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Dilys Sefakor Kpongor

Spatially explicit modeling of sorghum (*Sorghum bicolor* (L.) Moench) production on complex terrain of a semi-arid region in Ghana using APSIM

ABSTRACT

An increasing human population and decreasing fallow periods have resulted in a rapid decline in soil productivity in the semi-arid region of Ghana, which is characterized by low-input subsistence agriculture. Soils are inherently poor and contain little to support crop production. Attempts by smallholders to increase production have resulted in the concentration of nutrients in the homestead fields through the use of animal manure and crop residues from the distant bush farms. This has contributed to spatial variability in soil nutrients and soil organic carbon (SOC).

The study area was classified into land-use trajectories based on a rural rapid appraisal technique with the aid of the farmers in the community and by remote sensing quick-bird imagery. The influence of land-use trajectories on soil nutrient stocks was evaluated. Spatial distribution of soils and soil properties and the factors influencing their distribution were assessed in a landscape of 1.5 km^2 selected within the study area. Data on soil chemical and physical properties collected were analyzed with geostatistical techniques for their spatial dependency. The Agricultural Production Systems sIMulator (APSIM), a crop simulation model, was calibrated for sorghum (*Sorghum bicolor* (L.) Moench) and evaluated for yield response to inorganic nitrogen (N) and phosphorous (P) fertilizer treatments in two farm types (homestead fields and bush farms).

Land-use trajectories are revealed to have influenced the nutrient stock of the soils in the study area. Furthermore, the impact of farmers' management activities on nutrient stocks was significant. Though a non-parametric test revealed distinct soil types, considerable variability could be observed within individual soils based on their chemical and physical properties. The distribution of soil parameters in the selected landscape was influenced by the soils, farmers' management practices and topography. APSIM predicted the grain yield response of sorghum to both N and P application with an overall modified internal coefficient of efficiency of 0.64. A gradual decline in grain yield was observed over the 29-year simulation period in both the homestead fields and the bush farms, with yields being much lower in the latter. If crop residues were returned to the fields, half the mineral N fertilizer was needed in the homestead fields to produce the average grain yields produced on the bush farm with full fertilization. Temporal variability in grain yield was consistently higher with the removal of crop residues, irrespective of farm type. APSIM is responsive to both organic and inorganic fertilizer applications in the study area and also highlights the essential role of crop residues and inorganic fertilizer in influencing the temporal variability in sorghum grain production and hence the impact of farmers' management practices on food security. This is evident in the rapid decline in soil organic carbon accompanied by a decline in grain yield after 29 years of cropping. The use of inorganic fertilizer and incorporation of crop residues (organic matter) are critical for attaining food security in the study area.

Räumliche Modellierung von Sorghum- (*Sorghum bicolor* (L.) Moench) Produktion in einem komplexen Gelände in einer semi-ariden Region in Ghana mit APSIM

KURZFASSUNG

Im semiariden Teil Ghanas haben Bevölkerungswachstum und verkürzte Brachezeiten zu einer Verringerung der Bodenfruchtbarkeit geführt. Bei geringen Inputs herrscht Subsistenzlandwirtschaft vor. Böden sind von Natur aus arm und unterstützen Pflanzenbau nur wenig. Versuche von Kleinbauern, die landwirtschaftliche Produktion zu verbessern, haben zu einer Konzentration von Pflanzennährstoffen in den hausnahen Feldern geführt, in dem dort Dung und Ernterückstände von weiter entfