5.3.4 *Potential nutrient return through litterfall*

Returns of nutrients to the forest floor increased (except for P) with duration after conversion and attained a maximum in forest and 30-year-old shaded-cocoa system (Table 5.5). Except for K and Mg, forest land-use had the greatest potential return of all nutrients through litterfall and decreased in the order Ca > N > Mg > K > P in forest, 3 and 15-year-old and in the order Ca > N > K > Mg > P in 30-year-old plots (Table 5.5)

Table 5.3 Chemical composition of leaf litter from forest and cocoa land-use systems.

Composition	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Lignin (mg g^{-1} DM)	112 ± 9.4^{b}	141 ± 1.1^{a}	146 ± 0.05^{a}	143 ± 0.3^{a}
Polyphenol (mg g^{-1} DM)	18 ± 1.5^{b}	27.1 ± 1.0a	27.7 ± 1.8^{a}	33.9 ± 2.9^{a}
C (mg g^{-1} DM)	433 ± 7.2^{a}	426 ± 13^{a}	428 ± 18^{a}	436 ± 24^{a}
N (mg g^{-1} DM)	17.0 ± 0.6^{a}	9.5 ± 0.2^{b}	10.0 ± 0.4^{b}	14.8 ± 0.8^{a}
Polyphenol/N Ratio	1.06 ± 0.08^{b}	2.93 ± 0.04^{a}	2.77 ± 0.23^{a}	2.36 ± 0.35^{a}
P+N/N ratio	2.06 ± 0.08^{b}	3.86 ± 0.06^{a}	3.78 ± 0.23^{a}	3.37 ± 0.35^{a}
C/N Ratio	25.6 ± 1.1^{b}	45 ± 0.71^{a}	42.9 ± 1.5^{a}	31.6 ± 2.65^{b}
L:N Ratio	6.61 ± 0.55^{b}	14.9 ± 0.2^{a}	14.7 ± 0.61^{a}	9.9 ± 0.89^{b}

Mean values for the different land-uses with the same superscript are not significantly different at $P < 0.05$ level using Tukey's HSD range test. (N=4 and DM is dry matter)

Table 5.4 Correlations between the decay coefficient (k_L) and parameters of litter quality, and canopy openness in the forest and shaded-cocoa stands.

Parameters of litter quality	R	P
Polyphenol	-0.67	0.320
Lignin	-0.89	0.023*
Nitrogen	0.98	0.018*
C:N Ratio	-0.82	0.012*
Polyphenol:N Ratio	-0.11	0.001*
Lignin:N Ratio	-0.97	0.003*
Polyphenol+N:N Ratio	-0.60	0.048
Canopy openness	0.62	0.381

* Significant at $P < 0.05$; R= Correlation coefficient P=Probability Level

Table 5.5 Potential quantities of nutrients (kg $ha^{-1} yr^{-1}$) returned to the soils annually by litter fractions in litterfall.

Land-uses	kg $ha^{-1}yr^{-1}$				
	N	P	K	Ca	Mg
Forest					
Leaf	117 ± 8.2	7.6 ±1.1	26.2 ± 2.5	131 ± 12.1	29.0 ±1.3
Twigs	15.3 ±1.7	0.7 ±0.08	3.0 ± 0.66	15.2 ± 1.0	2.4 ± 0.12
Floral parts	20.4 ±2.3	1.5 ±0.05	2.6 ± 0.54	18.1 ± 1.3	4.4 ± 0.2
Total	153.0	9.8	31.8	165.0	35.8
Cocoa 3 years					
Leaf	43.7± 2.4	4.14±0.75	10.6 ±1.0	72.7 ±3.5	29.9 ±1.6
Twigs	0.54±0.11	0.04±0.00	0.54±0.15	0.73±0.11	0.35 ±0.08
Floral parts	0.89±0.11	0.12±0.05	0.60±0.12	0.70 ±0.11	0.31±0.06
Total	44.8	4.30	11.7	74.1	30.6
Cocoa 15 years					
Leaf	68.0 ±4.8	3.12 ±1.0	21.8 ±2.6	121 ±9.7	53.0 ± 2.5
Twigs	4.86 ±1.0	0.42 ±0.08	5.16 ±1.0	7.98 ±1.1	3.24 ±0.6
Floral parts	6.48 ±1.3	0.56 ±0.12	6.88 ±1.0	10.6 ±1.3	4.32 ±0.6
Total	79.3	4.10	33.8	139.7	60.6
Cocoa 30 years					
Leaf	104 ±12.5	2.7 ±1.0	45.4 ±3.2	126.0 ±12.4	42.8 ±4.2
Twigs	10.0 ± 1.7	0.6 ±0.1	9.3 ± 2.0	11.1 ±2.0	4.4 ±1.0
Floral parts	19.4 ± 2.1	1.4 ±0.7	7.1 ±1.2	12.9 ±2.4	5.4 ±1.0
Total	133.6	4.7	61.8	150.0	52.6

Values are means ±SEM of 12 traps form each treatment over 2 year

5.3.5 *Fine roots productivity, turnover and nutrient contribution*

Productivity of fine roots differed significantly ($F_{3,\ 47}$ = 8.43; P = 0.034) among treatments (Table 5.6). Turnover rates were 0.79, 0.87, 0.96 and 1.04 for 3, 15, and 30 year-old and forest plots respectively. Annual contribution of fine roots to nutrient inputs through turnover of fine roots is in Table 5.7. Nitrogen (N), P, K, Ca and Mg fluxes through fine roots turnover ranked in the order Forest > Cocoa 30yrs > Cocoa 15yrs > Cocoa 3yrs. Estimated nutrient inputs from turnover of fine roots varied from 2 (P) to 47 (Ca) kg $ha^{-1}yr^{-1}$ in 3 and 30-year-old cocoa systems respectively (Table 5.7).

Table 5.6 Fine roots biomass productivity, production and turnover rate along a cocoa chronosequence.

Land-use	Fine Roots Productivity (FRP) (kg ha^{-1} $year^{-1}$)	Fine Roots Biomass (FRB) (kg ha^{-1})	Fine roots Turnover rates (FRP/FRB = k_F yr^{-1})
Forest	3,453 (±354)[a]	3,333 (534)[a]	1.04 [a]
Cocoa 3 years	1,806 (±231)[b]	2,276 (375)[b]	0.79 [b]
Cocoa 15 years	2,835 (±264)[b]	3,252 (400)[a]	0.87 [b]
Cocoa 30 years	4,235 (±406)[a]	4,415 (534)[c]	0.96 [a]

Mean fine roots biomass and fine roots productivity for the different land-uses with the same superscript are not significantly different at P < 0.05 level using Tukey's HSD range test.

Table 5.7 Annual contributions of fine root turnover to N, P, K, Ca and Mg nutrient inputs in forest and cocoa land-uses in Ashanti, Ghana.

Land-use	[1]Fine roots turnover (kg $ha^{-1}yr^{-1}$)	(kg $ha^{-1}yr^{-1}$)				
		N	P	K	Ca	Mg
Forest	3,591	19	5	36	47	21
Cocoa 3 years	1,427	12	2	9	18	3
Cocoa 15 years	2,466	25	3	17	21	12
Cocoa 30 years	4,066	31	5	18	36	25

[1]Fine roots turnover was determined by multiplying fine roots turnover rates by fine roots productivity.

5.4 Discussions

5.4.1 Litterfall production

Litter production is a major process by which carbon and nutrients are transferred from vegetation to soil. Total litterfall showed a significant increase with time after forest conversion ranging from 5.0-10.4 Mg ha^{-1} (Table 5.1) and were within the ranges recorded for shaded cocoa agroforestry and tropical secondary forests in several studies. Owusu-Sekyere *et al.* (2006) for instance found that in the semi-deciduous forest zone of the Ashanti region in Ghana, mean annual litter produced by primary and secondary forests was both 7.9 Mg ha^{-1} while that for cocoa plantation was 6.9 Mg ha^{-1}. Opakunle (1989) also reported an annual litterfall rate of 11.7 Mg ha^{-1} in a 22-year old cocoa plantation in a lowland rainforest area in Ibadan, Nigeria. Similarly Isaac *et al.* (2005) measured litterfall rates ranging from 3.2 to 10.4 Mg $ha^{-1}yr^{-1}$ in 25-year-old chronosequence of cocoa plantations located in the moist semi-deciduous forest in the Western Region of Ghana. Vitousek and Sanford (1986) observed above-ground inputs within a tropical forest to be between 8.8 and 10.5 Mg $ha^{-1}yr^{-1}$. Multi strata-systems have been found to have litterfall rates ranging from 6 to 20 Mg $ha^{-1}yr^{-1}$ (Szott *et al.*, 1991). Hartemink (2005) reviewed the results of research on nutrient cycling in cocoa ecosystems and found that litterfall ranged from 5 Mg $ha^{-1}yr^{-1}$ in Ghana to more than 21 Mg $ha^{-1}yr^{-1}$ in Venezuela. In this study, biomass inputs via litterfall had reached natural forest levels by 30 years suggesting a sustained level of litter inputs (Isaac *et al.*, 2005).

5.4.2 Seasonality of litterfall production

Litterfall may be affected by physical factors such as the mechanic action of wind and rain or physiological responses of the plants to environment changes (ICP Forests, 2004;

Santiago and Mulkey, 2005). Litter production increased in the dry season, indicating that the physiological response to drought and reduced humidity plays a major role in this process. These factors together with lower night temperatures that prevail during the dry seasons are known to stimulate abscisic acid synthesis in plant foliage, which, in turn, stimulates leaf senescence (Yang *et al.*, 2003). Most litterfall studies in tropical forests have demonstrated a strong seasonality of leaf litterfall, with the dry season being the peak of litterfall (Wieder and Wright, 1995; Lawrence and Foster, 2002). Seasonal pattern of litterfall largely depended on the factors responsible for leaf senescence and abscission (Lian and Zhang, 1998). The pattern of litterfall in this study, which is consistent with patterns in vegetation forms under seasonal climates, is different from those found in vegetation forms under climates without dry seasons, such as the Atlantic rain forest, where the production peak is in the rainy season, indicating an effect of mechanical factors (Moraes *et al.*, 1999).

5.4.3 Decomposition coefficient and litter quality

The patterns of litterfall and litter stock accumulation resulted in monthly decomposition coefficients exhibiting similar temporal patterns across the chronosequence (Figure 5.1). Decomposition coefficients were largest in the rainy seasons i.e., between the months of April to November with peaks in May and October. The smaller rates were recorded during the dry period between December and March. Coefficients tended to decrease from forest to cocoa systems. Many researchers have developed predictors or indices of decomposition and nutrient release (Mtambanengwe and Kirchman 1995; Mafongoya *et al.* 1998). These indices which include ratios of carbon to nitrogen (C:N), polyphenol to nitrogen (PP:N), lignin to nitrogen (L:N), and polyphenol plus lignin to nitrogen (PP +

L):N ratios are all apparently valid. However, other factors such as site conditions may also be important moderating factors (Anderson and Swift, 1983; Mafongoya *et al.*, 1998). The significantly greater annual decomposition coefficient (k_L) recorded in natural forest compared to cocoa systems may reflect structural and litter quality differences with litter on natural forest floor being of higher quality than litter in shaded-cocoa systems. Though this study did not differentiate between leaves from cocoa and upper canopy trees, earlier studies by Isaac (2003) confirmed that cocoa leaves constitute the dominant litter (about 60%) in litterfall under similar shaded cocoa systems in the western region of Ghana. Observed trends in decomposition can be linked to increases in litter lignin and polyphenols because of the predominance of cocoa leaves in leaf litterfall under cocoa systems. Non-significant differences in C:N and L:N ratios in forest and 30-year-old shaded-cocoa systems were expected to have resulted in similar decomposition coefficients in the two systems. These coefficients however differed significantly. This suggests that the decomposition process is very complex with multiple concurrent factors. One might be the general effect of the occurrence of more adapted soil biota and local decomposers in forest sites compared to anthropogenic sites to influence decomposition (Goma-Tchimbakala and Bernhard-Reversat, 2006; Anderson and Swift, 1983). The study indicates that concentrations of N and L in litterfall, the ratios of C:N, L:N and PP+L:N ratios correlated significantly with decomposition coefficients. Additionally, L and PP were significantly correlated to N. It may be assumed that among the quality parameters assessed, L and N are the main factors controlling decomposition in these systems.

5.4.4 Potential nutrient return through litterfall

Leaf litter constituted between 78-92% of total litterfall and contributed a very high proportion of nutrient potentially returned in litterfall. Along the chronosequence, 77-98% of N, 70-97% of P, 64-95% of K, 80-99% of Ca and 81-99% of Mg in total litterfall were returned in leaf litterfall with the other proportions coming from floral and twig litterfalls. The recorded fluxes potentially returned in total litterfall to the forest floor in this study were within the ranges reported for several studies. Schroth *et al.* (2001), citing from the works of Murray (1975) reported that 5 Mg $ha^{-1}yr^{-1}$ litterfall produced in a typical cocoa farm shaded by forest trees in West Africa returned 79 and 4.5 kg of N and P respectively to the forest floor, while Beer *et al.* (1998) reported that, the 5.7 Mg $ha^{-1}yr^{-1}$ litter from *C. alliodora* shade trees in a Costa Rican coffee plantation contained 114, 7 and 54 kg of N, P and K respectively. For the cocoa plantations in this study, nutrient return increased steadily from 3-years after conversion attaining maximum values in the forest and 30-year-old plots. This is a reflection of the fact that being older stands, these sites have accumulated more nutrients over time. Additionally there were no nutrient exports as in the case of forests, while reduced yields in the 30-year-old plots imply that these systems are more closed and therefore had reduced nutrient ‘leakages’.

5.4.5 Nutrient return through fine roots turnover

Turnover rates of fine roots were 79, 87, 96 and approximately 100% of fine roots production in 3, 15, and 30 year-old cocoa systems and forest plots respectively. Turnover of fine roots is important for returning nutrients to the soil. However, nutrient inputs to the forest soil through fine roots renewal were much less than inputs provided by litterfall across the chronosequence. According to Munoz and Beer (2001), the significance of the inputs from fine roots may be higher than the absolute values may suggest. This is because nutrients from renewal of fine roots are incorporated into the soil within the rooting zone rather than being deposited on the soil surface as is the case with leaf litter, where losses especially nitrogen may be greater (Munoz and Beer, 2001). They showed that turnover of fine root was close to 1.0 in shaded cocoa with *Erythrina poeppigiana* or *Cordia alliodora* in Costa Rica with nutrient inputs estimated to be 23-24 kg N, 2 kg P and 14-16 kg K ha^{-1} $year^{-1}$. These input values are comparable to results obtained in the present study where estimated inputs ranged from 16-31 kg N, 2-5 kg P and 9-18 kg K $ha^{-1}year^{-1}$ for 3 and 30 year-old cocoa plots respectively.

5.5 Summary and conclusions

The rate of litterfall production and stand litter increased along the chronosequence (i.e. from 3 year-old to mature (15 and 30-year-old) cocoa and forest land-uses. Forest and older shaded-cocoa systems exhibited greater annual litterfall and stand litter pools compared to the 3-year-old shaded-cocoa systems. The increasing plant litter biomass may suppress nutrient cycles in cocoa sites through nutrient sequestration in surface litter, but may also facilitate the slow release of N during decomposition of litter.

Along the chronosequence, 77-98% of N, 70-97% of P, 64-95% of K, 80-99% of Ca and 81-99% of Mg in total litterfall were returned in leaf litterfall with the other proportions coming from floral and twig litterfalls.

The decomposition rates of different litter types did not vary significantly between cocoa systems, and rates of decomposition for all litter types were considerably faster in the forest sites than in the cocoa systems. The difference of annual decomposition coefficient (k_L) values between forest and cocoa systems may reflect structural and litter quality differences. This confirms the possible effect of litter quality being more important than other biological or physical factors in determining the rate of decomposition in cocoa systems. The occurrence of poorly adapted soil biota and/or the reduction in the local decomposer community following forest clearing may be also involved though this needs to be confirmed through further research.

With fine roots turnover ranging from 1,427 to 4,066 kg $ha^{-1}yr^{-1}$ for 3 and 30-year-old shaded cocoa systems respectively, nutrient inputs from turnover of fine roots varied from 2 (P) to 47 (Ca) kg $ha^{-1}yr^{-1}$ in 3 and 30-year-old cocoa systems respectively.

It is concluded that litter quality had an important influence on the rate of litter decomposition. The findings of the current study support the hypotheses that conversion of forest to shaded-cocoa land-use results in a reduction in decomposition rates because of litter quality changes and that decomposition rates will correlate to litter quality differences in cocoa ecosystems.

Findings of the study provide positive evidence and support for the farmer practice of replanting farms at age 30-years or greater due to declining yields for both ecological and economic benefits (Asare, 2006). At this stage, nutrient release from the accumulated “litter bank” provides the advantage of “forest rents” that accrue to farmers when natural forests are cleared for agricultural practices.

The study showed that 78, 86, 94 and approximately 100% of fine roots produced in 3, 15, and 30 year-old cocoa systems and forest plots respectively were renewed annually. Fine roots turnover decreased immediately after conversion (3 years) but increased as land-use systems aged. Nutrient inputs to the soil through renewal of fine roots were much less than inputs provided by litterfall across the chronosequence.

In this chapter, the dynamics of nutrient recycling through litterfall and fine roots turnover, as well as the factors driving the recycling process were investigated. However, the quantification of rainfall nutrient fluxes is also important for evaluating biogeochemical cycles with nutrient or solute transport. In the next chapter, I look at the patterns of nutrient fluxes and their magnitudes in incident rainfall, throughfall, stemflow, and leaching and harvest exports to give a comprehensive picture of nutrient flows in shaded-cocoa agro-ecosystems. The quantification is done at the farm level.

CHAPTER 6

NUTRIENT FLUXES IN INCIDENT RAINFALL, THROUGHFALL AND STEMFLOW IN SHADED-COCOA SYSTEMS IN A HUMID SEMI-DECIDUOUS FOREST IN GHANA

Abstract

A study of nutrient input fluxes in rainfall, throughfall and stemflow as well as outputs through leaching and cocoa bean exports was conducted along a land-use chronosequence (forest, 3, 15 and 30-year-old cocoa farms) in the semi-deciduous forest zone of the Ashanti Region of Ghana. Mean annual inputs of nutrients in incident rainfall were 5.7 kg N, 0.14 kg P, 13.6 kg K, 9.43 kg Ca and 5.6 kg Mg ha^{-1} yr^{-1}. Rainfall loading or net canopy exchange (throughfall plus stemflow minus incident rainfall) was negative for total N (NH_4^+ + NO_3^-) at all sites, indicating net N absorption from incident rainfall. For P and the basic cations, concentrations increased in throughfall relative to precipitation, and net fluxes were positive indicating net cation enrichment after passing through the forest canopies. There were significant differences in incident rainfall, throughfall and stemflow chemistry. Nutrient balances under forest were positive for P, K, Ca and Mg and negative for N under forest land-use. While the mean balances of N and P under cocoa land-use were negative with net annual losses of 11.1 and 0.51 kg $ha^{-1}yr^{-1}$ respectively, the mean balances for K, Ca and Mg were positive with net annual gains of 1.6, 8.3 and 4.2 kg $ha^{-1}yr^{-1}$ respectively. Annual losses of N constituted only small proportions of total nutrient stocks in soil. To enhance nutrient cycling and improve balances, findings suggest the efficient recycling of the 543 kg $ha^{-1}yr^{-1}$ of cocoa pod husks which are capable of contributing 6.2 kg N, 0.5 kg P, and 18.3 kg K, 4.3kg Ca and 2.0 kg Mg $ha^{-1}yr^{-1}$.

Key words: Nutrient balances, fluxes, throughfall, stemflow, incident rainfall, nutrient monitoring

6.1 Introduction

In sub-Saharan Africa, stakeholders and decision makers are increasingly recognizing the depletion of soil nutrients as the major constraint to sustainable agriculture and rural development (Smaling *et al.,* 1996). Soil fertility depletion on smallholder farms has been cited as the fundamental biophysical cause responsible for the declining per capita food production in Africa (Sanchez *et al.,* 1996). Roy *et al.* (2001), and Stoorvogel and Smaling (1990) estimate that nutrient depletion for Ghana in 2000 was: 35 kg N, 4 kg P, 20 kg K loss per ha annually resulting from human activities. From the position of cocoa in the country's socio-economic development, and the declining yields being experienced on smallholder farms, cocoa production could benefit from a proper understanding of its nutrient input and output dynamics.

To be able to design management systems characterized by optimum correspondence between nutrient supply and demand and thus closed internal nutrient cycles, it is necessary to have information not only about the magnitude of the respective nutrient fluxes, but also about their patterns and the factors that determine these patterns. Though nutrient fluxes have repeatedly been measured in the humid tropics, rarely have they been measured in agricultural and agroforestry systems (Brinkmann, 1983; Hölscher *et al.*, 1998; Opakunle, 1991). As a consequence, information on the magnitudes of the various input and output fluxes and their dynamics is scarce (Juo and Manu, 1996; Kotto-Same *et al.*, 1997).

Throughfall and stemflow are important pathways for nutrient return to the forest floor and can influence soil physical and chemical properties by adding available nutrients

(Swank and Henderson 1976; Likens *et al.,* 1977). Despite their importance, very few studies have comprehensively examined the effects of anthropogenic disturbances on nutrient cycling through these three pathways and their dynamics remain relatively unknown in cocoa systems. The goal of this study is to contribute to the understanding of the degree of nutrient addition and/or losses in cocoa agro-ecosystems and advance management recommendations for enhancing nutrient cycling processes in cocoa land-use systems. This has been done by characterizing the magnitudes of nutrient fluxes via precipitation, throughfall and stemflow, as well as fluxes through harvest and leaching losses under shaded-cocoa systems in the lowland semi-deciduous forest zone in the Ashanti Region of Ghana during the 24-month period from January 2006-2008. The resulting balances were also evaluated.

The specific objectives of this study were to:

(i) Quantify nutrient fluxes through incident rainfall, throughfall, stemflow and crop residues, and losses from harvest exports and leaching in shaded-cocoa systems.

(ii) Estimate nutrient balances under forest and different aged shaded-cocoa systems.

(iii) Identify possible interventions for enhancing nutrient cycling and improving the efficiency of nutrient management in cocoa systems.

6.2 Materials and methods

6.2.1 Site description and establishment of sample plots.

A general description of the study sites including climate, vegetation and dominant soil types and the approach adopted for the study are in sections 2.1, 2.2, 2.3 and 2.4 of the general methodology in Chapter 2.

Plots for the collection of stemflow, throughfall and bulk precipitation for nutrient flux determination were established as described in section 4.2.2 of Chapter 4.

6.2.2 Nutrient flow Model

Roy *et al.* (2001) adapting the pioneering works of Smaling *et al.,* (1996) and Van den Bosch *et al.* (1998) on nutrient flows at different spatial scales presented the nutrient monitoring (NUTMON) concept for soil-level nutrient monitoring (Figure 5.1). The concept included five inflows (IN1: mineral fertilizer, IN2: organic fertilizer, IN3: atmospheric (wet and dry deposition), IN4: biological nitrogen fixation and IN5: sedimentation), and five outflows (OUT1: harvested products, OUT2: removal of crop residues, OUT3: leaching, OUT4: gaseous losses and OUT5: erosion). For this study, the NUTMON concept was applied at the soil-crop level to capture the relevant input and output fluxes. The fluxes estimated were IN3 (rainfall input through wet and dry deposition), OUT1 (harvested exports) and OUT3 (leaching). IN1 and IN2 were not relevant, as farms studied do not apply inorganic or organic fertilizers. Since cocoa farms are not irrigated, sedimentation (IN5) plays no role. Because of the well-drained nature of sites and the presence of dense cocoa leaf litter on the plantation floor, it was assumed

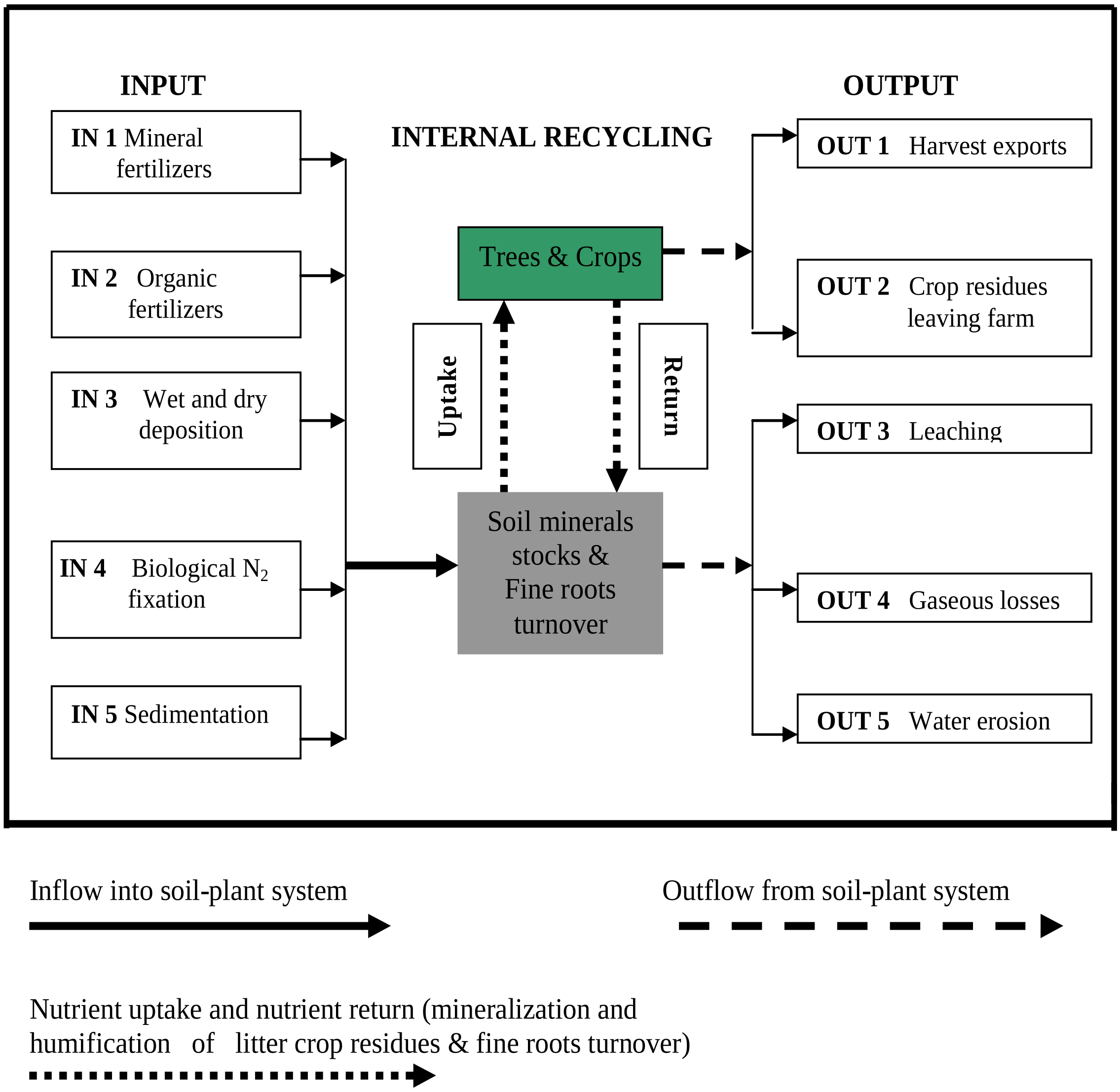

Figure 6.1. Conceptual framework for major nutrient inflows (IN), outflows (OUT) and internal recycling in a soil-plant system. Adapted from *Roy et. al.*, (2001).

that OUT2, OUT4 – (gaseous losses) and OUT5- (water erosion) do not contribute to nutrient outputs in the system. Internal recycling was the subject of study in chapter 5.

6.2.3 Measurement of incident rainfall, throughfall and stemflow

Incident (Open Area) Rainfall

Open area incident rainfall was measured with ten (10) metalloplastic collectors (Plate 6.2) fitted with collecting funnels (surface reception area of all collecting funnels was 0.363 m^2 or 3.63 $x10^{-5}$ ha). Each collector-unit consisted of a 15-L metalloplastic bucket with a 215mm-diameter plastic funnel fixed to the lid by solidified inert silicon sealant. The narrow neck of each funnel had a piece of 2-mm nylon gauze to prevent insects, litter and other coarse debris from entering the collectors and a table tennis ball to reduce evaporation. Each bucket-funnel collector unit was held in place by a four-legged wooden stand at about 90 cm above the soil to prevent forest floor splash-contamination. Gauzes were changed and/or cleaned regularly to avoid blockages. The collectors were positioned in an open field in such a way that they were not within the projection of the tallest trees and there was little chance of contamination from rain drops splashing neighboring foliage. Measurements of incident rainfall were taken fortnightly. Monthly samples were pooled together and subsamples taken from the mixed samples for chemical analyses in duplicates at the laboratories of the Soil Research Institute, Kumasi.

Throughfall

Throughfall (TF) was collected using a total of 48 plastic collectors (or 4 collectors per plot) similar to those used for the collection of open area incident rainfall. Surface reception area of all four (4) collecting funnels per plot is 0.145 m^2 ($1.45x10^{-5}$ ha) or

0.0363m^2 per funnel (Plate 6.2B). To minimize errors, improve the precision of estimates related to canopy variability, reduce the number of collectors required and to ensure that mean concentrations can be considered as independent, positions of the collectors were changed from time to time after each sampling (Lloyd and Marques, 1988). Each month, fortnightly samples of throughfall from similar plots were pooled and subsamples taken from the mixed samples for chemical analyses in duplicates.

Stemflow

Stemflow (SF) was collected from forest, 15 and 30-year-old cocoa systems using 4 collectors per site over three replicates giving 12 samplers for each land-use. Trees that were fitted with stemflow collars were selected purposively based on having basal diameter equal to or close to the average for the block. Stemflow collars consisted of a 25-mm-diameter rubber hose slit longitudinally and sealed to the trunk in an upward spiral with ½’’ steel nails and an inert silicon sealant. The lower complete portions of hosing directed the stemflow into 15-L plastic collectors placed firmly on the forest floor (Plate 6.1C). The collars were mounted at breast height (1.3 m above the forest floor). Each month, fortnightly samples from similar plots were pooled to give one monthly stemflow sample. Subsamples were subsequently taken from the composite samples for chemical analyses in duplicates at the laboratories of the Soil Research Institute, Kumasi.

6.2.4 Preservation and analysis of throughfall, stemflow and or incident rainfall samples

One (1ml) formaldehyde/chloroform was added each month to each sample to prevent microbial (mainly bacterial and algal) growth. Samples were stored in a dark cold room at 3^{o}C until nutrient analysis was performed (usually within two weeks). All samples were filtered through 0.45µm Whatman filter papers prior to analysis. Concentrations of sodium (Na^{+}), K^{+}, Ca^{2+} and Mg^{2+} concentrations (mgL^{-1}) were measured by atomic absorption spectroscopy and NO_3^{-} and NH_4^{+} concentrations were determined colorimetrically; pH values were measured using a glass electrode.

6.2.5 Nutrient output fluxes

Leaching

Leaching was assumed significant only for N and K (Roy *et al.,* 2001; Kanmegne *et al.*, 2006). Annual leaching losses of nitrogen (N_L) and potassium (K_L) in (kg ha^{-1}year^{-1}) were estimated from improved pedo-transfer functions as described by Lesschen *et al.,* (2007) as:

$$N_L \text{ (kg/ha/yr)} = (0.0463+0.0037 \times P/CL) \times (F_N + D \times NOM - U) \qquad (6.1)$$

$$K_L \text{ (kg/ha/yr)} = -6.87 + 0.0117P + 0.173 \times F_K - 0.265 \times CEC \qquad (6.2)$$

Mean annual rainfall (P) in millimeters over the last 10 years was collected from meteorological office in the district, while C the percentage clay content of the soil, L the thickness of the soil layer in meters, F_N and F_K the mineral and organic N and K addition respectively, D the litter decomposition rate, U the uptake by cocoa crop (kg ha^{-1}yr^{-1}) and CEC the cation exchange capacity in cmol kg^{-1} were all determined from field measurements on the research sites.

Cocoa beans nutrient exports

Annual cocoa yields (kilograms per hectare) over the past five years for the project district were obtained from the Cocoa Services Division (CSD) of the COCOBOD in the district. To determine nutrient contents of seeds, samples of dry cocoa beans were collected from 24 farmers from the six project communities (4 from each community) during the major and minor cocoa purchasing seasons. On each of the four cocoa purchasing seasons, samples from each of the six communities were pooled together, three (3) sub-samples were taken, milled and each subsample analyzed for carbon, nitrogen and other macronutrient concentrations in duplicates. From the values obtained from the sub-samples, the mean concentrations of carbon, nitrogen and basic cations (P, K, Ca and Mg) were calculated (n=12 for each nutrient element). Total annual nutrient exports through harvested beans (kg $ha^{-1}yr^{-1}$) were estimated by multiplying mean nutrient concentrations in cocoa beans by the annual yield.

6.2.6 Management interventions for enhancing nutrient cycling

Management interventions for enhancing nutrient cycling were identified by assessing nutrient recycling pathways (chapter 5), and evaluating current land preparation and other farmer production and fertility management practices with the potential of disrupting the cycling process (chapter 7). Based on empirical evidences obtained, interventions are recommended for bridging the disruption in the recycling process.

6.2.7 Data processing and flux calculations

Nutrient inputs from incident rainfall was estimated from the records of a conventional rain-gauge (0.0127m^2 collecting surface area) over the ten-year period covering 1996-

2005 (Chapter 2, Figure 2.2) at the MoFA /COCOBOB meteorological station at Nkawie located approximately 5 km from the nearest research plot. For the purposes of comparison, volumes of water collected in incident rainfall, throughfall and stemflow were converted to depth equivalents of incident rainfall in millimeters of rainfall (12.5 mls of rainwater is equivalent 1mm depth) and expressed as percentage of incident rainfall in millimeters.

Throughfall water volumes collected from each land-use were extrapolated to volumes on a per hectare per year basis and corrected for the basal area of stems (i.e. the area over which throughfall was collected was one hectare minus the area of stems). The total stem basal areas sampled were 1.36, 9.68, 10.8 and 40.5 m^2 in the 3, 15 and 30-year-old cocoa fields and forest respectively. Mean stemflow water yield ($litre^{-1}month^{-1}$) was calculated for each land-use and converted to stemflow water yields based on the number of trees per hectare. For both throughfall and stemflow, volumes of water yield collected per month for the sampling period were summed up and extrapolated to provide estimates on an annual basis.

Hydrological fluxes were estimated for incident rainfall, throughfall and stemflow as volume weighted means by multiplying individual nutrient concentrations by their sample volumes, summing and then dividing by the total volume collected (Schrumph *et al.*, 2006)**.** The annual nutrient inputs (kg ha^{-1}) of N, P, K, Ca and Mg in incident rainfall, throughfall and stemflow were found by multiplying their respective volumetric weighted mean concentrations by the total volumes collected per annum. The fluxes of total input (rain-based) and rainfall loading were as defined by Chuyong *et al.* (2004)) and calculated as follows:

Total (rain-based) input = Throughfall + Stemflow (6.3)

Rainfall loading = (Throughfall + Stemflow) – Incident rainfall (6.4)

Total nutrient fluxes in throughfall and stemflow minus the input in precipitation (rainfall loading) is equivalent to the amount of nutrients leached from leaves (Lui *et al.*, 2003; Lilienfein and Wilcke, 2004). These estimated nutrient fluxes (kg $ha^{-1}yr^{-1}$) in incident rainfall, throughfall, stemflow and rainfall loading were used to compare nutrient input fluxes between the different land-uses.

6.2.8 Statistical analysis

The analysis of variance (one-way ANOVA) and Tukey's HSD test was used to test for significant effects of land-use age on nutrient concentrations in stemflow and throughfall at 5% probability level. Regressions and correlations were also employed as tools for statistical tests and to establish trends and relationships between parameters. All statistical analyses were performed using Statistix 7.0 statistical software (Analytical Software, 2000).

Plate 6.1 Setup for the collection of (A) incident rainfall, (B) throughfall and (C) stemflow water samples

6.3 Results

6.3.1 Water inputs

Incident Rainfall

The incident rainfall (monthly means) recorded within the study area for 2006 and 2007 was 1,376 mm (Table 6.1). This is slightly higher than the annual mean rainfall of 1,308 mm (range 931 - 1,596 mm) in the district for the period 1997-2006. The rainfall distribution pattern of the study site is strongly seasonal. Maximum rainfall was recorded in May (273.6 mm) and October (349.4 mm) corresponding to the peaks of the major and minor rainy seasons respectively. On the average, sixty-eight rainy days were recorded with the highest number of rainy days in May (12 days) and October (18 days) for the major and minor rainy seasons respectively.

Throughfall

There were considerable temporal variations in the amounts of throughfall collected between all land-uses (Table 6.1). The total amounts of throughfall collected were 1,053, 1,147, 1,167 and 1,244 mm corresponding to an average of 77, 83, 85 and 90% of incident rainfall respectively in the forest, 3, 15, and 30 year-old cocoa land-uses. No throughfall was generated in December. Individual throughfall volumes expressed as a percentage of incident rainfall ranged from 0% (in periods with little or no rainfall - December in all the land-uses) to 117% in October in the 30-year-old plots. Monthly throughfall was strongly correlated with incident rainfall (R^2= 0.94, 0.95, 0.95 and 0.61 in forest, 3, 15 and 30 year-old cocoa land-uses respectively, $P < 0.05$).

Table 6.1. Mean monthly records (mm) of incident rainfall and throughfall in forest, 15 and 30-year-old cocoa plots in the Ashanti Region. Throughfall estimates are expressed in depth equivalence of incident rainfall.

Month	Incident Rainfall		Throughfall (mm)			
	Amount (mm)	No. of wet days	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa30 years
January	42.0 ±1.6	1	16.8 ±0.9	22.4 ±2.5	21.7 ±3.5	25.9 ±3.2
February	34.2 ±1.3	2	18.5 ±1.2	27.6 ±2.2	20.6 ±1.5	17.1 ±2.9
March	82.3 ±6.8	8	69.3 ±6.7	68.6 ±8.3	71.9 ±8.5	77.2 ±7.4
April	140.8 ±4.7	7	93.9 ±8.8	95.2 ±8.2	108 ±10.5	133.8 ±15.3
May	273.6 ±12.0	12	193.0 ±8.5	251.0 ±10.2	268.8 ±8.3	201.1 ±10.1
June	75.6 ±7.9	3	93.2 ±4.7	70.3 ±3.3	73.9 ±2 .5	93.9 ±8.5
July	101.7 ±8.6	5	94.0 ±6.7	99.0 ±8.5	98.5 ±5.6	109.3 ±9.3
August	16.5 ±5.4	1	5.0 ±1.0	6.4 ±2.2	9.2 ±1.2	5.7 ±1.0
September	177.2 ±10.7	5	141.5 ±5.0	147.7 ±4.2	138.7 ±3.1	143.1 ±4.0
October	349.4 ±23.5	18	292.2 ±14.2	312.7 ±15.6	320.9 ±14.6	408 ±18.3
November	65.8 ±8.7	4	35.7 ±3.3	45.8 ±1.0	35 ±3.7	28.4 ±1.6
December	17.1 ±2.6	2	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
TOTAL	1376.2	68	1053.1	1146.7	1167.2	1243.5

Incident rainfall, throughfall and number of wet days are means for 2006 and 2007.

Stemflow

Total stemflow collected (expressed in mm equivalent of rainfall) was 20.2, 23.1 and 19.7 mm corresponding to 1.5, 1.7 and 1.4% of incident precipitation in forest, 15 and 30-year-old cocoa plots respectively (Table 6.2). Monthly stemflow volumes expressed as a percentage of incident rainfall ranged from 0 % in periods with little or no rainfall to 1.9 % during periods of high rainfall. Monthly stemflow was correlated with incident rainfall (R^2 = 0.57, 0.60, and 0.82) in forest, 15 and 30-year-old cocoa land-uses respectively.

6.3.2 Dynamics of canopy interception

Average amount of rainfall intercepted in forest, 15 and 30-year-old cocoa systems during the period expressed as a percentage of incident rainfall is given in Table 6.3. During the months of December - February and August, incident rainfall was low and proportion of total rainfall intercepted by canopy was highest during these periods among all the land-uses (Figure 6.2). In general, interception loss correlated negatively with rainfall (Figure 6.3).

6.3.3 Nutrient input fluxes

Nutrient concentrations in incident rainfall, throughfall and stemflow

The chemical composition of precipitation in the area was dominated by K, Ca and N. Phosphorus (P) recorded the least concentration (Table 6.4). Significant differences (($F_{3, 47}$ =4.47; P= 0.0066)) were observed between incident rainfall and throughfall in concentrations of nutrient elements, and enrichment occurred within forest and cocoa systems for P, K, Ca and Mg. The ratio of nutrient concentration in throughfall to

Table 6.2 Mean monthly records (mm) of incident rainfall and stemflow in forest, 15, and 30-year-old plots in the Ashanti Region. Stemflow estimates are expressed in depth equivalent of incident rainfall[1].

Month	Incident Rainfall		Stemflow (mm)		
	Amount (mm)	No. of wet days	Forest	Cocoa 15 years	Cocoa 30 years
January	42.0 ±4.6	1	0.3 ±0.1	0.2 ±0.1	0.4 ±0.2
February	34.2 ±3.3	2	0.4 ±0. 2	0.5 ±0.2	0.6 ±0.2
March	82.3 ±6.8	8	1 .1 ±0.6	1.0 ±0.3	0.8 ±0.5
April	141 ±4.7	7	3.8 ±1.0	2.7 ±0.9	2.5 ±1.1
May	274±12.0	12	3.3 ±0.9	5.2 ±1.0	4.6 ±1.0
June	75.6 ±7.9	3	2.4 ±0.4	2.5 ±0.4	1.8 ±0.2
July	102 ±8.6	5	1.9 ±0.7	3.9 ±1.6	2.2 ±0.4
August	16.5 ±5.4	1	trace	trace	trace
September	177 ±10.7	5	2.6 ±0.5	2.0 ±0.4	1.9 ±0.4
October	349 ±13.5	18	3.5 ±0.5	4.3 ±0.4	4.1 ±0.4
November	65.8 ±8.7	4	0.9 ±0.2	0.8 ±0.2	0.8 ±0.2
December	17.1 ±2.6	2	0.0 (0.0)	0.0(0.0)	0.0 (0.0)
TOTAL	1376.2	68	20.2	23.1	19.7

[1]Incident rainfall, stemflow and number of wet days are means for 2006 and 2007.

Table 6.3. Mean distribution (mm, %) of throughfall, stemflow and canopy interception compared to incident rainfall (IR) in forest, 3, 15 and 30-year-old cocoa systems.

Land-use	Throughfall		Stemflow		Canopy interception and evaporation	
	mm	% of IR	mm	% of IR	mm	% of IR
Forest	1,053	76.5	20.2	1.5	302.8	22.0
Cocoa 3 years	1,147	83.3	n.d	n.d.	n.d	n.d.
Cocoa 15 years	1,167	84.8	23.1	1.7	185.8	13.5
Cocoa 30 years	1,243	90.4	19.7	1.4	112.8	8.2

n. d. Not determined

incident rainfall under forest system for instance was 5.7 for P; 4.2 for K; 1.6 for Ca and 2.6 for Mg, while for the 30-year-old cocoa plot it was 4.3 for P; 4.5 for K; 2.4 for Ca and 2.1 for Mg. Concentration of total N (NH_4^+ and NO_3^-) in throughfall was smaller than in incident rainfall indicating net N absorption from rainfall after passing through forest and cocoa canopy.

Concentrations of P, K, Ca and Mg in stemflow were significantly greater ($F_{3, 47}$ =12.13; P= 0.0057) than in incident rainfall. Generally, the enhancements in stemflow concentration with respect to rainfall were smaller compared to throughfall indicating absorbtion of nutrients particularly P, Ca and Mg from the solution flowing along the trunk surface. While the concentrations of N, P, Ca and Mg were smaller in stemflow compared to throughfall across the chronosequence, the concentrations of K in stemflow were greater than in throughfall in both 15 and 30-year-old plots (Tables 6.4 and 6.5).

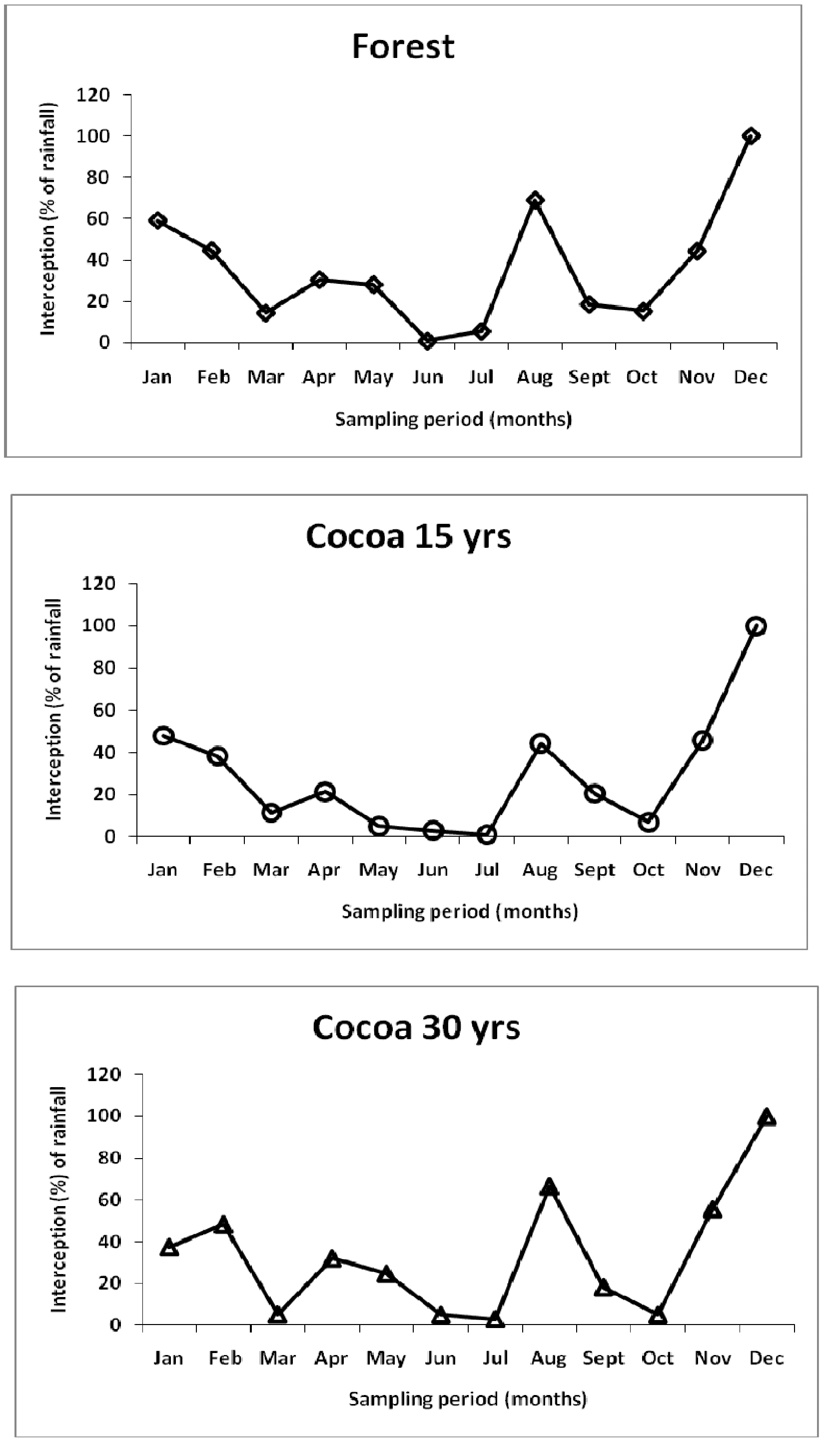

Figure 6.2. Monthly distribution of rainfall interception (%) in forest, 15 and 30-year-old cocoa plantations in Nwabiagya, Ashanti, Ghana.

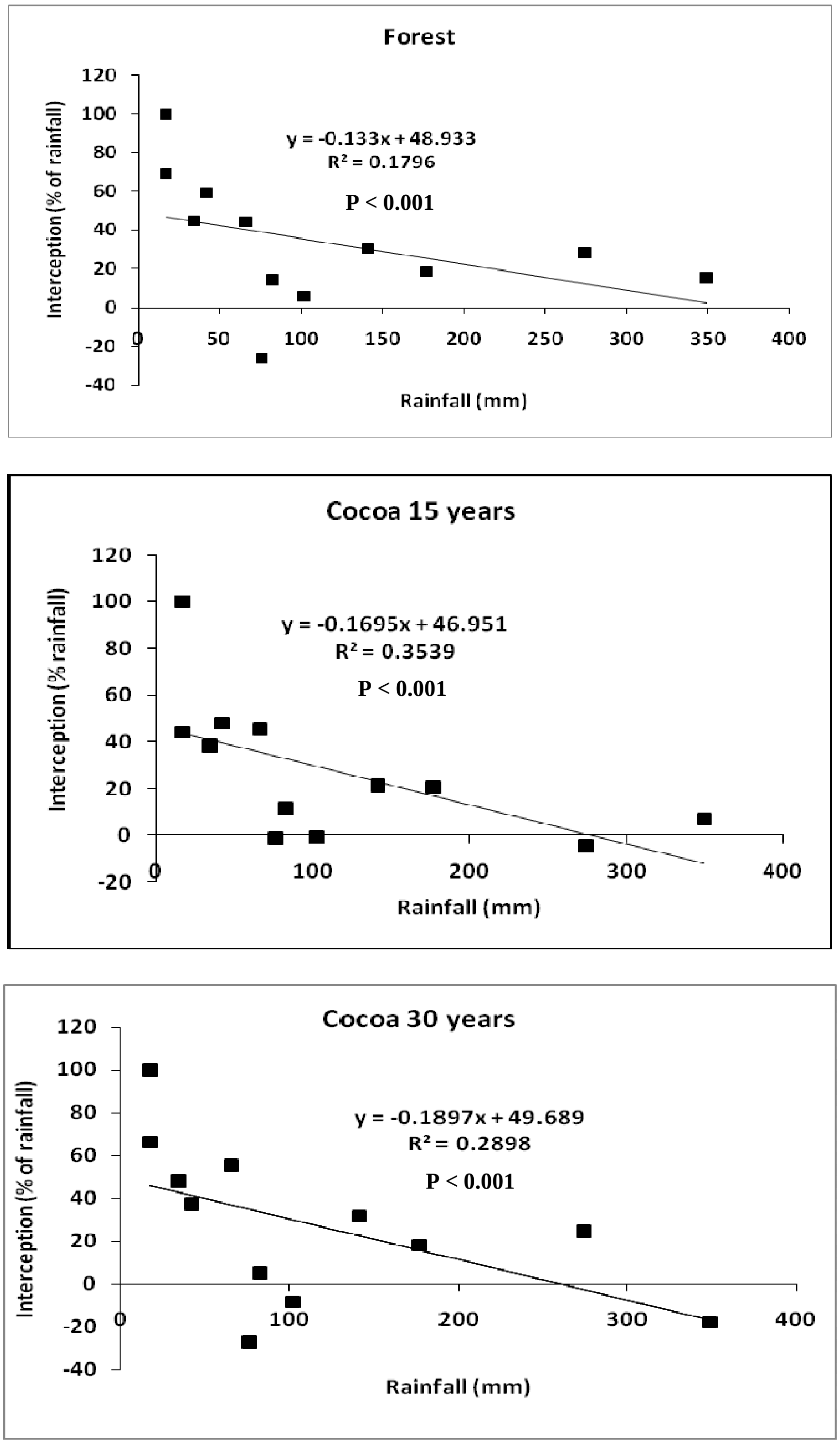

Figure 6.3. Relationship between % rainfall interception and rainfall in forest, 15 and 30-year-old cocoa plots in Atwima Nwabiagya, Ashanti.

Table 6.4 Volume-weighted concentrations (±SE) of N, P, K, Ca and Mg in incident rainfall and throughfall in forest and cocoa plots. Nutrient concentrations in throughfall are compared incident rainfall and F and P values associated with the treatments are given.

Nutrient source	Land-use	Nutrient concentration (mg/L)					
		Tot N	P	K	Ca	Mg	pH
Incident Rainfall		0.46[a] ±0.18	0.03[a] ±0.01	1.23[a] ±0.20	0.65[a] ±0.10	0.41[a] ±0.11	5.7[a] ±0.10
Throughfall	Forest	0.28[b] ±0.12	0.17[b] ±0.02	5.22[b] ±1.60	1.04[ab] ±0.70	1.05[b] ±0.30	6.2[b] ±0.14
	Cocoa 3 years	0.32[b] ±0.10	0.09[c] ±0.03	0.09[c] ±0.03	0.88[a] ±0.55	0.99[ab] ±0.33	6.0[ba] ±0.16
	Cocoa 15 years	0.30[b] ±0.11	0.12[c] ±0.02	3.41[c] ±1.50	1.72[c] ±0.19	1.36[b] ±0.50	6.2[b] ±0.09
	Cocoa 30 years	0.33[a] ±0.11	0.13[c] ±0.05	5.54[b] ±3.00	1.53[bc] ±0.70	0.85[ab] ±0.17	6.2[b] ±0.09
F -values		5.02	5.0	14.04	6.54	12.32	4.07
P		0.0017	0.0018	0.001	0.0034	0.005	0.0047

Mean concentrations in the same column for incident rainfall and throughfall in the different land-uses with the same superscript are not significantly different at $P < 0.05$ level using Tukey's HSD range test. F-values were calculated based on all samples (n=19) of 2-year sampling for each element.

Table 6.5 Volume-weighted concentrations (±SE) of N, P, K, Ca and Mg in incident rainfall and stemflow in forest and cocoa plots. Nutrient concentrations in stemflow are compared to incident rainfall and F and P values associated with the treatments are given.

Nutrient source	Land-use	Nutrient concentration (mg/L)					
		Tot N	P	K	Ca	Mg	pH
Incident Rainfall		0.46^{a} ±0.18	0.03^{a} ±0.01	1.23^{a} ±0.20	0.65^{a} ±0.10	0.41^{a} ±0.11	5.7^{a} ±0.10
	Forest	0.23^{b} ±0.17	0.07^{b} ±0.03	5.73^{b} ±1.97	1.00^{ab} ±0.33	0.68^{ab} ±0.14	6.7^{b} ±0.10
Stemflow	Cocoa 15 years	0.25^{b} ±0.11	0.08^{b} ±0.02	7.00^{b} ±1.64	1.42^{a} ±0.55	1.10^{a} ±0.50	6.6^{b} ±0.2
	Cocoa 30 years	0.30^{b} ±0.07	0.04^{ab} ±0.02	6.44^{b} ±2.10	0.91^{ab} ±0.30	0.63^{ab} ±0.12	6.5^{b} ±0.22
F –value		15.77	3.48	11.58	14.32	22.43	8.18
P		0.001	0.0025	0.000	0.013	0.001	0.0001

Mean concentrations in the same column for incident rainfall and stemflow in the different land-uses with the same superscript are not significantly different at $P < 0.05$ level using Tukey's HSD range test.

The weighted monthly pH values (6.0-6.2) in throughfall were significantly greater ($F_{3, 47}$ =4.07; P= 0.0047) than in incident rainfall with a pH value of 5.7. Significant differences ($F_{3, 47}$ =8.18; P= 0.0001) in pH were also observed between incident rainfall and stemflow water (Table 6.5).

Annual nutrient fluxes through incident rainfall, throughfall and stemflow

The fluxes of nutrients in incident rainfall, throughfall, stemflow and the net flux to the forest floor under forest and cocoa systems are in Table 6.6. Incident rainfall input fluxes were 5.7, 0.41, 13.6, 9.43 and 5.6 kg $ha^{-1}yr^{-1}$ for N, P, K, Ca and Mg respectively. The estimated amounts of nutrients reaching the forest floor annually as rain-based inputs (throughfall + stemflow) in forest and cocoa systems indicate that throughfall contributed about 99% of N, P, K, Ca and Mg rain-based inputs. Stemflow contributions were insignificant. Nitrogen on the other hand was absorbed by forest and cocoa canopies. Amount of N reaching forest floor as rain-based input was 3.1, 3.6 and 4.9 kg $ha^{-1}yr^{-1}$ in forest, 15 and 30-year-old cocoa plantations respectively.

6.3.4 Nutrient output fluxes

Cocoa beans harvest exports

Cocoa bean seed yields over the 5-year-period (2002-2007) for the Atwima Nwabiagya District was 464.0±76.2 kg $ha^{-1}year^{-1}$ (COCOBOD Nkawie, personal communication). Based on this yield output, nutrients exported annually through cocoa beans harvests were 5.38, 1.25, 4.32, 1.16 and 1.39 kg ha^{-1} for N, P, K, Ca, and Mg respectively (Table 6.7).

Table 6.6 Nutrient fluxes (kg $ha^{-1}yr^{-1}$) in incident rainfall, throughfall, stemflow and rainfall loading in forest and shaded-cocoa land-use systems.

Nutrient source	Land-use	Nutrient fluxes (kg $ha^{-1}year^{-1}$)				
		N	P	K	Ca	Mg
Incident rainfall		5.70	0.41	13.6	9.43	5.60
Throughfall	Forest	3.10	1.32	56.7	11.5	9.40
	Cocoa 3 years	3.25	0.65	32.4	9.96	10.7
	Cocoa 15 years	3.54	0.74	35.2	14.7	14.0
	Cocoa 30 years	4.82	1.32	58.5	15.9	10.0
Stemflow	Forest	0.04	0.01	0.56	0.16	0.10
	Cocoa 3 years	ND[1]	ND	ND	ND	ND
	Cocoa 15 years	0.05	0.01	1.07	0.28	0.25
	Cocoa 30 years	0.03	0.003	0.39	0.07	0.04
Rainfall Loading [2] (Foliar leaching)	Forest	-2.56	0.92	33.7	2.27	3.90
	Cocoa 3 years	ND[1]	ND	ND	ND	ND
	Cocoa 15 years	-2.11	0.34	23.1	5.57	8.70
	Cocoa 30 years	-0.85	0.91	39.7	6.57	4.40
Total Rain-based input [3]	Forest	3.14	1.33	56.9	11.7	9.50
	Cocoa 3 years	ND	ND	ND	ND	ND
	Cocoa 15 years	3.59	0.75	36.3	15.0	14.3
	Cocoa 30 years	4.85	1.32	58.9	16.0	10.0

[1] ND – not determined
[2] Rainfall Loading (net flux in throughfall) = (throughfall + stemflow) – Incident Rainfall
[3] Total Rain based input = Throughfall + Stemflow

Table 6.7 Quantities (kg $ha^{-1}yr^{-1}$) of nitrogen, phosphorus, potassium, calcium and magnesium lost through leaching and seed beans export in forest and cocoa land-use systems.

Land-use	Nutrient source	Total nutrient losses (kg ha^{-1} yr^{-1})				
		Total N	P	K	Ca	Mg
Forest	Leaching	6.7	0	7.3	0	0
	Harvest	0	0	0	0	0
	Total	**6.7**	**0**	**7.30**	**0**	**0**
Cocoa 3 years	Leaching	18.2	0	7.9	0	0
	Harvest	0	0	0	0	0
	Total	**18.2**	**0**	**7.90**	**0**	**0**
Cocoa 15 years	Leaching	9.0	0	7.7	0	0
	Harvest	5.38	1.25	4.32	1.16	1.39
	Total	**14.4**	**1.25**	**12.0**	**1.16**	**1.39**
Cocoa 30 years	Leaching	13.8	0	7.3	0	0
	Harvest	5.38	1.25	4.32	1.16	1.39
	Total	**19.2**	**1.25**	**11.6**	**1.16**	**1.39**

Leaching losses

The quantities of nutrients lost through leaching and harvest are in Table 6.7. The least N leaching losses (6.7 kg $ha^{-1}yr^{-1}$) occurred in the forest while the largest (19.2 kg $ha^{-1}yr^{-1}$) was in the 30-year-old cocoa farm. Amounts of potassium leached were similar (12 kg $ha^{-1}yr^{-1}$) in productive (15- and 30-year-old) cocoa systems. Generally, nutrient losses were greater on productive farms compared to forest and 3-year-old plots.

6.3.5 Input and output balances of nutrients

The annual fluxes of N, P, K, Ca and Mg received as inputs through incident rainfall and the amount lost as outputs through leaching and cocoa crop harvests (in the case of cocoa fields), and their resulting balances are in Table 6.8. In both forest and 3 year-old plots, P, K, Ca and Mg balances were positive; N loss was only marginal in forest (1.0 kg $ha^{-1}yr^{-1}$) but more than ten-fold on cocoa plots at 3 years. On 15 and 30-year-old cocoa plots, N and P balances were negative but K, Ca and Mg balances were positive.

The nutrient balances expressed as percentages of the total nutrient stocks (0-60 cm soil depth) in each land-use system are shown in Table 6.9. The balances for cocoa land-use are the means for each nutrient input-output balance for the productive (i.e., the 15 and 30-year-old) cocoa farms only. Generally, net nutrient losses under forest were smaller than under productive cocoa systems. For example while the net annual losses of total N for forest land-use was 1.0 kg $ha^{-1}yr^{-1}$ or 0.01% of total forest soil N stocks, it was 11 kg $ha^{-1}yr^{-1}$ or 0.2% of stocks in the productive cocoa systems. The gains in K, Ca and Mg were more positive in forest than in the cocoa systems.

Table 6.8 Annual input-output fluxes of N, P, K, Ca and Mg through incident rainfall, leaching and harvests and their resulting balances in forest and cocoa land-use systems.

Land-use	Input-output source	kg ha^{-1}				
		N	P	K	Ca	Mg
Forest	Input: Rainfall	5.70	0.41	13.6	9.43	5.60
	Output: Leaching	6.70	0	7.3	0	0
	Output: Harvest	0	0	0	0	0
	Balance	**-1.00**	**+0.41**	**+6.3**	**+9.43**	**+5.60**
Cocoa 3 years	Input: Rainfall	5.70	0.41	13.6	9.43	5.60
	Output: Leaching	18.2	0	7.90	0	0
	Output: Harvest	0	0	0	0	0
	Balance	**-12.5**	**+0.41**	**+5.70**	**+9.43**	**+5.60**
Cocoa 15 years	Input: Rainfall	5.70	0.41	13.6	9.43	5.60
	Output: Leaching	9.00	0	7.70	0	0
	Output: Harvest	5.38	1.25	4.32	1.16	1.39
	Balance	**-8.68**	**-0.84**	**+1.58**	**+8.27**	**+4.21**
Cocoa 30 years	Input: Rainfall	5.70	0.41	13.6	9.43	5.60
	Output: Leaching	13.8	0	7.30	0	0
	Output: Harvest	5.38	1.25	4.32	1.16	1.39
	Balance	**-13.5**	**-0.84**	**+1.98**	**+8.27**	**+4.21**

Table 6.9 Nutrient balances; losses (-) and gains (+) (kg/ha/yr), and soil nutrient stocks ($kg\ ha^{-1}$ for 0-60 cm depth) under forest and cocoa land-use systems.

Land-use/ Nutrient	Net nutrient losses/gains ($kg\ ha^{-1} yr^{-1}$)	Net nutrient losses/gains as a percentage of soil stocks (%)	Soil nutrient stocks ($kg\ ha^{-1}$)
Forest			
N	-1.00	-0.01	8,365
P	+0.41	+3.40	12
K	+6.30	+0.77	815
Ca	+9.43	+0.13	6,807
Mg	+5.60	+0.51	1,108
***Cocoa**			
N	-11.1	-0.19	5,717
P	-0.84	-17.0	4.9
K	+1.63	+0.18	914
Ca	+8.27	+0.10	8,124
Mg	+4.21	+0.16	2,705

*Mean balances and stocks are for productive cocoa agro-ecosystem (i. e. means for 15 and 30-year-old plots) since 3-year-old plots are not yet productive.

6.4 Discussions

6.4.1 Nutrient Inputs

Incident rainfall

Incident rainfall is not only an important source of nutrient input to the forest ecosystem but also an important means of nutrient transfer from the forest canopy to the forest floor (Chuyong *et al.,* 2004). Inputs through incident rainfall originate from wet deposition, which includes N-fixation through lightning, as N dissolves in water, and precipitate during rainfall. This is an important source of nitrogen, especially for the wet tropics, where many lightning storms occur (Bond *et al.,* 2002). Most of the basic elements probably originate from dust through dry deposition (Leite and Valle, 1990; Leeschen *et al.,* 2007).

According to Chuyong *et al.,* (2004), the concentrations of nutrients in incident rainfall are determined by many natural and anthropogenic factors including wind movements, incidence of fires and dusts, and distance from the sea. In the present study, Ca concentration was relatively high especially in the early wet season. Calcium is generally associated with airborne soil dust (Lovett and Lindberg 1984; Møberg *et al.*, 1991). The fine silt fractions in harmattan dusts carried from their source in the Chad basin for instance are known to be relatively rich in Ca. Tiessen *et al.* (1991) recorded ratios of Mg: K: Ca of 0.37:0.82:1 in northern Ghana, whilst Stoorvogel *et al.* (1997) found ratios of 0.11: 0.71:1 in trapped dust in the Taï Region of Côte d'Ivoire. The influence of the harmattan winds in the study district between the months of December to February could probably explain the high Ca contents in rainwater especially during the early parts of the rainy season. Concentrations of Mg in incident rainfall have been associated with maritime air masses. The study site experiences some maritime effect on the air masses especially in the main wet season when the inter tropical convergence zone moves to the North of West Africa with the moisture-laden SW Monsoon winds influencing all areas south of the convergence zone to cause rainfall.

Nutrient return through throughfall

In the present study, annual throughfall of 1,053, 1,147, 1,167 and 1,244 mm corresponds to 77, 83, 85 and 90% of total incident rainfall respectively for forest, 3, 15 and 30-year-old cocoa plots. High throughfall in these forests may reflect the relatively high rainfall during the rainy seasons. Parker (1983) indicates that the amount of precipitation controls the magnitude of throughfall.

The proportional amounts of throughfall recorded in the study are similar to, and lie within the range recorded for several other studies and provide a useful basis for comparisons between studies conducted in tropical and lowland eco-regions. In lowland rainforest in Sabah and in central Kalimantan, Asdak *et al.,* (1998) reported throughfall was 81 and 87% of annual rainfall respectively, while Marin *et al*., (2000) found it to be 91 and 85% respectively in central and western Amazonian lowland forest. Chuyong *et al.,* (2004) working in the Korup National Park in the Cameroons recorded throughfall volumes corresponding to 96.6 and 92.4% of incident rainfall with stemflow constituting 1.5 and 2.2% of the annual incident rainfall in two different forest types.

Precipitation chemistry is dramatically changed when rain passes through the forest canopy (Lovett and Lindberg, 1984). Three processes govern the chemical composition of throughfall: concentration due to the evaporation from the wet canopy, washout of the dry deposition e.g. dusts, vegetal and animal debris, decomposition over the vegetation and leaching of the nutrients in internal plant parts (Marques and Ranger 1997; Forti and Neal, 1992). For temperate forests, Parker (1983) concluded that throughfall tends to be enriched in base cations and depleted in NH_4^+ and NO_3^-, relative to precipitation. Our study and others in tropical rain forests, show a clear pattern of increased base cation fluxes in throughfall compared to precipitation (Table 5.4). This is particularly true for K, which typically can be 5-10 times greater than in rainfall (Asbury *et al.*, 1994; McDowell 1998, Veneklaas and van Ek, 1990). In this study, the weighted concentrations of K in throughfall for forest, 30, 15 and 3-year-old cocoa farms respectively were 4.2, 3.9, 2.5 and 2.4 fold the concentration of K in incident rainfall. For calcium, the ratio ranged from 1.4 for the 3-year-old plot to 2.0 for the 15-year-old farm. External origin (dry deposition) and internal cycling (leaching process) can account for most elements, with different intensities. Quantities of nutrient elements leached depend on levels of exchangeable elements in foliage and is driven by exchange reactions with rainfall-supplied hydrogen ions (Yawney *et al.,* 1978; Fan and Hong, 2001). The H^+ ions in rainfall easily displace those nutrients that are mobile within the plant and are translocated outside the cytoplasm. Thus K, a mobile nutrient in plants, is more easily leached to throughfall than Ca, which is incorporated into cell walls (Johnson and Lehmann, 2006). Foliar uptake occurs when lower elemental concentrations are found in plant tissue than in rainfall. The extent to which individual nutrients are leached appears to be dependent on the mineral nutrient status of the plant, and the balance that exists among elements (Yawney *et al.,* 1978).

The pH increased significantly from incident rainfall to throughfall in forest and cocoa stands. The increase could be caused by alkaline dust and ash on the vegetation canopy. As vegetation burns (bush fires) are common in the region, deposition of ash especially during the dry season could be the main cause of observed pH increase. Bruijnzeel (1989) has observed that when discussing nutrient fluxes with rainfall collected from bulk samplers, one has to bear in mind that they could be easily contaminated.

Nutrient return through stemflow

Stemflow production may be highly variable within a particular eco-region as a result of site specific differences. These include canopy structure and stand density (Martinez-Meza and Whitford, 1996), the presence or absence of epiphyte mats (Veneklaas and Van Ek , 1990), species composition and variation in bark texture (Navar *et al.,* 1999) and precipitation event frequency, duration, magnitude, and intensity (Crockford and Richardson, 2000; Kuraji *et al.,* 2001). The amount of precipitation partitioned by trees to stemflow ranges over more than three orders of magnitude, accounting for 0.07 – 22% of incident rainfall in a range of precipitation regimes (600-7,100 mm year^{-1}) in both temperate and tropical climates (Johnson and Lehmann, 2006). Stemflow volumes in our study constituted 1.5, 1.4 and 1.7% of incident rainfall in forest, 15 and 30-year-old cocoa plots respectively. These are in agreement with values obtained in the lowland rainforest of Sabah and central Kalimantan, where stemflow constituted 2 and 1% respectively of incident rainfall, and in central and western Amazonian lowland forests where values were 1 and 2% of incident rainfall (Lloyd and Marques 1988; Marin *et al.,* 2000).

Solute concentrations of P, Ca and Mg in stemflow were in most cases smaller than in both throughfall and incident rainfall while K concentration was greater in stemflow compared to throughfall. This could be attributed to the selective absorption of nutrients by the epiphytic bryophytes (mosses and lichens) growing on the stems/boles of cocoa trees as a result of the moist conditions that prevail under cocoa canopies. According to Houle *et al*., (1999), epiphytic plants and lichens contribute to uptake of nutrients from intercepted rainfall. Lui *et al.*, (2003) have also observed that the chemical composition of throughfall and stemflow may be affected by cryptogamic epiphytes through the selective uptake and or release of elements within moist forests.

Generally, stemflows' contribution to nutrient fluxes of rainfall origin to the forest floor is quoted to be between the ranges of 1 and 20% (Parker, 1983). Contributions of stemflow to total rain-based inputs in this study were 0.1-1.4, 0.2-1.6, 0.7-3.0, 0.4-2.0 and 0.1-1.7% for N, P, K, Ca and Mg respectively across the chronosequence. In a cocoa agro-ecosystem in south-eastern Nigeria, the contribution of stemflow to the total nutrients in rainfall (throughfall plus stemflow) in the 22-year-old plantation ranged from 1.9% for N to 11.4% for K (Opakunle, 1989). It appears that the contribution of stemflow to nutrient cycling differs among ecosystems with different species composition, different morphology and different structure (Bellot and Escarre, 1991; Tajcmann *et al.*, 1991).

Canopy interception

Canopy interception varies with the nature of canopy, leaf structure and size, raindrop intensity and raindrop size and other climatic conditions (Eaton *et al.*, 1973; Parker, 1983; Tsutsumi, 1977; Balieiro *et al.*, 2007). The smaller evaporation and interceptive losses of water in 30-year-old plots are attributable to the open canopy (resulting from tree mortality) that did not completely cover the soil. Additionally, the smaller stature of cocoa trees compared to the forest trees. In different eco-regions, interception losses will largely vary depending on amount of rainfall per annum and the proportion of rain falling in the day and night as this largely determines the degree of canopy evaporation (Parker, 1983).

Annual nutrient inputs

Contribution of rainwater to nutrients fluxes into the system was generally small approximately 6.0 kg $ha^{-1}yr^{-1}$ for N and Mg, while that of P, K and Ca were 0.41, 13.6 and 9.43 kg $ha^{-1}yr^{-1}$ respectively. Incident rainfall nutrient fluxes recorded in this study are smaller than that recorded by Leite and Valle (1990) in shaded and un-shaded cocoa systems in Bahia Brazil where rainwater contributions of N, P and Mg were respectively 43, 1 and 9 kg $ha^{-1}yr^{-1}$. Globally, rainfall N deposition rates are estimated to be 5 kg N $ha^{-1}yr^{-1}$ for less densely populated and non-industrial countries and range from 20 kg N $ha^{-1}yr^{-1}$ to 50 kg N $ha^{-1}yr^{-1}$ in countries of Western Europe and parts of China (Sheldrick *et al.*, 2003). Mengel and Kirkby (1996) also discussed that wet deposition for N can be as high as 60 kg $ha^{-1}yr^{-1}$ depending on proximity to a city and amount of precipitation. Fluxes in this study fall within the lower brackets. This is most probably due to the fact that sites for this study are located in an area with virtually no industries hence the likelihood of pollutants in the form of dry and wet deposition are minimal (Chiwa *et al*., 2003; Lovett *et al.,* 2000)

Largest increase in throughfall and (after incident rainfall has passed through the canopy) in all the land-uses was observed for K (Table 5.6), indicating that K had the largest possibility of leaching from canopy followed closely by Ca. This has been reported in the literature by Parker (1983), and Forti and Neal (1992).

Subtracting the average flux of elements in rainwater from the sum of the fluxes in throughfall and stemflow, the net flux of elements absorbed by leaves or leached from leaves to the soil (rainfall loading) in throughfall is obtained (Lian and Zhang, 1998; Chuyong *et al*., 2004). The net fluxes of N across the chronosequence was negative indicating absorption of N by canopy while positive values for the basic nutrients indicate leaching (recycling) of these nutrients from foliage. Under the forest land-use for instance 69, 59, 19 and 41% of P, K, Ca and Mg respectively in total rain-based inputs were recycled to the forest floor while for the 30-year-old plots, recycling accounted for 69, 67, 41 and 44% of nutrients (P, K, Ca and Mg respectively) getting to the forest floor as rain-based inputs. As a general trend, input rates of P were the least across the chronosequence as a result of the small quantity of native P in plant and soil systems.

6.4.2 Nutrient output

Cocoa bean harvests and leaching

According to Hartemink (2005), most nutrients in cocoa systems are lost by the removal of pod husks (where these are exported from farms for other uses) and cocoa seed beans. In the present study 5.4 kg N, 1.0 kg P, 4.3 kg K, 1.2 kg Ca and 1.5 kg Mg $ha^{-1}yr^{-1}$ respectively were removed through seed beans export. These values are smaller compared to 20, 4 and 10 kg $ha^{-1}yr^{-1}$ of N, P and K respectively recorded by Hartemink (2005) when data from six countries were pooled together. The large harvest yields (an average of 1000 kg ha^{-1}) from these countries probably explains these high removal rates. It is not clear if these are from fertilized systems but it does appear that the soils in question were more fertile than our soils and some were from experimental sites, which are better managed than pertains on the small farmer fields in our study. With the on-going mass spraying exercise of cocoa farms in the country coupled with improved farm hygiene practices being extended to farmers, cocoa yields in the district are increasing (COCOBOD, personal communication). It should be expected that these would translate into increased nutrient exports.

Leaching is an important pathway for nutrient losses in soils in the humid tropics (Lesschen *et al.*, 2007). Leaching is a significant loss mechanism only for some nutrients only (Roy *et al.,* 2003) especially in cocoa systems. In the tropics, P is tightly bound to soil particles and leaching in this study was assumed to involve only N and K (Roy *et al.,* 2003; Kanmegne *et al.,* 2006). Leaching losses from the present study (6.7-18.2 kg N ha^{-1}) and (7.3-7.9 kg K ha^{-1}) for forest and 3-year-old cocoa plots respectively are low compared to mean annual losses of 22 kg N and 17 kg K recorded in a study with cocoa on Alfisols in Bahia (Leite, 1985). Reports from cocoa on Psamments in the lowlands of Venezuela showed that leaching losses under traditional shaded-cocoa were low, though leaching may be high when inorganic fertilizers are applied in such light-textured soils (Aranguren *et al.,* 1982).

Cocoa pod husks

Several authors (e.g. Ahenkorah and Akrofi 1969; cited by Appiah *et al.,* 1997; Hartemink, 2005) have confirmed that nutrient losses in cocoa systems are considerably greater when the nutrient contents of husks which are usually left at pod breaking points are considered. The 543 kg ha^{-1} of cocoa pod husks produced on farms in the study contained 6.2 kg N, 0.54 kg P, 18.3 kg K, 4.3 kg Ca and 2.0 kg Mg ha^{-1} respectively, which shows that K removal by husks is very high. If returned to the soil, pod husks could compensate for losses of N, K, Ca and Mg through cocoa beans exports. Under current practices, nutrients in pod husks are concentrated on just a small portion of the cocoa fields. Analysis of soil samples from pod breaking points indicated greater average organic C percentage of 4.4% compared to 2.5 %, and greater total N % of 0.6 compared to 0.19 % recorded for samples further away from the pod breaking bays. There is therefore the need to develop management strategies that will lead to more efficient utilization of nutrients from natural sources such as pod husks. To derive maximum benefit, farmers would need to be educated on how to handle diseased pods so as not to spread other disease causing pathogens.

6.4.3 Input and output balances of nutrients

Recorded nutrient balances in the study indicated that generally the least loss of net nutrients was under forest land-use while the largest losses were found in the 3-year-old shaded-cocoa system. Using the nutrient balance approach, the net removal of N was 11 kg ha^{-1} yr^{-1}. However results of the chronosequence study (Chapter 4, Table 4.7) showed a higher annual decline of N stocks (0-60 cm) of 0.8 % of initial forest stocks, which is about 66 kg $ha^{-1}yr^{-1}$. This suggests possibility of additional N output pathways (e.g. volatilization losses), which were not measured using the nutrient balance approach. Dechert *et al.*, (2005) made similar observations in Central Sulawesi, Indonesia and stated that partial nutrient balances on their own may not be very good indicators of nutrient sustainability of land-use systems.

In the case of P, annual decline was about 10% of initial forest stocks in the 0-60 cm depth. This is worrying as P may be generally more limiting because of the small mass in circulation in most forests and the small inputs from the atmosphere to compensate for losses from the available pools. Losses of ecosystem P are generally attributed to fixation and/transformation of extractable P by iron and aluminium oxides in highly weathered acid soils, and phosphates in near neutral soils (Anderson and Spencer 1991; Szott *et al.*, 1999).

Lastly K, Ca and Mg do not appear to be limiting in these cocoa systems since balances are positive (+1.63, +8.27 and +4.21 respectively) most probably as a result of deep root capture to replace those removed through harvests and the absence of exports under forest land-use. The results suggest that farmers who are in position to pay for chemical fertilizers could opt for P fertilizers.

6.4.4 Promoting new management techniques

It is envisaged that, cocoa pod husks when recycled could modify and marginally improve nutrient balances in these cocoa systems. The current practice of leaving husks piled at breaking points not only concentrates nutrient at a particular area (usually out of the reach of most of cocoa trees on farms), but also serves to harbor pathogens which could lead to disease outbreaks on farms. If cocoa pod husks are efficiently recycled then the balances of -11.1, -0.51, +1.63, +8.27 and +4.21 respectively for N, P, K, Ca and Mg will improve to -4.9, +0.03, +19.8, +12.6 and +6.21 respectively. The major challenge is to develop efficient ways of utilizing pod husks as a source of nutrients. This calls for further studies. First study needs to investigate why farmers do not make use of pod husks as soil amendments, and then secondly, to find the most appropriate way/s to use pod husks. Using pod husks to improve soil fertility would also serve to improve farm hygiene on cocoa farms as pod husks have been noted to harbour disease-causing pathogens (Anim-Kwapong, *personal communication*). It could be possible to bury pod husks systematically from one end of the farm towards the other end. Pod husks could also be composted and applied to the farm. Farmers would need to be trained as to how this can be done effectively.

6.5 Summary and conclusions

The main source of external nutrient input to the small-holder shaded cocoa systems is incident rainfall. The contribution of incident rainfall's to nutrient fluxes to the forest floor was estimated to be 6.0 kg N, 0.5 kg P, 14.0 kg K and 9.0 kg Ca and 6 kg Mg $ha^{-1}yr^{-1}$. Base cations are increased in throughfall while total N is reduced compared to precipitation. Nitrogen (N) inputs to the forest floor are mainly from incident rainfall while P, K, Ca and Mg inputs are due to canopy leaching. Nutrient fluxes in throughfall in forest and shaded cocoa systems ranged between 3.1 – 4.82 kg N, o 65 – 1.32 kg P, 32.4 – 58.5 kg K, 9.96 – 15.9 kg Ca and 9.4 – 14.0 kg Mg $ha^{-1}yr^{-1}$. Stemflow contributions of nutrients to the forest are insignificant. Nutrient dynamics of stemflow solution associated with epiphyte interactions fall in two groups. Potassium in stemflow was enriched while N, P, Ca and Mg are impoverished (indicating absorption by epiphytes and microbes) compared to throughfall concentrations.

Input-output balances of nutrients indicated that total N balance was marginally negative under forest land-use while P, K, Ca and Mg were positive. Under shaded-cocoa systems, annual balances were negative for N but accounted for relatively small fractions (below 1%) of total N stocks and suggest sustainable nitrogen nutrition under these systems. Available P losses in shaded cocoa systems were high amounting to 17% of soil stocks.

There is the need to adopt management strategies that will minimize P losses and improve P balance. The high losses of P from shaded-cocoa systems need to be compensated for. High soil N stocks and positive balances of K, Ca and Mg suggest that farmers could reduce the use of N fertilizers. To compensate for P deficits and enhance N recycling under shaded-cocoa systems, management options proposed include:

a) The efficient utilization of cocoa pod husks (CPH) as soil amendments
b) The application of phosphatic fertilizers, and
c) The conscious introduction of N-fixing trees at the time of plantation establishment or in the case of old farms, planting them in gaps created by dying cocoa or upper canopy trees. Nitrogen fixing trees could also be densely planted along boundaries and pruned at the start of the rainy seasons and the prunings applied as mulch.

Results of soil fertility-related studies conducted at lower spatial scales as in this study can be used to provide a forum for dialogue and debate between scientists/extension agents and policy formulators with end-users on management interventions and options to enhance nutrient cycling. What farmers do to sustain fertility on their farms depends on their knowledge and understanding of nutrient cycling processes. Consequently, the next chapter explores farmers' local knowledge and perceptions of soils and soil fertility processes. How do these perceptions influence farmers' fertility management strategies? How do farmer perceptions match scientific assessments of soil fertility? How can farmers, scientists and extension agents cooperate to facilitate innovations for enhanced nutrient cycling and policy formulation for nutrient management? In chapter 7, I respond to these questions by exploring farmers' local knowledge of soil fertility in the research district.

CHAPTER 7

FARMERS' LOCAL KNOWLEDGE AND PERCEPTIONS OF SOILS IN RURAL COMMUNITIES IN A SEMI-DECIDUOUS FOREST ZONE IN GHANA

Abstract

Farmers' local knowledge and perceptions of soils and their fertility processes play a significant role in fertility management systems and are important for the participatory development of interventions to sustain productivity. A field study of 192 farm households was conducted in the Atwima Nwabiagya District of the Ashanti Region of Ghana to assess farmers' local knowledge and understanding of soil fertility and fertility processes, and how this knowledge influences their soil fertility management strategies. Farmer's local knowledge on soils was not age, location, marital status, or gender dependent, and socio-economic characteristics were consistent between research communities. Their perceptions of soil fertility centred around observable plant and soil related characteristics namely, soil colour, crop yield , soil's water holding capacity, stoniness, difficulty to work soil, type and abundance of indicator weeds, colour of leaves or the level of deficiency symptoms observed on crops, crop growth rate and presence and abundance of soil macro-fauna. The quantitative perceptions and knowledge of farmers matched scientific assessments of fertile and infertile soils in several respects. The results suggest the integration of local and scientific knowledge to facilitate the processes of for formulations of policies and development plans for agriculture using truly participatory, gender sensitive, collaborative and capacity-building approaches.

Key words: Local soil knowledge; soil fertility processes; fertility indicators; nutrient cycling; participatory and collaborative approaches.

7.1 Introduction

Indigenous knowledge, also referred to as ethno-science, traditional, local, folk, and native knowledge can be defined, relative to agriculture in its broadest sense, as accumulated knowledge, skill and technology of local people derived from their direct interaction with the environment (Altieri, 1990). Though based on experience passed from one generation to the next, local knowledge nevertheless changes, adapts and assimilates new ideas. It can be quite specific to location and may vary between individuals from different social groups according to differentiating factors such as age, gender, wealth, ethnicity and occupation (Pawluk *et al.*, 1992).

The literature on farming systems research recognizes that traditional subsistence farmers throughout the tropics maintain a deep understanding of their local ecosystems; and that their knowledge of soils and their management plays an important role in developing more sustainable farming systems (Krogh and Paarup-Laursen, 1997; Talawar and Rhoades, 1998; Quansah *et al.*, 2001). Several studies have been undertaken to assess farmers' knowledge and perceptions about soils (e.g. Talawar and Rhoades, 1998; Corbeels *et al.*, 2000; Ali, 2003). Research in this area has predominantly focused on documenting how farmers classify their soils (Birmingham, 2003; Sandor and Furbee, 1996). Less attention has been paid to farmers' perceptions of soil fertility and understanding of nutrient cycling processes and how these influence management practices. With increasing use of participatory research approaches, it is becoming clear that farmers' knowledge and perceptions of their soils and the identification of locally relevant indicators of soil quality are important resources for the development of technologies and management interventions (Asiamah *et al.*, 1997; Steiner, 1998;

Mulder, 2000) and for effective collaboration between farmers, scientists and extension workers to sustain productivity. WinklerPrins (1999) stresses that research needs to move towards linking local soils knowledge with sustainable land management, and Osunade (1992) emphasizes that the hope for sustainable agriculture rests on the integration of all experiences rather than reliance on one tradition at the expense of the other. However, the research literature largely fails to address the methodology for integrating the two knowledge systems for sustained land-use management. This study aims at examining farmers' local knowledge and perceptions of soils and their fertility processes and to recommend an approach for integrating local and scientific soil knowledge.

The specific objectives are to:

a) Identify farmers' local knowledge and perceptions of soil fertility and nutrient cycling processes and how they influence soil fertility management practices.

b) Determine indicators that are consistent with farmers' knowledge and concept of soil fertility and to find out the extent to which these correspond to scientific indicators.

c) Recommend a framework for integrating local and scientific soil knowledge for facilitating innovations for enhanced nutrient cycling.

This work is a step towards development of a method that will allow agricultural researchers and planners to understand and use local knowledge in combination with scientific understanding of soil fertility concepts. While 'knowledge' and 'perceptions' are perhaps subjective words, in this study, they are considered to be the understanding and mental images (obtained through the senses) the farmers had regarding their farm landscape as reflected in their response to both open, informal interviews and specific questions (Bellon, 2001; Leeuwis and Van den Ban, 2004).

7.2 Materials and methods

7.2.1 Site Description

A general description of the study sites including climate, vegetation and dominant soil types are described in sections 2.1, 2.2, 2.3 and 2.4 of the general methodology in Chapter 2.

7.2.2 Data collection and analyses

The study methodology was based on interviews (through questionnaire administration), focus group discussions and laboratory analysis of soil samples. The seven communities where the questionnaires were administered were selected after an initial reconnaissance visit to 13 communities. Questionnaires were pre-tested in one of the project communities that resulted in the re-formulation and modification of some terminologies. Subsequently questionnaires were administered to one hundred and ninety-two (192) randomly selected households in seven farming communities. Data gaps were filled by daily reviewing of completed questionnaires and conducting three focus group interviews, one before and the other two after questionnaire administration. Data collected was subjected to descriptive analysis of simple proportions and percentages using the SPSS Version 12 statistics software. In addition, chi-square (χ^2) analysis was used to test for independence of farmers' responses on communities and on farmers' personal, social and demographic characteristics (Gomez and Gomez, 1984).

7.2.3 Soil sampling and fertility assessment on selected fields

From the farmers interviewed, a subset of 21 (three from each community) was selected at random and asked to indicate their most fertile or infertile fields. Seven farms designated as fertile and another seven designated as infertile were selected. From each of these fields a 30 m x 40 m plot was demarcated and composite soil samples were taken to a depth of 0-15 cm from twelve spots along an S-shaped transect, air-dried and prepared for chemical analysis as described in section 3.2 of Chapter 3 under ‘Soil sampling and chemical analysis’.

7.3 Results

7.3.1 Respondents' personal and demographic characteristics

The age of respondents ranged between 17 and 78 years with an average of 43 years. Thirty-five percent of respondents were females and 65% males. A significant proportion of respondents (77.8%) had been educated at least up to the basic education level (i. e. primary, JSS and MSLC levels), while 14.9% had no formal education. Only 1.9% had had tertiary level education. There were no significant differences between farmers in relation to sex, age groups, marital status, and ethnic origin, membership of organized farmer groups and in educational background (Table 7.1).

7.3.2 Farmers' indicators for soil fertility

Indicators used by farmers to assess the fertility status of their soils, the specific indicators used to classify soils as fertile or infertile and the proportions of farmers mentioning those indicators are in Table 7.2.

Following the approach of Dezbiez *et al.,* (2004), these fertility indicators could be grouped into: i). ***Soil characteristic indicators*****:** soil properties that the farmers felt characterized fertile or infertile soils, ii). ***Crop performance indicators*****:** crop characteristics reflecting soil fertility status, iii) ***Topographical indicators*****:** factors relating to the position of field along the toposequence which the farmers felt influenced soil fertility and, iv). ***Biological***

Table 7.1 Chi-square Analysis of differences in selected personal and demographic characteristics of respondents in communities in the Atwima Nwabiagya District.

Personal/demographic Characteristic	COMMUNITIES Akrofrom % (n = 31)	Amanchia % (n = 45)	Apaahkrom % (n = 10)	Kyreyiasi % (n = 19)	Nkaakom % (n = 38)	Nkonteng % (n = 24)	Seidi % (n = 24)	χ^2 Value	Significance
Sex								χ^2 =12.073	
M	10.3	14.8	3.9	8.9	13.3	8.4	7.0	df = 6	NS
F	4.9	12.3	1.1	0.5	6.5	4.0	5.0	p-value = 0.061	
Age Group									
17-36 yrs.	4.9	7.4	2.5	1.1	7.6	4.9	1.1	χ^2 = 21.550	NS
37-55 yrs.	8.4	12.3	2.2	6.5	7.6	4.3	3.8	df = 24	
>55 yrs.	2.0	7.4	1.1	2.7	5.9	4.3	3.8	p-value = 0.606	
Marital Status									
Married	10.3	23.8	2.7	8.6	16.2	11.9	4.9	χ^2 = 10.784	
Single	1.1	1.6	0.5	1.1	2.7	1.6	1.1	df = 18	
Divorced	1.6	2.7	0.5	0.5	1.6	0.0	0.0	p-value = 0.903	NS
Widowed	1.6	1.6	0.5	0.0	0.5	0.0	0.5		
Educational Status*									
Primary	5.9	4.3	1.1	1.6	3.2	2.2	1.6		
JSS	1.6	2.7	0.0	0.7	3.9	3.2	0.0		
SSS	0.5	1.6	0.5	0.5	1.1	0.5	0.0	χ^2 = 50.717	NS
MSLC	5.9	14.1	2.7	5.9	10.8	3.2	3.2	df = 36	
Com./Voc./Tertiary	0.0	0.0	0.0	1.2	0.0	0.0	0.7	p-value = .0530	
None	0.5	7.0	0.0	0.5	1.6	4.3	1.0		
Ethnic Origin								χ^2 = 6.966	
Indigene	11.9	27.6	3.9	8.6	17.8	11.9	4.9	df = 6	NS
Migrant	2.7	2.2	0.5	1.6	3.20	1.6	1.6	p-value = 0.342	
Membership of Farmer associations									NS
Yes								χ^2 = 9.930	
No	5.4	7.6	1.1	3.9	1.60	7.0	1.6	df = 6	
	9.2	22.2	3.2	6.5	16.8	6.5	4.7	p-value = 0.128	

Source: Author's Field Survey, February 2007.

*(JSS=Junior Secondary School; SSS= Senior Secondary School; MSLC= Middle School Leaving Certificate)

Table 7.2 Farmers' specific indicators and percentage of farmers mentioning those indicators for assessing soils as fertile or infertile.

Indicator	Fertile soils	Infertile soils
Crop performance		
▪ Crop growth rate (38%)	▪ Fast/high growth rate (22%)	▪ slow plant growth (24%)
▪ Crop yield (86%)	▪ Consistently high yields (83%)	▪ Low yields (76%)
▪ Colour of leaves of growing crops (36%)	▪ Large green leaves (35%)	▪ Small/stunted yellowish leaves (10%)
Soil characteristics		
▪ Soil colour (100%)	▪ Dark colour (92%)	▪ White/pale/light (75%)
▪ Moisture holding capacity (86.5%)	▪ High (75%)	▪ Low (62.4%)
▪ Soil workability (85%)	▪ Easy to work (74%)	▪ Difficult to work (79%)
▪ Stoniness of soil (48%)	▪ Few stones and pebbles present (19%)	▪ Numerous stones and pebbles present (27%)
Biological characteristics		
▪ Presence of worm casts (70%)	▪ Numerous wet worm casts (68%)	▪ Few worm casts (65%)
▪ Presence of soil macro-fauna (65%)	▪ Earthworms, beetles and millipedes present (55%)	▪ Few (38%)
i. Presence of indicator weeds (58.2%)	▪ *Chromolaena odorata* with large green leaves	▪ *Chromolaena odorata* with small yellow leaves ▪ Grassy weeds
Topographical factors		
▪ Position on slope (25%)	▪ Valley bottom, lower middle slope (16.0%)	▪ Upper slopes/summits (6%)

Field Survey Data, February 2007.

indicators: plants (other than crops) or animals whose presence or growth reflected soil fertility status. According to the farmers, fertile soils are dark in color (92% of respondents), consistently produce high crop yields (83% of respondents), have high water retention capacity (75%), are easy to work (74% of respondents), have numerous wet worm casts (70%), produce crops and plants with large green leaves (35%), and have 'soil animals' present (65%). The farmers indicated further that, infertile soils on the other hand are difficult to work (79%), give low yields (76%), are pale or light colored (75%), and have low moisture holding capacity (62%).

7.3.3 Local soil fertility related terminologies

Farmers use diverse terminologies to express the fertility status and other fertility-related attributes of soil (Table 7.3). *Asaase* (land/soil) and *nortiɛ* (soil) are used interchangeably. Soil with high fertility status is variously described as *asaase a sradeɛ wo mu* (land/soil with fat), *asaase a aduane wo mu* (land/soil with food) or *asaase a ahourden wo mu* (land/soil with strength). Soil with low fertility is described as *asaase no abrɛ* (the land/soil is tired), *asaase mu sradeɛ asaη* (the fat in the soil/land is finished), *asaase mu ahoɔden asa*ŋ (the strength in the soil/land is diminished) or *asaase mu aduane asaη* (the food in the land is finished).

Land that has been fallowed long enough to regain its strength is described as *asaase biriɛ* (matured/ripe land). Red and clayey soils are referred to as *nortiɛ kɔkɔɔr* and *nortiɛ twintwaan(* literally elastic soil) respectively, *while* white/pale soil *is* described as *nortiɛ fitaa or nortiɛ fufuo.* Sandy soil is simply described as *anwhia.*

Table 7.3 Local soil fertility and related terminologies and concepts.

Local Akan Terminology	Literal meaning	Explanation/meaning or scientific equivalent
Asaase	Land (or soil)	Soil
Ahoɔden	Strength	Fertility
Sradeɛ	Fat	Soil nutrients
Aduane	Food	Soil nutrients
Asaase a sradeɛ wo mu	Land/soil with fat	Fertile soil
Asaase a ahoɔden wo mu	Land/soil with strength	Fertile soil
Asaase a aduane wo mu	Land/soil with food	Fertile soil
Asaase no yɛ din	The land/soil is hard	High density/hard soil
Asaase no abrɛ	The land/soil is tired	Soil has reduced fertility
Asaase mu ahoɔden asaŋ	The strength in the land/soil is finished	The soil nutrients are depleted
Asaase mu aduane asaŋ	The food in the land/soil is depleted	The soil nutrients are depleted.
Nortiɛ	Soil	Soil
Beposo	On the hill	Upland soil
Asaase tuntum	Black soil	Fertile soil
Asaase biriɛ	Ripe soil/land	Dark soil
Nortie fitaa/fufuo	White soil	Light soils
Nortiɛ kɔkɔɔr	Red soil	Heavy/ clayey soils
Nortiɛ twintwaan	Elastic soil	Clayey soil
Afornwea	Wet sand/soil	Sandy/alluvial soils

Field Survey Data: February 2007.

7.3.4 Farmers' understanding and knowledge of soil fertility and nutrient cycling processes

Farmers' knowledge and understanding of certain concepts related to soil fertility and fertility maintenance are in Table 7.4. Majority of the farmers displayed an excellent knowledge and understanding of the causes of soil fertility decline, the fate of litter on the forest floor, the roles of macro-fauna and soil organic matter. They were also able to recognize soils with high organic matter. About 80% of respondents attributed fertility decline to continuous cropping without fertilizer (organic or inorganic) application. Ninety seven percent of respondents explained that plant litter and organic materials decompose and provide plant nutrients. All respondents have observed soil macro-fauna notably earthworms, centipedes/millipedes, termites, ants and beetles in soils on their farms. Majority (85.4 %) of farmers) articulated their belief and understanding that soil macro-fauna facilitate the breakdown of organic materials and help in improving soil fertility.

7.3.5 Farmers' soil fertility management practices.

The most widely used fertility management practices include slash and no burn *(proka)*, application of crop residues and retention of selected trees on farmlands used by 80, 75 and 36% of farmers respectively.

Other practices adopted by farmers to sustain fertility are application of poultry manure (17% of respondents), inorganic fertilizer application (13%), minimum tillage (13%) and fallowing (11%) (Table 7.5). The selective retention of trees during land clearing also constitutes an important component of soil fertility management by farmers.

Table 7.4 Summary of some of the responses to questions relating to farmers' knowledge of soil fertility related concepts and the proportion of farmers giving those responses. Percentages are proportions of respondents giving the responses indicated.

Concept	Responses and frequency (%)
Causes of fertility decline	Continuous cropping without fertilizer application (79.1%), deforestation (15.3%), low rainfall (9.5%), high rainfall (8.4%), bushfires (7.6%).
Recognition of soil organic matter in soil	Black colour of soil (85.2%), presence of soil fauna (54.8%), high water holding capacity (39.5%), smell and odour from soil (7.4%).
Role of soil organic matter	Provides plant nutrients and improves soil fertility (96.6%), improves water holding capacity (62.3%), improves soil texture (feel) and permeability (24.7%); attracts soil fauna (26.7%)
Role of soil macro-fauna	Feed on, and break down soil organic material and improve soil fertility (85.4%), damage crops and cause diseases (23.3%), create channels in soils for air and water (21.4%)
Constraints to organic materials' management and utilization	Transportation problems (60.9%), labour shortage (25.2%); lack of information and knowledge on utilization of SOM (59.2%), offensive odour (4.4%)
Fate of fallen litter	Decomposes and releases nutrient to soil (97.5%), don't know (2.5%)

Sums over 100% are due to multiple responses.

Field Survey Data, February 2007.

Fifty-two (52) upper-storey tree species were mentioned by farmers as being present in the cocoa farms and annual crop land-use systems in the district (Table 7.6). All farmers (100%) interviewed said that all the indigenous tree species on their farms were selectively left during land preparation, while the fruit trees (mainly mangoes, avocadoes and citrus were planted) as initial shade trees. Trees are generally classified as either positively or negatively influencing soil fertility (Tables 7.7 and 7.8). A number of trees namely *onyina, nyankyrene, wawa* and *odum* classified as positively influencing fertility by some farmers were also classified as negatively influencing fertility by others.

7.3.6 Comparison of farmer and researcher perceptions of soil fertility through soil chemical analysis

The results of the chemical analysis of soils identified by farmers as fertile and infertile are shown in Table 7.9. Mean pH values were 6.3 (fertile soils) and 5.6 (infertile soils) with most individual soil pH values falling within the ranges of 4.7 – 6.5 indicating strongly to mildly acidic conditions. There was a strong correspondence between the farmers' assessment of fertility and measured soil chemical characteristics. Fields that were described by farmers as fertile were found on average to have significantly higher percentage organic matter, total N, available P, exchangeable K and soil pH.

Table 7.5 Soil fertility management practices and their main constraints in the Atwima Nwabiagya District, Ashanti Region.

Soil fertility management practice	**Frequency (%)****	**Local Terminology**	**Constraints**
Slash and no burn (Zero burning after land clearing)	79.8	*proka*	• Termite infestation, • Bushfires
Application of crop residues (No burning after harvesting)	74.6	*proka*	• Termites
Retention of trees on croplands	35.6	*Ye gya ndua wɔ asase no so*	• Timber felling on farms • Too much shade
Application of poultry manure & composting *(mainly vegetable growers).*	16.6	*Ye de akokɔ bini gu asaase no so*	• Transportation, • Lack of knowledge in compost preparation • Labour, • Scarcity • Smell and odour
Inorganic fertilizer application	13.3	*Ye gu Fert*	• High cost of fertilizers
Minimum tillage (chemical weed control)	12.6	*Yɛ ŋhye nwura (proka)*	• High cost of spraying machines • Improper application procedures
Fallowing	12.3	*Ye gya asaase no to hɔ*	• Fragmentation/shortage of farmlands • Population growth

** Frequencies are percentages (%) of responding farmers who mentioned the indicated soil fertility management practices alone. Suma of percentages add up to more than 100% because of multiple responses.

Field Survey Data, February 2007.

Table 7.6 Tree species selectively left or planted on food crops and cocoa farms in the Atwima Nwabiagya District , Ashanti Region, Ghana.

Tree No.	Scientific name	Local Name	Family
1.	Alstonia boonei	*nyamedua*	Apocynaceae
2.	Albizia ferruginia	*awiemfosamea*	Mimosoceae
3.	Alchornia cordifolia	*gyama*	Euphorbiaceae
4.	Antiaris toxicaria	*kyenkyen*	Moraceae
5.	Bosqueia angolensis	*okure*	Moraceae
6.	Bombax buonopozense	*Akata/akonodie*	Bombacaeae
7.	Cedrella odorata	*gyenegyene*	Miliaceae
8.	Ceiba pentandra	*onyina*	Bombacaceae
9.	Celtis mildbraedii	*esa*	Ulmaceae
10.	Citrus sinensis	*ankaa/akutu*	Rutaceae
11.	Cola gigantea	*waapuo/otaapuo*	Sterculiaceae
12.	Elaeis guineensis	*abe*	Palmae
13.	Entandophragma angolensis	*edinam*	Meliaceae
14.	Entandophragma cylindricum	*sapele*	Meliaceae
15.	Entandophragma utile	*efuobrodedwo*	Meliaceae
16.	Ficus anomani	*odoma*	Moraceae
17.	Ficus capensis	*domene*	Moraceae
18.	Ficus exasperata	*nyankyrene*	Moraceae
19.	Funtumia elastica	*funtum*	Apocynaceae
20.	Khaya spp.	*Mahogany*	Meliaceae
21.	Lannea welwitschii	*kumnini*	Anacardiaceae
22.	Mallatus oppositofolius	*nyanyafrowa*	Euphorbiaceae
23.	Mangifera indica	*amango*	Bignoniaceae
24.	Margaritaria discoidea	*papea*	Euphorbiaceae
25.	Milletia thoningii	*sante*	Papilionaceae
26.	Millisia excelsa	*odum*	Moraceae
27.	Morus mesozygia	*wonton*	Moraceae
28.	Newbouldia laevis	*susumesa*	Bignoniaceae
29.	Persea americana	*Paya (pear)*	Lauraceae
30.	Piptadeniastrum africanum	*dahoma*	Mimosoceae
31.	Pterygota macrocarpa	*kyreye*	Sterculiaceae
32.	Pycanthus angolensis	*otie*	Myristicaceae
33.	Rauvolfia vormitoria	*kakapenpen*	Apocynaceae
34.	Ricinodendron heudelotii	*wama*	Euphorbiaceae
35.	Solanum erianthum	*pepediawuo*	Solanaceae
36.	Spathodia campanulata	*kokuoonisuo*	Bignoniaceae
37.	Spondias mombin	*atua*	Anacardiaceae
38.	Sterculia tragacantha	*sofo*	Sterculiaceae
39.	Terminalia superb	*ofram*	Combretaceae
40.	Terminalia ivorensis	*emire*	Combretaceae
41.	Tetrapleura tetraptera	*prekese*	Mimosoceae
42.	Tieghemellia heckelii	*abako*	Sapotaceae
43.	Trichilia monadelpha	*tanuro*	Meliaceae
44.	Triplochiton scleroxylon	*wawa*	Sterculiaceae
45.	Uvariastrum pierreanum	*akumabae*	Annonaceae
46.	Amphimas pterocarpoides	*yaya*	Caesalpiniaceae
47.	*	*adukuro*	
48.		*danan*	
49.		*wasaninkrumah*	
50.		*kutreamfo*	
51.		*owono*	
52.		*menyedua*	

*Scientific and family names of species 47-52 could not be identified

Table 7.7 Tree species most mentioned as positively influencing fertility of soils and/or having other desirable attributes in traditional land uses. (The frequency is the percentage of farmers who mentioned the species**).**

Local name	Scientific name	Frequency (%)	Attributes that make species desirable
Ofram/framo	Terminalia superba	21.5	- Does not produce too much shade. - Draws water from the deeper layers.
Onyina	Ceiba pentandra	21.0	- Floral and leaf litter fall improves soil upon decomposition in rainy season. - Gathers dew in the dry season and prevents soil from drying. - Woody parts decompose rapidly and add to fertility. - Soil around always wet.
Nyankyrene	Ficus exasperata	18.0	- Stumps exude water when cut
Wawa	Triplochiton scleroxylon	11.5	- Leaf litterfall improves soil fertility - Woody parts decompose rapidly and add to soil fertility
Nyamedua	Alstonia boonei	10	- Provides good shade and maintains soil moisture. - Gathers dew/exudes water.
Odum	Milicia excelsa	9	- Provides good shade, improves microclimate. - Leaf litter improves soil conditions.
Sesemasa	Newbouldia laevis	8.5	- Gathers dew especially in the dry season. - Narrow crown cover and therefore provides just enough shade.
Kookuonisuo	Spathodia campanulata	7.5	- Leaf litterfall improves soil fertility.
Okore	Trilepisium madascariense	7	- Provides good shade, improves microclimate. - Leaf litter improves soil conditions. - Root exudates contribute to improving soil fertility.
Paya	Persea americana	6.5	- Good as initial shade tree. - Decomposing litter and fallen fruits improve soil fertility. - Provides extra income from fruits sale

Percentage sums of over 100% are due to multiple answers, ie, farmers mentioning more than one tree specie for particular attributes.

Field Survey Data, February 2007.

Table 7.8 Tree species most mentioned as negatively influencing fertility of soils and/or having other undesirable attributes in traditional land uses. (The frequency is the percentage of farmers who mentioned the species)

Local name	Scientific name	Frequency (%)	Attributes that make species undesirable
Onyina	Ceiba pentandra	24.0	- Large crown and produces too much shade
Nyankyrene	Ficus exasperata	23.5	- Absorbs a lot of water from soil - Leaves decompose slowly - Canopy intercepts rainfall and especially dew
Waapuo/ Otaapuo	Cola gigantea	23.5	- Leaves decompose slowly
Wawa	Triplochiton scleroxylon	16.5	- Absorbs a lot of water from soil - Leaves decompose slowly - Branches break and destroy crops - spreads mistletoes
Akata	Bombax buonopozense	9.0	- Hosts and spreads mistletoes - Branches are brittle, break and destroy crops - Thorny bark causes injury
Odum	Milicia excelsa	4.5	- Leaves decompose slowly
Dahoma	Piptadeniastrum africanum	2.5	- Dense canopy - Extensive root system - Draws a lot of water from soil and dries soil beneath canopy
Gyenegyene	Cedrella odorata	2.5	- Offensive smell - Repels useful organisms
Esa	Celtis mildbraedii	2.0	- Draws a lot of water from soil and Dries soil beneath canopy
Kyenkyen	Antiaris toxicaria	1.5	- Draws a lot of water from soil and makes it very dry

Percentage sum of over 100% are due to multiple answers, i.e., farmers mentioning more than one tree specie for particular attributes.

Field Survey Data, February 2007.

Table 7.9 Chemical analysis in the top 0 -15 cm soil depth of fields classified as fertile and infertile by farmers. Values are means (±SE) from seven different plots (n=7).

Soil chemical parameters	Fertile soil	Infertile soil
pH	6.5 (±0.48) [a]	5.6 (±0.61) [b]
Total Nitrogen (%)	0.27 (±0.05) [a]	0.13 (±0.05) [b]
Available Bray's P (ppm)	3.12 (±0.86) [a]	2.10 (±0.59) [b]
Available Bray's K (ppm)	136.1 (±16.1) [a]	90.4 (±16.3) [b]
Organic Matter (%)	2.90 (±0.51) [a]	1.93 (±0.33) [b]
Base Saturation (%)	95.5 (±2.84) [a]	82.7 (±7.7) [b]
Bulk density (gm/cm^3)	1.19 (±0.14) [a]	1.44 (±0.17) [b]

Mean parameters (in the same row) for fertile and infertile soils with different superscripts not significantly different at $P < 0.05$ level using Tukey's HSD range test.

7.4 Discussion

7.4.1 Farmers' concepts and indicators of soil fertility and their terminologies

Results of the study show that farmers in the Atwima Nwabiagya district of Ashanti Region have a well-defined and comprehensive set of indicators that they use to classify and assess the fertility status of their soils. Generally, these are characteristics of the soil they can see, feel, or smell and are based on their experiences gained from cultivating their fields. Their indicators include colour of soil, crop yield, water holding capacity, colour of leaves or deficiency symptoms, the presence of indicator weeds, crop growth rate /vigor and the presence or absence of macro-organisms. In their studies on local soil knowledge and differential soil fertility management practices in the Wassa Amenfi and Wenchi Districts, Moss (2001) and Adjei-Nsiah *et al.,* (2004) reported farmers coming up with indicators and soil fertility concepts and terminologies similar to what was recorded in the present study. Similar indicators have been identified by studies in other parts of the world. In Kenya for example, farmers' criteria for distinguishing soil productivity included ease of tillage, soil moisture retention, and the presence of weeds and soil invertebrates (Murage *et al.,* 2000). In northern Ethiopia, Corbeels *et al.,* (2000) found that farmers distinguished three different soil types according to yield, topography, soil depth, colour texture, water holding capacity, and stoniness.

In these and other ethnopedological studies (e.g. Sandor and Furbee, 1996; Gobin *et al.*, 2000), soil colour was the most widely used indicator by farmers to classify their soils and local people link black soil colour to high organic matter content. This was also the case in our study where black soils (*nortiɛ tuntum), also known as* (*asaase biriɛ*) matured/ripe soil are the most fertile, and white/pale soil (*nortiɛ fitaa/fufuo)* are the least fertile and are a result of lands being farmed continuously with little or no organic inputs. According to Krull *et al.,* (2004), soil color is often used as the highest categorical level in many soil classification systems and good soil conditions are associated with dark-brown colours near the soil surface, which is linked to relatively high organic matter levels, good soil aggregation and high nutrient levels (Peverill *et al.,* 1999).

More than half of farmers interviewed mentioned the presence of certain weeds as indicators of soil fertility. Most farmers observed that the presence of grassy weeds indicated decrease in fertility status of the soil. While some authors have noted that the ability of weeds to act as unambiguous indicators is limited because their presence may reflect cropping practices rather than soil conditions, Corbeels *et al.,* (2000) and several others (e.g. Barrios *et al.,* 1994; Fujisaka *et al*., 2000; Mango, 2000; Murage *et al.,* 2000) report that the use of weed species as indicators of soil fertility are widespread.

Apart from the use of specific indicators to describe the fertility status of soils, other terminologies include *sradeɛ* (fat), *aduane* (food), *aduane asa* (food is finished), *ahoɔden asa* (strength is finished), *twintwaan* (elastic) and '*asaase ahoɔden a ɛbua nɔbayɛ*' literally meaning the strength of the land that helps crops. As some farmers explained, strength (*ahoɔden)* denotes the soils ability to provide *sradeɛ (fat)* or *aduane* (food) as well as moisture to sustain not only plants but also macro-fauna during unfavorable periods. Farmers' concept of soil fertility therefore goes beyond nutrient provision during favorable growth periods alone. These terminologies should be viewed as an aggregate of concepts referring severally to the lands ability to provide plants with moisture, nutrients, physical support, beneficial macro-fauna, even resistance to diseases and indeed all other conditions required to enable the plant to satisfactorily go through a complete life cycle and survive during unfavorable periods.

Knowledge of soil fertility related processes and perceptions

Though farmers displayed variable depths of knowledge regarding fertility processes, results of the interviews indicate that, there is a large degree of fairly coherent and consistent shared knowledge between farmers and scientists. As well as recognizing soils with organic matter, a large proportion of farmers could explain the principal cause of fertility decline, the roles of soil organic matter, surface litter and soil macro-fauna. Farmers' knowledge of the biological component of the soil was limited to organisms that were visible to the eye, (i.e. macro and meso-fauna), and included earthworms, centipedes and millipedes, ants, snails, termites and beetles. Farmers are well justified in their observations that soil macro-fauna (or soil animals as they called them), positively influence soil properties. The macro-fauna are responsible for the primary decomposition, the first mechanical breakdown of freshly fallen plant material (Fragoso and Lavelle, 1992). Unlike the macro-fauna, soil microorganisms were never mentioned when farmers were describing soil biological activity. Farmers had a limited understanding of the existence of soil microorganisms as these were not visible, and no farmer could articulate the role of microorganisms in decomposition of vegetative matter. This indicates that farmers still possess rather large knowledge-gaps regarding phenomena that they cannot see. The importance of farmer understanding of microbial processes cannot be overstated, as management practices have the ability to affect soil microbial populations, and thus can change subsequent ecosystem functions that such microorganisms regulate (Grossman, 2003).

As farmers obviously have the capacity to understand processes that are visible, e. g. earthworm tunneling, their knowledge can be enhanced by training activities specifically focusing on 'invisible' ecosystem processes, such as microorganism activity where farmers can visualize complex or difficult-to-observe topics in a controlled setting (Sinclair and Walker, 1999). Formalized linkage of research institutions to rural producers via change agents (Castillo and Toledo, 2000) and hands-on activities such as litter bag experiments has been shown to be successful (NSTA, 1996).

7.4.2 Soil fertility management practices

Farming and soil fertility management practices in the study area have evolved over a long period and farmers have learnt to adopt fertility management practices relevant to their farming objectives and their socio-economic conditions as was asserted by Adedipe *et al.,* (2004). Zero burning (80% of farmers) and the retention of crop residues (75%) came up as the most widely used fertility management systems, an indication of a change from the traditional slash and burn/shifting cultivation system that was practiced when farmlands were abundant and population low (Table 7.5). Retaining trees on farmlands, manure and inorganic fertilizer application, minimum tillage and fallowing in that order of importance are the other techniques 12 to 36% farmers use to sustain fertility. Indeed fallowing (12%) is the least popular mainly because of land scarcity due to population growth.

The use of burning: slash and burn-slash and no burn.

Traditionally, farmers in southern Ghana burn the cut vegetation after clearing virgin or fallowed land. Farmers' principal reasons for burning the cut vegetation during land preparation are to rid the farm of excessive debris and obtain access to the land more easily. Only about 6% of the responding farmers admitted to consciously using burning as a soil fertility management tool while 80% of farmers said they use zero burning (*proka*) with the aim of sustaining or improving soil fertility. These farmers however agreed that, when land has been fallowed for a number of years, burning at least for the first season cannot be avoided, as it facilitates easy access to land for planting. An emerging trend in land preparation and weed control is the adoption of minimum tillage practices especially during the minor season. About a fifth of respondents (13%) use weedicides mainly (gramoxone, atrazine, and roundup) and plant through dead trash without tilling the land. Not only does the trash/mulch decompose and enrich the soil but also it saves on the labor cost of weeding.

Management and application of crop residues and composting

About 80% of all farmers claimed they do not burn crop residues (e. g. maize stalks) on their food crop farms but leave them on their farms as *in-situ* mulch. However, cocoa farmers have not developed a way of using pod husk residues as soil amendments. According to Adedipe *et al.,* (2004), farmers in south-western Nigeria bury cocoa pods mainly as an environmental management practice but also probably to return nutrient to the soil. It might be worth finding out why Ghanaian farmers do not utilize pod husks to improve soils. Obviously, there is the need to develop effective ways of using pods husks as soil amendments at the farm level compared to the present practice of piling husks at the pod breaking bays. Though the Cocoa Research Institute of Ghana is reported to have developed potash fertilizer from dried pod husks, the innovation is yet to be widely disseminated to farmers for use at the farm levels.

Fallowing and retention of trees on farmland

The traditional method of restoring soil productivity in traditional cropping systems is '*yei gya asaase no ato hɔ*' or leaving the land to fallowing. The longer the fallow period, the better the level of fertility generated. However, population pressure and land fragmentation have led to a shortening of the fallow periods (Quansah *et al.*, 2001). In the present study, farmers (12%) who are lucky to be able to leave their fields to fallow do that for 1-3 years.

Trees retained on farmlands (either in fallows or in continuous cropping systems) constitute the principal means by which soil organic matter is added to the soil. Useful or desirable tree species were those that improve micro-climate through shading and production of large quantities of easily decomposable plant litter, regulate soil moisture, provide fruits and food products, and have medicinal values. Some tree species considered by many farmers to play important roles in restoring soil fertility were also considered by a significant number of farmers to be undesirable on farms. This difference in perception appears to be more of a reflection of the importance a farmer places on a particular tree species, the differences in perceptions of integrating trees with crops, and the effects the trees are perceived have on crops at different stages of tree growth (Amanor, 1996; Nkyi, 1989).

Application of inorganic fertilizers

The use of mineral fertilizers is limited. Only 13% of farmers admitted to having used inorganic fertilizers within the last 3 years. This is mainly attributed to a lack of purchasing power on the part of most farmers. Some farmers especially those belonging to the Ministry of Food and Agriculture (MoFA) and the Sustainable Tree Crops Project (STCP) facilitated farmers groups intimated that they would use fertilizers if they had the means. The cocoa farmers through the farmer field schools (FFSs) have observed the general improvements on the demonstration farms because of fertilizer application and the improved management practices being promoted at FFSs. Fertilizer use is restricted to food crop farms.

Indeed apart from farmers attending the STCP farmer field schools who have seen improvements on demonstrations farms to which fertilizers have been applied, majority of farmers were of the opinion that "cocoa forests" like natural forest do not need soil amendments since like all forest soils, these soils are fertile.

7.4.3 Explaining farmer's current soil fertility management practices

Farmers' preferred choice of fertility management practices ranked in the order- slash no burn > application of crop residues> retention of trees > inorganic fertilizer > fallowing. An analysis of farmers' choice and use of particular soil fertility management practices can be made using Leeuwis and Van Den Ban's model for understanding farmers' practices (Leeuwis and Van Den Ban, 2004; Adjei-Nsiah *et al.,* 2004). The model suggests that what farmers do or do not do depends on four composite variables. These are: their '*evaluative frame of reference'* or what the farmers know and believe to be true about the biophysical and social environment, *'perceived self-efficacy'* or their confidence in their own capabilities to perform a practice which includes their perceived ability to mobilize resources and accommodate risks, the *'perceived effectiveness of the social environment'* which relates essentially to the issue of *trust in others and the ability* *of the socio-economic environment to support them,* and finally on the *'perceived social pressure'*, or the desires and expectations that other actors (e.g. spouses, children, relations, village leaders, etc.) have regarding the performance of certain practices.

A look at the soil fertility management practices and the proportions of responding farmers adopting the various practices, shows that a practice such as slash and burn/shifting agriculture which used to be widely practiced is currently being employed by fewer farmers, while in its stead a practice like zero burning (*proka*) in its different forms and the retention of trees on farmlands are being preferred. Although in the past, most farmers would fallow, slash and subsequently burn fields, the practice has reduced as a result of farmers' knowledge (evaluative frame of reference) with respect to the adverse long term effects of burning. When we consider farmers' evaluative frame of reference regarding the current use of zero burning (*proka*) and the other most preferred practices, it is obvious that in a situation where it is no more possible to fallow farmlands long enough to regain fertility, farmers know and maintain belief in the positive qualities of *proka* for the purpose of sustaining soil fertility, increased/sustained yields and greater income expectations, and reduced labour requirements for weeding. With their knowledge and understanding about the role of plant and leaf litter, they are adopting alternative practices based on fertility sustenance through litter/plant residues application. Obviously, they have the capabilities, skills and competencies (perceived self-efficacy) and can mobilize the resources for the application of their preferred practices. With fertilizer application for instance, not only did farmers express their inability to pay for fertilizers (perceived self-efficacy) as a reason for not using it, but some who belonged to farmers' groups and were privileged to be provided with fertilizers through the MoFA also said that on a number of occasions, fertilizers provided to them on credit did not arrive at the time they needed it i.e., adequate arrangement (perceived effectiveness of social environment) was not made to ensure that they were delivered on time. Though cocoa farmers were aware of the high fertility levels of soils at the pod breaking points and could explain the source of this high fertility, cocoa pod husks were never used consciously as soil amendments as knowledge and capability for pod utilization is low, i.e. there are bottlenecks in terms of the availability of technical skills and competencies (as related to perceived self efficacy) for their effective utilization.

7.4.4 Farmers' local soil knowledge and scientific pedology – any convergence?

According to Doran and Parkin (1994) and Barrios *et al*. (2006), technical indicators of soil quality usually include parameters such as bulk density, pH, effective rooting depth, water content, soil temperature, total C and electrical conductivity, while local indicators are often more variable and include crop yield and vigor, soil color, soil texture and structure, and the presence/absence or abundance of local plant and soil invertebrate species. Fields described by farmers as fertile were found on average to have significantly greater values of percentage of organic matter, total N, available P, exchangeable K, base saturation, a greater pH and smaller bulk density than those described as infertile (Table 7.9). This is very similar to the results of Murage *et al.* (2000) in Kenya where productive soils as identified by farmers, had significantly higher soil pH, effective cation exchange capacity, exchangeable cations, extractable P and total N than non-productive soils. Similarly, Corbeels *et al.* (2000) found that the classification used by farmers for fertile and infertile soils in the semi-arid highlands of Tigray, Northern Ethiopia, correlated well with scientists' classification of soil fertility status. Results of this study strongly indicate that not only is there sufficient overlap between perceptions and understanding of soil fertility by farmer and researcher but there is also significant agreement on most of the basic concepts from both farmers' and scientific points of view. Bentley (1992) has argued that both farmers and scientists/researchers have considerable knowledge of agriculture and traditions of experimentation but very different knowledge systems. While scientific research can provide the breadth of understanding of soil biophysical processes, farmers can provide the context-specific knowledge required to adapt this understanding to their local biophysical and socio-economic conditions and, local agricultural extension staff and other facilitators can play an important role in enhancing this essential link between the two worlds (Desbiez *et al.,* 2004).

7.4.5 Facilitating integration of local and scientific soil knowledge for enhanced nutrient cycling - Conceptual inputs and linkages

Having established that there is a strong correspondence between farmers' assessment of soil fertility and scientific perspectives; it is argued amongst others that, there is the need to take advantage of the complementary nature of local and scientific soil knowledge to facilitate their integration. Approaches to integration should aim at creating opportunities for the intensive sharing of knowledge and experiences, joint learning and reflection based on mutual respect (Engel, 1997), involving farmers and scientists/extensionist using truly participatory, gender sensitive and collaborative approaches. The success of integration is contingent upon the quality of interrelationship between farmers on the one hand and scientists on the other.

A suggested framework of inputs and linkages for the integration of local and scientific soil knowledge is given in Figure 7.1. The framework identifies two soil knowledge systems; the Local Soil Knowledge (LSK) and the Scientific Soil Knowledge (SSK). The influence of these two knowledge systems together with prevailing natural environmental phenomena (e.g. rainfall, temperature, etc), existing institutional frameworks and prevailing socio-economic conditions constitute the main driving forces controlling farmer technical practices that give rise to existing agro-ecosystem structure and their dynamics. Though sharing common core concepts, both knowledge systems nevertheless have gaps (Barrios *et al.,* 2006), that can be filled and/or complemented by each other through the facilitating roles of the R & D institutions in a participatory manner to produce a hybrid ethno-scientific-knowledge. Since local knowledge changes, adapts and assimilates new ideas as suggested by Pawluk *et al.* (1992), the resulting ethno-scientific-knowledge feeds back into knowledge systems, refining and enriching them in the process and improving the structure and dynamics of the agro-ecosystem. It is envisaged that, this should result in a sustained agro-ecosystem characterized by enhanced nutrient cycling and, sustained environment and productivity.

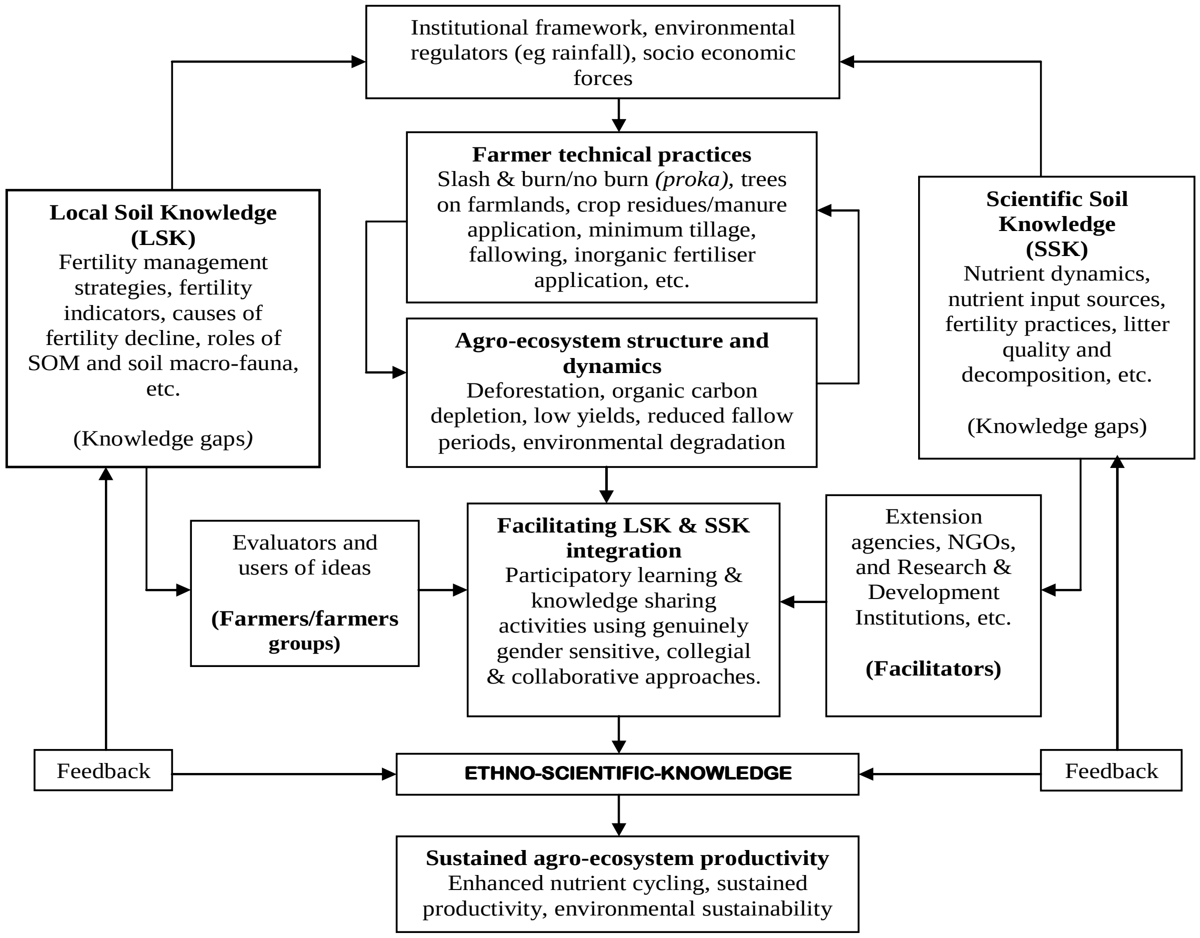

Figure 7.1. Epistemological inputs and linkages for facilitating the integration of local and scientific soil knowledge for enhanced nutrient cycling

7.5 Summary and Conclusions

Farmers in the Atwima Nwabiagya District in the Ashanti Region of Ghana have an intimate and a well-developed knowledge system about their soils, nutrient provision through litter decomposition and nutrient loss processes. This knowledge system is made up of experiences and phenomena that they can visualize and information retained from colleague farmers and extension officers.

They perceive fertile soils as being dark in colour, have good moisture holding capacity, produce consistently high yields, easily worked, characterized by the presence of soil macro-fauna and less gravelly in nature. Their practices for sustaining soil fertility and enhancing nutrient cycling build on local systems of knowledge and closely relate to their understanding of soil fertility processes. The research has established that apart from local perceptions of soil fertility, biophysical variables, socioeconomic and demographic factors such as monetary value of various management techniques heavily influence which techniques farmers implement following the acquisition of such information. Traditional methods of restoring soil productivity are giving way to other practices such as zero burning (*'proka').* Trees retained on farmlands play important roles in fertility sustenance, as they constitute the principal means by which soil organic matter is added to the soil.

Whereas scientific frameworks tend to be based on intrinsic soil characteristics that can be quantified independently of the context, the local approach which uses such terminologies as fat *(sradeɛ),* strength *(ahoɔden)* and food *(aduane)* to express soil fertility status, and integrates complex soil-plant-water relations and interactions in terms of factors such as soil colour, yield levels, growth rates and vigour, texture and workability, soils ability to hold water, presence of soil fauna, and weed indicators in the wider ecological context is probably more holistic than scientific perspectives.

Findings from the study have confirmed that there is sufficient overlap between farmers' and researchers' soil fertility knowledge. There is therefore the need for useful dialogue as the basis for developing a sustainable approach to managing soil fertility. Scientific research and knowledge can provide the breadth of understanding of soil biophysical processes while farmers can provide the context-specific knowledge required to adapt this understanding to local biophysical and socio-economic conditions. The agricultural ministries, local agricultural extension staff and NGOs, universities and agricultural research institutions and local governments can play an important role in facilitating this essential linkage by consciously adopting capacity building, participatory learning, collaborative management and gender sensitive approaches that will serve to fill gaps in both farmer and scientific knowledge. Increased farmer participation and the inclusion of farmer perspectives in the national agricultural development planning and policy formulation processes are imperative.

CHAPTER 8

SUMMARISING SYNTHESIS: CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The semi-deciduous tropical forests of the Ashanti region have been subjected to continuous clearing for the cultivation of food and tree crops over several decades. There is the need for the development of productive and sustainable land-use systems to sustain crop productivity especially in the low external input cocoa agroforestry systems practiced in the area. To be able to do this, calls for a good understanding of the ecological processes responsible for nutrient cycling in these systems. The overall goal of the study is to provide quantitative information on the effects of forest conversion to shaded-cocoa agroforestry system on standing biomass and soil physico-chemical properties to promote system sustainability. The fluxes and patterns of nutrient inputs through litterfall, throughfall, stemflow, plant residues, turnover of fine roots and nutrient losses from cocoa harvests and leaching were also studied. Additionally farmers' local knowledge of soils, soil fertility and fertility management strategies were investigated.

8.2 Impact of forest conversion on biomass production and carbon and nutrient stocks in shaded-cocoa systems

Estimates of above-ground vegetation biomass confirm the presence of relatively high total plant biomass and carbon stocks, as well as available nutrients in tropical forests and shaded-cocoa systems. Above-ground C and N were heavily affected by land-use change, but C stocks were less affected. Stability of soil carbon pools following forest conversion to tree-based agricultural land-use as observed in this study have also been reported by Ewel *et al.* (1981), Koto-Same *et al.* (1997) and Kauffman *et al.* (1998). Soil N stocks were consistently larger than above-ground stocks. Johnson *et al.* (2001) reported similar trends when comparing the accumulation of carbon and major nutrients in biomass and soil in a primary forest in Amazonia. Conversion of forest affected above-ground plant biomass and its nutrient pools and stocks more drastically than below-ground nutrients. From the original 209 Mg ha^{-1} in the forest land-use, standing tree biomass reduced by 94% to 13 Mg ha^{-1} after 3 years while stocks of soil organic carbon and nitrogen in the 60 cm depth remained stable after conversion of the forest. Under a changing climate, the role of shaded-cocoa systems in carbon sequestration has been demonstrated. Between 3 and 30 years after conversion, above-ground and soil compartments of the cocoa system sequestered on the average 3.6 Mg C ha^{-1}yr^{-1}.

While available P declined with increasing farm age as a result of nutrient exports through bean harvest and P fixation (immobilization) in insoluble forms as organo-mineral complexes (Walker and Seyers, 1976), Ca stocks increased and exchangeable K and Mg remained fairly stable and even showed the tendency to increase probably as a result of a “nutrient pumping” effect of deep rooting cocoa and shade trees in the cocoa system and the decomposition of surface litter (Dechert *et al.*, 2005). The overall decline in total soil quality at 3 years after conversion of the forest implies that the use of conservative land preparation methods to conserve and manage nutrient stocks and flows would ensure sustainability.

8.3 Litterfall and litter nutrient dynamics under shade cocoa systems.

Litterfall production and litter decomposition, and turnover of fine roots represent major pathways for element transfer from vegetation to soils, and play an important role in regulating nutrient cycling, and in maintaining soil fertility in the ecosystem. Forest and 30-year-old cocoa land-uses exhibited greater annual litterfall rates compared to 3 and

15-year old plots. Litterfall production recorded in this study are all within ranges recorded for shaded cocoa systems and tropical secondary forests in several studies (Owusu-Sekyere *et al.,* 2006; Isaac *et al.,* 2005; Hartemink, 2005; Szott *et al.,* 1991 and Opakunle 1989).

The litter decomposition coefficients k_L ranged from 0.217 to 0.354 and decreased significantly from forest to cocoa systems. This may be a reflection of structural and litter quality differences. Recycling through litterfall (leaves, twigs and floral litterfall) and turnover of fine roots constitute the most important pathway of nutrient return to the forest floor. Nutrient potentially returned to the forest floor through litterfall ranged from 4.3 kg $ha^{-1}yr^{-1}$ for P to 165 kg $ha^{-1}yr^{-1}$ for Ca in 3-year-old and forest plots respectively are in agreement with Schroth *et al.,* (2001) who reported similar inputs for west African shaded-cocoa farms. Estimated inputs from turnover of fine roots varied from 2 to 47 kg $ha^{-1}yr^{-1}$ for P and Ca in 3 and 30-year-old cocoa systems respectively and are comparable to results obtained by Munoz and Beer (2001). Trends across the chronosequence suggest that parameters of soil dynamic processes under cocoa systems approach forest values as cocoa farms age. Carbon to nitrogen (C:N), L:N, PP:N ratios and total N compared to PP and lignin contents alone are more important in influencing litter decomposition and nutrient release than biological or physical factors such as microbial biomass or canopy openness in these cocoa systems.

8.4 Nutrient fluxes and balances in incident rainfall, throughfall and stemflow

This study has adapted the methodology of nutrient monitoring (NUTMON) to the specific realities of cocoa systems in the humid semi-deciduous forest zone to quantify the input and output fluxes associated with rainfall, leaching and crop harvests as well as resulting balances. Several factors such as canopy architecture, leaf area index, density and structure of plantation, rainfall intensity and raindrop size can be responsible for differences in the magnitudes of fluxes resulting from "rainfall-forest" interaction (Opakunle, 1989; Leite *et al.,* 1999; Calder, 1998), whereas geographical locations, proximity to industrial zones, urban centres or marine areas and burning occurrence are the others related to water composition (Leclau *et al.*, 2003).

The studied canopies - natural forest and shaded-cocoa, significantly altered concentrations of nutrients in incident rainfall. There was a clear pattern of increased P and base cations and decreased NH_4^+ and NO_3^- fluxes in throughfall relative to incident rainfall as a result of canopy leaching of cations and absorbtion of NH_4^+ and NO_3^- from incident rainfall. This is in agreement with several other studies in temperate and tropical forests (e.g. Parker, 1983; Opakunle 1989; Forti and Neal 1992; Chuyong *et al.,* 2004; Zeng *et al.,* 2005 and Schrumpf *et al.,* 2006). Compared to incident rainfall and throughfall, stemflow contribution of water and nutrient input to the forest floor constitutes only a small percentage (Schroth *et. al.,* 1999; Lui *et al.,* 2002).

Precipitation loss due to canopy interception was estimated at 22, 14 and 8% in the forest, 15 and 30-year-old shaded-cocoa systems respectively. Seventy seven (77) percent of incident rainfall in natural forest reached the soil, while 83, 85 and 90% reached the soil under 3, 15 and 30-year-old shaded-cocoa systems. Contributions of rainwater to nutrient fluxes into the system were generally small, approximately 6 kg $ha^{-1}yr^{-1}$ for N and Mg, and 0.4 kg P, 13.0 kg Ca and 9 kg Mg $ha^{-1}yr^{-1}$. Phosphorus, K, Ca and Mg in incident rainfall contributed 62, 37, 62 and 39 % respectively of total rain-based inputs to the forest floor in the 15-year-old system while for the 30-year-old plots the contributions were 11, 23, 59 and 56 % respectively for the same elements.

In general, lowest net nutrient losses were found under forest and highest losses in shaded-cocoa systems. Under forest land-use, the nutrient balance was negligibly negative (-1.0) for N only but positive for P, K, Ca and Mg. Under cocoa land-use, the net nutrient balances (mean for 15 and 30-year-old plots) for N and P were negative with annual losses of -11.1 and -0.51 kg ha^{-1} respectively. Relative to the available stocks of N losses accounted only for small fractions of total N stocks. This emphasizes the importance of native soil fertility when comparing nutrient budgets between sites. Comparisons should always be made in relation to the total stocks of nutrient in a system (Dechert *et. al.*, 2005). The balances for K, Ca and Mg were positive with net annual gains of 1.6, 8.3 and 4.2 kg $ha^{-1}yr^{-1}$ respectively. The loss of growth limiting P was largest amongst the nutrients and was on the average, 10% of soil stocks under the productive cocoa land-uses.

8.5 Farmer perceptions and assessment of soil fertility and nutrient cycling processes

Farmers have profound and a well-developed knowledge system about their soils, and their nutrient loss and recycling processes. This knowledge system is made up of experiences and phenomena that they can visualize and information retained from colleague farmers and extension officers. They use indicators such as soil colour, yield levels, growth rate of crops, the degree to which soils can be worked, water holding capacity and weed indicators to assess the fertility status of their farm fields (Moss 2001; Adjei-Nsiah *et al.,* 2005; Murage Cobeels *et al*., 2000). Fertile soils are supposed to be dark in colour, easy to work, consistently produce high crop yields, have high water retention capacity, and produce crops and plants with green leaves. The role of soil micro-organisms is unknown to them. Farmers' knowledge and perception of soil fertility though purely qualitative tended to match the scientific assessment of fertile or infertile soils on their fields. Their use of these indicators, as well as other diverse terminologies such as *ahoɔden, sradeɛ, aduane, asaase biriɛ,* suggest that their perceptions are probably more holistic than scientific perceptions, and they see soil fertility as a broader concept than the soil's nutrient status alone.

Farmers use a diversity of techniques, many of which fit well into local conditions and build on their understanding and local knowledge systems of soil and soil fertility management. Trees retained on farmlands play important roles in sustaining fertility as they constitute the means by which soil organic matter is added to the soil. Due to increasing population and land fragmentation, the traditional method of restoring soil productivity in cropping systems- fallowing followed by slashing and burning of vegetation is giving way to practices such as *'proka'*, the retention of trees on farmlands, and on a limited scale inorganic fertilizer application.

Evidence has emerged that there is sufficient overlap between farmers' and researchers' knowledge and perceptions of soil fertility. There is therefore the need for a useful dialogue as the basis for developing sustainable approaches to managing soil fertility. Facilitators, scientists, researchers and extension agents can integrate the context-specific knowledge of farmers to local biophysical and socio-economic conditions through capacity building, participatory learning, and collaborative management and gender sensitive approaches. This will serve to fill gaps in knowledge base of farmers and scientists.

8.6 Major conclusions and recommendations

This has been an investigation to quantify the impact of land-use change and farmer knowledge and practices on nutrient stocks and flows in cocoa agroforestry systems and to promote system sustainability. The philosophy driving these research goals is based on the premise that science should be used to promote the well-being of small-scale farmers to develop more ecologically friendly farming systems by providing alternative management practices. Since solutions to agricultural problems are neither wholly technical nor wholly social, an attempt is made to integrate both technical and social approaches to this research and its applications.

The results of this study contribute to an understanding of the relationship between carbon and nutrient changes and duration after conversion of forest to shaded-cocoa systems. This study has added to knowledge on the dynamics of above and below-ground nutrients (N, P, and cations Ca, K and Mg) in soils associated with forest conversion to cocoa-based agriculture with time. It has quantified the magnitudes of nutrient input fluxes associated with incident rainfall, and rainfall partitioned into throughfall and stemflow as well as recycling through litterfall and turnover of fine roots under cocoa systems. The study has also confirmed findings by some researchers especially from other tropical forest areas.

8.6.1 Conclusions

The conclusions drawn from the results are:

(a) The major factor responsible for the depletion of carbon and nutrient stocks in agro-ecosystems is land clearing. Nutrient pools in above-ground biomass are more significantly affected compared to soil pools by conversion of forest to agricultural land-uses like shaded-cocoa.

(b) Soil organic carbon, available nitrogen and basic nutrient stocks in the 0-60 cm depth of this shaded-cocoa system remained relatively stable at least for the 30 years following shaded-cocoa plantation establishment on fields converted from forests. This implies that conversion of the forest to shaded-cocoa land-use does not mine the soil of its nutrients and with the addition of chemical fertilizer, the productivity of the soil can be maintained for many years.

(c) The behaviour of soil organic C, available P, and extractable K, Ca and Mg over time after forest conversion could be predicted using quadratic functions fitted to the land-use time series. The fitted functions explained 54 to 98% of soil behavior for N, P, K, Ca, and Mg in the 0- 60 cm layer but only 33% for organic carbon.

(d) In the early plantation development phase, total soil quality showed evidence of degradation (DI was -5) not noticeable when soil quality was assessed from the point of view of changes in total nutrient stocks alone with time. The integration of all soil physico-chemical parameters is required to assess soil quality changes along the chronosequence.

(e) Under a changing climate, the role of cocoa shade systems as effective tools for carbon sequestration is shown. By 30 years, above-ground and soil pools are sequestering 3.6 Mg C $ha^{-1}yr^{-1}$ for the entire shaded-cocoa system.

(f) Cocoa systems maintained an efficient nutrient recycling mechanism with pathways through litterfall and fine roots turnover accounting for the largest input sources in forest and cocoa systems. Pod husks may constitute a potential nutrient source especially for K and N, contributing 6, 0.5, 18, 4 and 2 kg $ha^{-1}yr^{-1}$ of N, P, K, Ca and Mg respectively to offset losses due bean seed harvest if the necessary management strategies are put in place.

(g) Though the input-output balances of N and P under shaded-cocoa system were negative, the indications are that system may not be N unsustainable as losses are a small proportion of total soil stocks. Available P is the most limiting in these systems. Levels of this nutrient shift from sufficiently available at early growth to limiting as cocoa system ages, suggesting that these systems do not meet P requirements over time.

(h) Soil fertility management practices of farmers are based on their perceptions and knowledge of soil fertility. In perennial cropping systems such as shaded-cocoa, they perceive the fertility processes as similar to what pertains in the natural forest, i.e., a self-sustaining system. Farmers therefore cash in on nutrient reserves of the "forest rent" in newly cleared secondary forests and subsequently nutrients recycled mainly through litterfall. Majority do not see the need for chemical fertilizers under shaded-cocoa systems which they say are comparable to forests.

(i) Farmers in Atwima Nwabiagya have a coherent and a well-developed knowledge system about their soils and their fertility processes and status. Local perceptions which integrate complex soil-plant-water relations and interactions in terms of factors such as soil colour, yield levels, growth rates and vigour, texture and workability, soils ability to hold water, presence of soil fauna and weed indicators in the wider ecological context are probably more holistic than scientific perceptions which tend to be based on intrinsic soil characteristics that can be quantified.

8.6.2 Recommendations

To sustain productivity, maintain soil fertility and minimize soil degradation, the following recommendations are made:

(i) *Adoption of conservative land preparation methods during plantation establishment:* With a decline in total soil quality as evidenced by a degradation index of -5 at 3 years after forest conversion, it is recommended that farmers reduce destructive land preparation methods but instead adopt conservative methods such as controlled burning, selective tree removal informed by farmers' knowledge of desired and undesirable shade trees, and minimal soil disturbance to reduce nutrient loss. The choice of intercrops during the plantation development phase and before canopy closure needs to be done judiciously and must of necessity include legume components for nitrogen fixation to enhance long-term and sustainable land-use.

(ii) *The enhancement of nutrient recycling:* Since nutrient recycling accounts for the largest nutrient input sources in forest and shaded-cocoa systems, it is recommended that any efforts at sustaining fertility under these low external input systems would be best served by interventions that target enhancing nutrient cycling and adopting tree management strategies that increase litter inputs. This can be achieved specifically through the introduction of N-fixing trees as shade/nurse trees during plantation establishment and along farm boundaries, the transfer of biomass from N-fixing trees planted along farm boundaries to cocoa farms, and the filling of gaps created through tree mortality.

(iii) *Efficient recycling of cocoa pod husks:* The development and dissemination of new management strategies to recycle efficiently, cocoa pod husks that are usually left piled up at pod breaking points on productive farms is strongly recommended. The challenge is to develop appropriate and effective ways of doing this through research. Possible ways of using cocoa pod husks could include evenly distributing husks over the entire field, burying pods at predetermined intervals from cocoa trees, burning dried cocoa pod husks at selected points on farms, and spreading the resulting ash over the field or rotating pod breaking points between several locations on cocoa farms.

(iv) *Application of phosphatic fertilizers:* High soil N stocks, marginally negative N balance and positive K balance suggest that K levels could be reduced in any inorganic fertilizer recommendation for cocoa. The application of phosphorus fertilizers are however required in older systems to maintain good commercial yields.

(v) *The integration of local and scientific soil knowledge:* The complementary nature of local knowledge to formally derived knowledge on soil fertility processes calls for the integration of new and established practices into a larger policy and institutional framework. To facilitate integration, the use of truly participatory, gender sensitive and collaborative learning approaches involving researchers, extension personnel, farmers and policy makers are recommended for the development and promotion of locally-specific fertility management packages and to increase farmer participation in the national agricultural development planning and policy formulation processes.

8.7 Recommendations for future research

Although a significant amount of useful quantitative information was provided, several aspects that could not be studied in-depth but posed questions which may be of significance for future research are presented below.

In-situ mineralization and nutrient uptake under shade and in gaps

In chapter 3, the effect of land-use change from forest to cocoa land-use on carbon and nutrient stocks and static pools in below and above-ground compartments were quantified. I recommend further research on the mechanisms involved in-situ mineralization of C and N, nutrient uptake and the dynamics and composition of soil microbial community along the chronosequence for a complete model of nutrient cycling within these low external input agroforestry systems. It would also be interesting to find out the effects of gaps and gap sizes on mineralization and nutrient cycling.

Fine roots nutrient contribution

This study provides a baseline of information on fine root dynamics (chapter 4) that can be used to answer important questions of ecosystem processes and overall forest productivity. We need to know more about timing of production and mortality for fine roots to understand competitive interactions between *Theobroma cacao* and upper-storey trees. Further work is needed to relate changes in fine root dynamics to other forest processes, such as soil microbial activity and overall forest productivity. It is not known whether fine root growth with increasing age along the chronosequence indeed translates into significant nutrient uptake in the light of possible nutrient re-translocation from senescing roots.

Re-defining fertilizer needs and application

Further studies may also be required in the areas of re-evaluating and refining fertilizer recommendations in the light of the farmers' limited resources, the possible differences in rainfall nutrient inputs as well as the suitability of soils especially cocoa for a more cost-effective use of fertilizers. Emerging cocoa areas are known to have soils unsuitable for cocoa cultivation and current blanket fertilizer recommendations may not be suitable. Important research issues include the provision of adequate information on technology availability and access, costs and benefits and their effects on the environment to help the farmers make informed decisions.

In-depth analysis of the use of satellite remote sensing tools in the humid tropics

Remotely sensed data have become essential in mapping land-use changes and in change detection. There is scope for further research and possible integration of scientific spatial analysis (i.e. using GIS) with the spatial perception of soils resources by farmers for improved implementation of site-specific management.

Farmer perceptions and new management strategies for pod husk utilization

It would be interesting to research into the reasons for the non-utilization of cocoa pod husks to improve soil fertility by farmers. Though farmers appreciated the role of pod husks in nutrient recycling, none of the farmers has experimented with its use. There is also the need to research into possible effective ways of applying cocoa pod husks as soil amendments at the farm level.

8.8 Limitations of the study

Although the results of this study provide useful data and information on local soil knowledge and the dynamics of nutrient flows and stocks along a thirty-year shaded-cocoa chronosequence in the Ashanti Region, there are a number of limitations that need to be taken into account when interpreting results presented.

1. The design of the study on local soil knowledge did not separate farmers' acquired soil knowledge from indigenous soil knowledge. It is likely that local knowledge as recorded includes acquired formal knowledge from extension agents as a result of interactions that have taken place between farmers and agricultural extension agents.

2. The most accurate way to calculate the biomass of trees in an open forest system is to measure the oven-dry-weight of trees through destructive sampling by directly felling them, oven-drying their components and weighing them. In the present study, generic regression equations developed for specific precipitation zones were used as plants could not be destructively sampled due to farmer-imposed limitations. In many tropical forests however, unique plants forms occur and the size of individual tree canopies could be smaller than those found in agroforestry settings, local regression equations need to be developed as the application of generic equations may lead to inaccurate biomass estimates (Brown 2002).

3. Under forest systems, dead tree biomass constitutes between 2-20% of above ground litter and constitutes a large proportion of carbon. Though most of the downed logs had been harvested as fuel wood, the exclusion of biomass of remnant dead logs could have led to an underestimation of above ground carbon stock.

4. The nutrient balances in this study represent results from only 2 years of research in a highly dynamic system, and nutrient balances measured in the next 2 years would probably differ from the present values. Current values are therefore not the average and can only be viewed as the balances for the period of the study.

5. Using the nutrient balance approach to assess nutrient loss always results in additional nutrient loss pathways (e.g. volatilization losses denitrification) not

being accounted for. The nutrient balance approach alone as adopted in chapter 6 could lead to an underestimation of nutrient losses.

Despite these limitations, the study nevertheless gives us a reasonable idea about the dynamics of nutrient flows, stocks and their balances as well as farmers' knowledge about soils and fertility processes in shaded-cocoa systems in the Ashanti Region, Ghana.

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APPENDIX TABLES

Appendix 1. Chemical properties of soils from forest and cocoa land-use systems on all sites.

Land-use/Age Of Plots	Depth (cm)	pH 1:1 H_2O	Org. C %	Tot. N %	OM %	Exchangeable Cations meq/100g				Tot . Exch Bases	Exch Al+H	CEC meq/	Base Saturation	Available Bray's	
						Ca	Mg	K	Na					ppm P	ppm K
Forest	0-10	5.81	2.95	0.24	5.07	9.88	6.94	0.27	0.18	17.27	0.28	17.55	98.40	3.93	125.1
Forest	10-20	5.43	1.75	0.50	3.01	2.61	1.74	0.24	0.18	4.77	0.20	4.97	95.97	2.38	82.29
Forest	20-60	6.25	0.55	0.30	0.95	2.54	2.00	0.16	0.23	4.93	0.13	5.06	97.43	2.33	42.79
Forest	0-10	6.19	2.94	0.18	5.05	8.81	1.60	0.44	0.12	10.97	0.15	11.12	98.65	0.62	100.39
Forest	10-20	5.55	0.74	0.07	1.28	7.21	0.80	0.27	0.15	8.43	0.15	8.58	98.25	0.41	69.12
Forest	20-60	4.43	0.30	0.02	0.52	4.41	0.13	0.14	0.14	4.82	0.83	5.65	85.31	0.57	52.66
Forest	0-10	5.72	2.96	0.47	5.09	8.42	1.90	0.48	0.29	11.09	0.18	11.27	98.40	1.68	119.79
Forest	10-20	5.63	0.83	0.24	1.43	5.41	0.80	0.40	0.23	6.84	0.15	6.99	97.85	3.22	68.12
Forest	20-60	4.49	0.35	0.08	0.60	3.23	1.02	0.38	0.31	4.94	0.22	5.14	96.10	0.57	42.53
Cocoa 3 yrs	0-10	5.16	2.19	0.13	3.77	5.61	2.14	0.42	0.18	8.35	0.10	8.45	98.82	4.03	162.92
Cocoa 3 yrs	10-20	4.37	0.17	0.01	0.29	2.40	0.27	0.08	0.13	2.88	0.40	3.28	87.80	1.60	74.06
Cocoa 3 yrs	20-60	6.81	0.28	0.02	0.48	3.20	1.20	0.10	0.06	4.56	0.13	4.69	97.23	1.35	41.14
Cocoa 3 yrs	0-10	6.48	2.02	0.19	3.47	9.88	4.01	0.44	0.15	14.48	0.10	14.58	99.31	2.53	120.14
Cocoa 3 yrs	10-20	6.06	0.70	0.07	1.21	4.14	1.74	0.20	0.21	6.29	0.15	6.44	97.67	1.88	70.76
Cocoa 3 yrs	20-60	5.58	0.35	0.03	0.60	3.87	0.67	0.16	0.17	4.87	0.20	5.07	96.06	1.14	70.76
Cocoa 3 yrs	0-10	7.12	2.15	0.19	4.30	8.01	6.68	1.01	0.25	15.95	0.08	16.03	99.5	0.41	148.11
Cocoa 3 yrs	10-20	5.28	1.23	0.13	2.12	9.35	6.19	0.49	0.35	16.38	0.25	16.63	98.5	0.30	106.97
Cocoa 3 yrs	20-60	4.63	0.27	0.04	0.46	5.47	2.00	0.39	0.18	8.04	0.15	8.19	98.17	0.31	113.55
Cocoa 15yrs	0-10	6.13	2.84	0.23	4.89	9.08	8.01	0.43	0.22	17.74	0.15	17.89	99.16	2.00	110.26
Cocoa 15yrs	10-20	4.71	1.05	0.09	0.95	4.41	3.34	0.30	0.15	8.20	0.53	8.73	93.93	Trace	75.70

Cocoa 15yrs	20-60	6.10	0.36	0.03	0.62	3.34	2.54	0.19	0.11	6.18	0.13	6.31	97.94	Trace	41.14
Cocoa 15yrs	0-10	6.13	2.39	0.21	4.13	13.22	4.54	0.57	0.30	18.63	0.15	18.78	99.20	1.86	93.80
Cocoa 15yrs	10-20	6.14	0.68	0.06	1.17	4.41	2.40	0.25	0.18	7.24	0.10	7.34	98.64	0.78	65.83
Cocoa 15yrs	20-60	5.05	0.41	0.04	0.71	2.94	3.20	0.16	0.13	6.43	0.20	6.63	96.98	0.31	72.41
Cocoa 15yrs	0-10	5.81	2.27	0.17	3.91	8.81	5.47	0.39	0.22	14.89	0.25	15.14	98.35	2.69	65.83
Cocoa 15yrs	10-20	5.47	0.67	0.07	1.16	4.27	2.27	0.23	0.18	6.95	0.15	7.10	97.89	1.81	52.66
Cocoa 15yrs	20-60	4.94	0.42	0.03	0.72	3.87	2.00	0.18	0.10	6.15	0.70	6.85	89.78	1.19	54.31
Cocoa 30 yrs	0-10	6.12	2.74	0.19	4.72	12.3	6.14	0.79	0.32	19.53	0.20	19.73	98.99	1.46	164.57
Cocoa 30 yrs	10-20	5.56	1.01	0.09	1.74	6.14	2.40	0.41	0.18	9.13	0.10	9.23	98.92	0.67	126.72
Cocoa 30 yrs	20-60	6.21	0.56	0.06	1.26	4.14	1.20	0.30	0.17	5.81	0.08	5.89	98.64	0.29	123.43
Cocoa 30 yrs	0-10	5.38	2.85	0.21	4.91	10.0	9.61	0.86	0.34	20.82	0.43	21.25	97.98	0.83	113.55
Cocoa 30 yrs	10-20	5.54	1.12	0.10	1.93	5.34	1.60	0.28	0.08	7.30	0.48	7.78	93.83	0.32	85.58
Cocoa 30 yrs	20-60	4.69	0.51	0.08	1.43	6.14	2.40	0.41	0.18	9.13	0.75	9.88	92.41	Trace	115.20
Cocoa 30 yrs	0-10	4.75	2.05	0.15	3.54	8.54	6.81	0.37	0.21	15.93	0.47	16.40	97.13	1.58	65.83
Cocoa 30 yrs	10-20	4.73	0.47	0.03	0.81	3.60	1.74	0.17	0.13	5.64	0.81	6.45	87.44	0.57	64.18
Cocoa 30 yrs	20-60	4.72	0.24	0.02	0.41	4.01	1.60	0.19	0.18	5.98	0.87	6.85	87.30	Trace	47.73

Appendix 2. Physical Properties of soils from forest and cocoa sites

Plot/Land-use Chrono-sequence	Depth (cm)	Mechanical Analysis			Bulk Density (gm/cm^3)	Soil Texture
		Sand %	Silt %	Clay %		
Forest	0-10	15.96	72.02	12.02	1.02	Silty loam
Forest	10-20	18.06	65.27	16.67	1.48	Silty Loam
Forest	20-60	18.38	57.18	24.44	1.42	Silty loam
Forest	0-10	22.86	69.11	8.03	1.03	Silty loam
Forest	10-20	21.82	58.11	20.07	1.34	Silty Loam
Forest	20-60	20.18	49.43	30.39	1.18	Clayey Loam
Forest	0-10	23.59	63.41	13.00	0.98	Silty loam
Forest	10-20	21.06	63.32	15.62	1.38	Silty Loam
Forest	20-60	19.87	59.35	20.78	1.42	Silty Loam
Cocoa 3 years	0-10	25.76	64.08	10.16	1.25	Silty Loam
Cocoa 3 years	10-20	28.62	59.17	12.21	1.43	Silty Loam
Cocoa 3 years	20-60	24.72	65.15	10.13	1.58	Silty loam
Cocoa 3 years	0-10	24.70	65.10	10.20	1.13	Silty loam
Cocoa 3 years	10-20	32.74	57.12	10.14	1.37	Loam
Cocoa 3 years	20-60	40.12	39.31	20.57	1.60	Silty loam
Cocoa 3 years	0-10	21.50	64.19	14.31	1.19	Silty Loam
Cocoa 3 years	10-20	24.34	63.25	12.41	1.55	Silty Loam
Cocoa 3 years	20-60	33.76	40.17	26.07	1.71	Loam
Cocoa 15 years	0-10	24.70	65.10	10.20	1.18	Silty loam
Cocoa 15 years	10-20	20.02	61.37	18.61	1.23	Silty Loam
Cocoa 15 years	20-60	15.68	62.21	22.11	1.47	Silty loam
Cocoa 15 years	0-10	15.42	72.27	12.31	1.27	Silty Loam
Cocoa 15 years	10-20	14.70	63.10	22.20	1.51	Silty loam
Cocoa 15 years	20-60	18.24	55.28	26.48	1.66	Silty loam
Cocoa 15 years	0-10	19.08	68.53	12.39	1.33	Silty Loam
Cocoa 15 years	10-20	23.76	56.08	20.16	1.47	Silty loam
Cocoa 15 years	20-60	25.18	48.21	26.61	1.65	Loam
Cocoa 30 years	0-10	25.32	60.05	14.63	1.31	Silty loam
Cocoa 30 years	10-20	22.84	47.12	30.04	1.45	Clay loam
Cocoa 30 years	20-60	27.74	32.11	40.15	1.54	Clay Loam
Cocoa 30 years	0-10	19.02	60.53	20.45	1.35	Silty Loam
Cocoa 30 years	10-20	20.32	55.31	24.37	1.41	Silty Loam
Cocoa 30 years	20-60	27.06	30.47	42.47	1.65	Clay
Cocoa 30 years	0-10	21.00	71.00	8.00	1.27	Silty loam
Cocoa 30 years	10-20	24.98	55.01	20.01	1.48	Silty Loam
Cocoa 30 years	20-60	28.40	47.35	24.25	1.70	Loam

Appendix 3: Litterfall production and stand litterstock accumulation on all sites

	Litterfall production ($Mg\ ha^{-1}$)				Stand litterstocks ($Mg\ ha^{-1}$)			
Month	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years	Forest	Cocoa 3 years	Cocoa 15years	Cocoa 30 years
2006 Jan	6.54	7.86	9.84	11.8	1.35	0.52	0.7	0.8
Feb	7.51	5.77	8.12	8.62	1.17	0.71	0.85	1.1
Mar	8.11	3.66	6.84	4.91	1.09	1.12	1.00	1.93
Apr	4.52	2.82	5.63	3.77	1.95	1.45	1.22	2.51
May	4.1	2.6	3.98	3.63	2.13	1.58	1.73	2.61
Jun	2.7	1.58	2.13	3.39	3.26	2.59	3.23	2.79
Jul	2.43	1.4	2.33	1.76	3.62	2.93	2.95	5.38
Aug	3.65	1.54	2.21	3.72	2.41	2.66	3.11	2.54
Sept	3.89	1.11	2.66	3.41	2.26	3.69	2.59	2.77
Oct	3.99	2.3	3.61	4.16	2.21	1.78	1.91	6.47
Nov	4.32	4.14	6.57	6.57	2.04	0.99	1.05	1.44
Dec	4.26	3.98	8.61	7.82	2.07	1.03	0.799	1.21
2007 Jan	5.93	6.95	12.53	11.27	1.5	0.82	0.75	0.93
Feb	5.91	6.36	10.8	11.6	1.51	0.89	0.87	0.91
Mar	6.01	6.25	8.73	9.22	1.48	0.91	1.02	1.14
Apr	5.23	6.12	7.88	7.57	1.7	0.93	1.19	1.39
May	2.45	2.82	3.8	3.47	3.63	2.02	2.47	3.03
June	3.12	2.11	3.27	4.1	2.85	2.7	2.87	2.56
Jul	3.3	1.86	2.24	3.77	2.7	3.06	4.19	2.79
Aug	3.68	1.26	2.72	3.62	2.42	4.52	4.19	2.9
Sept	4.77	1.21	3.4	3.52	1.87	4.71	2.76	2.98
Oct	3.88	2.4	4.55	4.21	3.71	2.38	2.06	2.49
Nov	4.97	4.64	7.67	6.84	1.79	1.24	1.22	1.54
Dec	4.26	4.98	8.68	8.62	2.09	1.14	1.08	1.22

Appendix 4: Total volume (litres/3.63 x 10^{-5} ha) of open area rainfall water samples collected from March 2006 to October 2007 in the study area.

Month	BULK PRECIPITATION SAMPLES AND VOLUMES COLLECTED										Total Volume (litres)
	1	2	3	4	5	6	7	8	9	10	
Mar 2006	3.1	2.7	3.0	3.3	3.1	2.9	2.9	2.9	2.7	2.8	29.4
April	5.1	5.1	5.2	4.8	5.1	4.9	4.9	4.8	5.1	5.3	50.3
May	9.9	9.7	9.8	9.7	9.8	9.7	9.8	9.9	9.7	9.7	97.7
Jun	6.2	5.9	6.1	5.8	6.9	7.2	6.7	5.8	5.6	6.5	62.7
July	3.9	4.5	4.1	3.7	4.3	4.0	3.9	4.5	3.4	3.6	39.9
Aug	0.5	0.7	0.70	0.5	0.4	0.5	0.6	0.6	0.5	0.9	5.90
Sept	6.5	6.4	5.9	6.0	6.1	6.3	6.2	6.8	6.3	6.8	63.3
Oct.	13.4	13.9	13.3	13.4	13.5	13.5	13.4	13.5	13.2	13.7	134.8
Nov	2.3	2.3	2.3	2.4	2.4	2.4	2.3	2.4	2.5	2.3	23.5
Dec.	6.3	6.3	6.0	6.2	6.1	6.2	6.3	6.0	6.0	5.9	6.1
Jan 2007	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	15.0
Feb	1.2	1.2	1.3	1.1	1.2	1.2	1.2	1.3	1.2	1.3	12.2
Mar	2.2	2.1	2.2	2.3	2.2	2.2	2.3	2.1	2.2	1.9	21.7
Apr	4.8	5.0	4.9	4.9	4.8	4.7	5.0	4.8	4.9	4.9	48.7
May	9.4	8.4	8.3	8.0	7.4	8.0	9.3	9.8	9.0	8.0	85.6
Jun	7.7	7.8	7.7	7.8	7.6	7.7	7.7	7.7	7.6	7.5	76.8
July	4.5	4.5	4.6	4.4	4.5	4.6	4.4	4.4	4.5	4.6	45.0
Aug	0.9	0.9	1.1	1.1	1.0	0.9	1.2	0.8	1.0	1.2	10.1
Sept	5.5	5.2	5.9	6.0	5.2	5.4	5.8	6.3	5.3	5.5	54.1
Oct	11.7	12.3	13.3	12.7	12.8	12.4	11.7	12.1	12.2	13.0	124.2

Appendix 5: Monthly concentrations (mg/L) of N, P, K, Ca, Na and Mg, pH and electrical conductivity in composite samples of incident rainfall collected from March 2006 to October 2007 in Ashanti Region, Ghana.

Month	NH_4-N mg/L	NO_3-N mg/L	Total N mg/L	P mg/L	K mg/L	Ca mg/L	Mg mg/L	Na mg/L	pH	Elect. Cond. µS/cm
Mar 2006	0.380	0.168	0.548	0.028	1.52	0.93	0.78	10.7	5.2	52.80
April	0.382	0.159	0.541	0.029	1.42	0.90	0.66	7.00	5.8	44.53
May	0.295	0.205	0.500	0.026	1.10	0.85	0.60	1.50	5.7	36.70
June	0.308	0.125	0.433	0.028	1.00	0.63	0.54	1.25	5.5	19.15
July	0.360	0.127	0.487	0.019	0.85	0.82	0.26	2.50	5.7	26.90
Aug	0.246	0.139	0.385	0.032	0.84	0.60	0.17	3.75	5.2	23.10
Sept	0.229	0.171	0.400	0.013	0.68	0.10	0.16	4.25	5.8	29.10
Oct	0.203	0.192	0.395	0.013	0.20	0.75	0.30	3.15	5.6	29.95
Nov	0.279	0.120	0.399	0.011	1.40	0.34	0.40	6.00	5.8	21.30
Dec	0.320	0.097	0.417	0.020	2.00	0.50	0.30	10.0	5.5	34.80
Jan 2007	0.304	0.130	0.534	0.035	1.80	0.40	0.60	5.00	6.4	42.50
Feb	0.427	0.108	0.535	0.088	2.50	0.25	0.21	3.50	6.8	61.40
Mar	0.380	0.160	0.544	0.026	1.66	0.90	0.77	11.0	5.5	24.30
Apr	0.382	0.145	0.527	0.020	1.41	0.90	0.33	7.00	5.8	44.70
May	0.285	0.142	0.427	0.026	0.90	0.85	0.60	1.90	5.7	36.70
Jun	0.283	0.026	0.309	0.019	1.10	0.83	0.54	1.25	5.5	24.19
Jul	0.246	0.139	0.266	0.042	0.78	0.57	0.18	4.75	5.2	13.10
Aug	0.226	0.152	0.378	.053	0.88	0.61	0.33	3.85	.1	54.27
Sept	0.199	0.100	0.299	0.043	0.58	0.33	0.11	3.55	6.0	76.23
Oct	0.123	0.110	0.233	.024	2.00	0.63	0.26	2.46	5.3	54.69

Appendix 6: Total volume (litres) of throughfall water samples collected from March 2006 to March 2006 to October 2007 in Forest, 3 year, 15year and 30 year – old cocoa land-use chronosequences.

Month.	Land-use/age			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
March 2006	9.9	9.8	10.4	12.6
April	14.9	13.6	14.0	15.7
May	26.2	33	36	37.3
June	13.3	13.6	12.4	13.4
July	14.9	15.4	16.2	15.6
August	5.0	5.2	5.6	5.1
September	20.2	19.8	18.5	19.0
October	41.7	43.2	40.1	43.5
November	5.1	4.4	5.0	7.5
December	0.0	0.0	0.0	0.0
Jan 2007	2.4	3.2	3.1	3.7
February	5.5	6.8	5.8	5.3
March	10.6	10.5	11.8	12.6
April	11.1	13.6	11	14.4
May	18.6	21.3	26.1	22.2
June	11.2	12.6	12.6	11.7
July	12.5	14.8	16.2	17.8
August	9.9	10.3	11.8	10.2
September	19.2	22.5	24.6	28.1
October	45.3	40.3	49.5	53.5

Values are means of samples from 3 plots.

Appendix 7: Concentrations (mg/L) of N, P, K, Ca, Mg and Na, pH and electrical conductivity in composite throughfall samples collected from March to October 2006 in forest and shaded cocoa land-use chronosequences in Ashanti Region, Ghana.

Land-use /Age	Date/ Month	NH_4-N mg/L	NO_3-N mg/L	Total Nmg/L	P mg/L	K mg/L	Ca mg/L	Mg mg/L	Na mg/L	pH	Elect. Cond. µS/cm
Forest	Mar	0.393	0.140	0.533	0.235	7.10	1.30	1.25	11.8	5.47	81.00
	April	0.311	0.160	0.471	0.241	7.60	1.20	1.08	23.5	6.40	70.00
	May	0.183	0.020	0.203	0.158	1.60	1.00	0.95	3.25	6.33	37.60
	June	0.173	0.043	0.216	0.150	4.21	0.88	0.93	9.00	6.40	56.80
	July	0.225	0.069	0.294	0.158	4.15	0.95	0.75	6.80	6.62	64.30
	Aug	0.062	0.053	0.115	0.091	5.70	0.98	2.15	15.3	5.70	78.40
	Sept	0.122	0.028	0.150	0.095	4.50	0.98	1.02	7.15	6.80	76.70
	Oct	0.068	0.061	0.129	0.018	2.85	0.97	0.30	3.00	7.50	67.70
	Nov	0.190	0.056	0.246	0.083	6.65	0.70	0.58	8.00	5.90	70.80
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.336	0.027	0.363	0.458	4.80	1.30	1.30	15.0	4.80	108.4
	Feb	0.376	0.056	0.432	0.301	8.40	1.40	1.27	11.8	6.30	77.10
	Mar	0.185	0.143	0.328	0.238	7.90	1.20	1.25	6.80	6.50	79.90
	Apr	0.309	0.172	0.481	0.211	7.30	1.22	1.11	7.00	6.40	70.00
	May	0.081	0.130	0.211	0.118	2.80	1.00	1.04	3.07	6.42	45.60
	Jun	0.382	0.059	0.441	0.115	2.91	0.88	0.98	4.50	6.40	55.40
	Jul	0.269	0.138	0.407	0.205	1.68	0.93	0.70	1.37	5.90	52.20
	Aug	0.064	0.044	0.108	0.121	5.00	0.92	2.05	15.7	4.87	68.40
	Sept	0.122	0.028	0.150	0.097	4.10	0.98	0.94	7.15	6.80	76.70
	Oct	0.066	0.041	0.107	0.016	9.85	0.91	0.31	3.00	7.50	67.70
Cocoa 3yrs	Mar	0.309	0.167	0.476	0.115	3.75	1.30	1.08	10.8	6.26	71.20
	April	0.290	0.210	0.500	0.066	1.85	1.10	1.05	8.75	6.05	58.48
	May	0.266	0.171	0.437	0.039	1.95	0.90	0.70	1.85	6.03	29.13
	June	0.328	0.135	0.463	0.034	1.83	1.08	0.88	4.25	6.19	52.53
	July	0.197	0.038	0.235	0.054	1.95	0.95	0.50	1.75	6.05	49.20
	Aug	0.075	0.025	0.100	0.094	4.70	0.85	2.35	17.5	6.10	71.50
	Sept	0.045	0.086	0.131	0.036	2.93	0.8	0.35	5.00	6.85	30.85
	Oct	0.118	0.042	0.160	0.040	1.15	0.75	0.33	9.50	5.90	30.00
	Nov	0.244	0.079	0.323	0.037	4.00	0.55	0.75	12.0	5.60	48.60
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.228	0.068	0.296	0.370	5.55	0.80	0.60	10.0	6.00	66.70
	Feb	0.307	0.098	0.405	0.103	3.60	0.56	0.39	3.90	5.80	69.60
	Mar	0.264	0.132	0.396	0.110	5.50	1.04	1.08	8.90	6.60	67.20
	Apr	0.240	0.125	0.365	0.071	2.45	1.03	1.00	8.90	6.20	56.10
	May	0.168	0.110	0.278	0.039	2.10	0.78	0.80	3.39	6.06	34.50
	Jun	0.117	0.110	0.227	0.026	1.81	0.91	0.79	2.96	6.39	53.08
	Jul	0.146	0.108	0.254	0.044	1.47	0.97	0.50	1.40	5.71	92.40
	Aug	0.279	0.064	0.110	0.047	6.13	1.78	2.50	4.60	6.95	34.75
	Sept	0.245	0.112	0.357	0.065	4.21	1.32	1.34	3.62	5.76	44.55
	Oct	0.186	0.124	0.310	0.057	5.66	0.65	2.65	6.32	5.55	47.54

Cocoa 15yrs	Mar	0.364	0.167	0.531	0.126	3.85	1.40	1.70	22.9	6.08	71.58
	Apr	0.378	0.177	0.495	0.090	2.20	1.07	1.86	9.25	5.97	79.60
	May	0.270	0.157	0.427	0.080	1.80	1.75	1.48	4.00	5.84	36.38
	Jun	0.312	0.188	0.500	0.124	2.10	1.05	1.85	6.75	6.17	36.33
	Jul	0.182	0.021	0.203	0.037	1.50	1.85	0.73	3.0	6.15	33.10
	Aug	0.060	0.029	0.089	0.096	3.00	2.85	1.25	17.5	6.65	33.80
	Sept	0.049	0.060	0.109	0.047	6.13	1.78	2.50	4.6	6.95	34.75
	Oct	0.064	0.046	0.110	0.023	1.60	1.10	0.50	7.1	6.40	34.60
	Nov	0.279	0.064	0.343	0.043	4.43	2.40	0.73	10.3	5.60	37.90
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.242	0.072	0.314	0.285	3.45	1.65	1.08	16.5	6.00	56.80
	Feb	0.143	0.082	0.225	0.098	7.40	2.05	1.28	4.0	6.60	66.60
	Mar	0.329	0.147	0.476	0.126	5.85	1.40	1.7	22.9	6.50	65.08
	Apr	0.299	0.152	0.451	0.099	4.50	1.14	1.49	8.75	6.00	75.60
	May	0.240	0.157	0.427	0.089	2.30	1.17	1.02	4.75	5.80	41.12
	Jun	0.297	0.077	0.374	0.100	1.95	1.05	0.90	5.1	6.10	36.33
	Jul	0.143	0.064	0.207	0.118	3.80	0.41	1.24	4.0	6.10	56.60
	Aug	0.242	0.072	0.314	0.185	4.25	1.44	1.68	10.5	6.20	57.80
	Sept	0.222	0.122	0.344	0.143	5.43	0.65	1.86	4.23	6.5	65.89
	Oct	0.146	0.113	0.259	0.085	2.33	1.65	0.95	3.32	5.8	45.32
Cocoa 30yrs	Mar	0.143	0.082	0.225	0.098	7.40	2.05	1.28	4.00	6.60	66.60
	Apr	0.329	0.147	0.476	0.126	5.85	1.40	1.7	2.29	6.50	65.08
	May	0.157	0.141	0.398	0.142	4.35	1.70	0.60	4.25	6.05	56.90
	Jun	0.342	0.169	0.511	0.136	4.00	1.10	0.65	1.50	6.40	31.45
	Jul	0.198	0.241	0.439	0.116	7.25	1.15	1.95	3.00	6.31	49.10
	Aug	0.296	0.065	0.361	0.146	5.10	1.20	0.68	1.70	6.13	43.33
	Sept	0.164	0.134	0.398	0.049	4.67	2.95	0.50	2.25	7.30	64.58
	Oct	0.186	0.305	0.491	0.046	3.00	0.73	0.45	5.50	7.00	40.85
	Nov	0.163	0.113	0.276	0.084	6.65	2.60	1.38	8.00	5.75	55.30
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.349	0.095	0.444	0.285	8.40	0.70	0.57	1.40	6.00	57.90
	Feb	0.177	0.095	0.272	0.096	6.30	1.50	0.17	4.20	6.00	64.00
	Mar	0.285	0.043	0.328	0.038	6.90	1.25	1.25	6.80	6.50	78.20
	Apr	0.300	0.173	0.473	0.120	5.80	1.10	1.12	8.70	6.03	55.00
	May	0.354	0.131	0.485	0.042	4.35	1.00	0.70	4.25	6.05	56.90
	Jun	0.338	0.114	0.452	0.071	4.00	1.17	0.65	1.35	6.00	31.45
	Jul	0.219	0.190	0.409	0.034	4.16	0.35	0.21	1.55	5.80	55.30
	Aug	0.224	0.094	0.318	0.120	3.55	0.53	1.10	4.30	6.30	56.80
	Sept	0.205	0.121	0.326	0.122	4.33	1.63	1.10	4.72	5.37	64.23
	Oct	0.200	0.111	0.311	0.214	5.11	1.28	0.73	2.54	5.91	54.98

Individual values are mean concentrations (duplicate subsamples) of pooled monthly water samples. No throughfall was generated in December

Appendix 8: Total volume (litres) of stemflow water samples collected from March to October 2007 in forest, 15 and 30 year–old cocoa sites

Month	Land-use/age		
	Forest	Cocoa 15 years	Cocoa 30 years
March 2006	46.5	35.6	33.3
April	154.1	96.6	110.2
May	135.8	187.5	200.5
June	97.6	89.4	76.4
July	76.8	140.7	96.9
August	0.0	0.0	0.0
September	107.5	69.7	82.3
October	134.4	154.1	178.7
November	35.7	27.5	35.0
December	0.0	Trace	0.0
January 2007	13.6	14.2	19.8
February	15.2	16.8	14.6
March	5.5	17.0	45.0
April	85.6	75.4	79.4
May	137.5	169.4	140.6
June	104.6	45.7	80.0
July	65.2	83.2	75.3
August	0	0	0
September	118.7	75.5	92.0
October	128.4	144.2	170.3

Appendix 9: Concentrations of N, P, K, Ca, Na, Mg (mg/l), pH and electrical conductivity in stemflow water samples collected from April to October 2006 in shaded cocoa land-use chronosequences in Ashanti Region, Ghana.

Land-use /Age	Month	NH_4-N mg/L	NO_3-N mg/L	Total N mg/L	P mg/L	K mg/L	Ca mg/L	Mg mg/L	*Na mg/L	pH	Elect. Cond. µS/cm
Forest	Mar	0.213	0.087	0.303	0.075	7.12	1.16	1.21	4.74	6.2	65.6
	Apr	0.240	0.143	0.383	0.129	4.20	1.15	0.65	5.00	6.6	42.4
	May	0.161	0.034	0.195	0.034	5.95	1.00	1.10	4.25	6.8	58.6
	Jun	0.135	0.052	0.187	0.035	2.35	1.50	0.25	2.25	7.0	45.0
	Jul	0.149	0.125	0.274	0.040	3.04	1.25	0.27	2.25	7.0	50.2
	Aug	-	-	-	-	-	-	-	-	-	-
	Sept	0.055	0.021	0.076	0.031	3.15	1.05	0.77	2.60	6.8	42.1
	Oct	0.093	0.013	0.106	0.094	6.40	1.05	0.65	2.85	5.9	62.8
	Nov	0.210	0.036	0.246	0.142	6.60	1.04	0.28	2.80	7.0	45.4
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.212	0.027	0.239	0.062	4.50	0.30	0.10	3.30	6.8	56.4
	Feb	0.267	0.068	0.335	0.030	4.00	1.24	0.88	10.7	7.2	49.3
	Mar	0.359	0.150	0.509	0.033	2.42	0.95	0.48	7.60	6.9	59.7
	Apr	0.283	0.093	0.376	0.028	2.72	0.85	0.60	2.40	7.2	36.7
	May	0.113	0.100	0.213	0.030	2.73	0.82	0.59	1.25	6.7	41.7
	Jun	0.137	0.093	0.230	0.038	1.73	0.90	0.62	1.50	6.2	35.7
	Jul	0.300	0.157	0.457	0.034	1.73	0.83	0.60	1.40	6.2	30.7
	Aug	-	-	-	-	-	-	-	-	-	-
	Sept	0.125	0.084	0.219	0.024	2.11	1.22	0.65	3.23	7.3	43.3
Cocoa 15yrs	Mar	0.229	0.095	0.324	0.067	4.56	1.75	1.05	3.6	3.8	55.85
	April	0.238	0.176	0.414	0.113	4.78	1.95	1.25	8.0	7.1	69.60
	May	0.262	0.052	0.313	0.031	8.80	2.88	1.93	2.0	6.4	77.75
	June	0.086	0.036	0.122	0.043	8.10	1.05	1.90	6.8	6.8	60.70
	July	0.176	0.035	0.211	0.045	8.15	1.15	1.55	7.5	6.7	60.60
	Aug	-	-	-	-	-	-	-	-	-	-
	Sept	0.148	0.044	0.192	0.035	7.20	1.10	0.50	2.15	6.8	49.90
	Oct	0.076	0.041	0.117	0.022	5.00	1.55	0.39	2.15	7.2	61.40
	Nov	0.168	0.071	0.239	0.085	11.3	0.97	1.17	8.5	6.7	54.00
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.171	0.056	0.226	0.130	6.60	1.06	1.16	8.7	6.1	55.70
	Feb	0.217	0.173	0.390	0.188	5.50	0.50	0.10	4.3	6.6	71.50
	Mar	0.230	0.123	0.353	0.036	3.94	1.12	0.55	9.10	7.2	59.33
	Apr	0.219	0.100	0.319	0.031	2.36	0.90	0.44	8.6	6.5	64.54
	May	0.232	0.112	0.344	0.023	2.50	0.88	0.54	3.4	7.3	36.70
	Jun	0.218	0.116	0.333	0.025	2.73	0.98	0.53	1.5	7.5	46.45
	Jul	0.308	0.128	0.436	0.033	1.78	0.85	0.50	1.5	6.2	30.67
	Aug	-	-	-	-	-	-	-	-	-	-
	Sept	0.132	0.065	0.197	0.043	8.20	1.24	1.51	4.2	6.4	55.56
	Oct	0.104	0.043	0.147	0.036	3.12	1.27	0.73	1.3	6.1	65.87

Cocoa	Mar	0.199	0.054	0.253	0.035	9.66	1.06	0.74	4.1	5.9	45.7
30yrs	Apr	0.272	0.048	0.320	0.037	3.75	1.75	1.05	2.8	7.1	101.8
	May	0.247	0.133	0.380	0.028	5.75	1.05	0.31	3.8	7.1	71.9
	Jun	0.247	0.189	0.436	0.028	9.40	0.85	0.48	3.3	7.0	32.8
	Jul	0.252	0.146	0.398	0.027	3.10	0.80	0.60	3.8	7.0	60.3
	Aug	-	-	-	-	-	-	-	-	-	-
	Sept	0.044	0.029	0.073	0.019	8.30	0.80	0.45	2.5	6.9	34.0
	Oct	0.298	0.054	0.352	0.058	11.7	0.50	0.76	2.7	6.3	60.1
	Nov	0.175	0.071	0.246	0.042	5.01	0.49	0.61	6.1	6.6	58.1
	Dec	-	-	-	-	-	-	-	-	-	-
	Jan	0.264	0.163	0.427	0.082	3.21	0.30	0.12	2.1	6.8	61.4
	Feb	0.312	0.093	0.405	0.056	4.51	1.46	1.17	9.7	7.2	48.8
	Mar	0.243	0.109	0.352	0.059	3.22	1.45	0.56	8.2	7.2	53.7
	Apr	0.199	0.122	0.321	0.040	4.30	1.24	0.75			
	May	0.289	0.139	0.428	0.050	3.46	1.31	0.65	5.4	7.3	38.63
	Jun	0.285	0.139	0.423	0.031	3.89	1.25	0.81	2.3	6.5	37.68
	Jul	0.244	0.092	0.336	0.028	3.75	0.65	0.95	1.7	4.4	69.50
	Aug	-	-	-	-	-	-	-	-	-	-
	Sept	0.210	0.094	0.304	0.026	5.43	0.85	0.67	3.6	5.4	44.65
	Oct	0.186	0.087	0.273	0.043	3.78	1.10	0.45	5.3	4.8	65.87

Individual values are mean concentrations (duplicate subsamples) of pooled fortnightly

Appendix 10. Mean annual nutrient return to forest floor through litterfall, fine roots turnover, throughfall, and stemflow in forest and cocoa land-use systems in the Nwabiagya District.

Land-use	Nutrients (kg ha^{-1})				
	N	P	K	Ca	Mg
Forest					
Litterfall	153	9.8	31.8	165	35.8
Throughfall	3.1	1.32	56.7	11.5	9.4
Stemflow	0.04	0.01	0.56	0.16	0.10
Fine roots turnover	19.0	5.0	36.0	47.0	21.0
Cocoa 3 years					
Litterfall (cocoa & upper canopy trees)	44.8	4.3	11.7	74.1	30.6
Throughfall	3.25	0.65	32.4	9.96	10.7
Stemflow	ND	ND	ND	ND	ND
Fine roots turnover	12.0	2.0	9.0	18.0	3.0
Cocoa 15 years					
Litterfall (cocoa & upper canopy trees)	79.3	4.1	33.8	139.7	60.6
Throughfall	3.54	0.34	35.2	14.7	14
Stemflow	0.05	0.01	1.07	0.28	0.25
Fine roots turnover	25.0	3.0	17.0	21.0	12.0
Cocoa-30					
Litterfall (cocoa & upper canopy trees)	133.6	4.7	61.8	150.0	52.6
Throughfall	4.82	1.32	58.5	15.9	10.0
Stemflow	0.03	0.003	0.39	0.07	0.04
Fine roots turnover	31.0	5.0	18.0	36.0	25.0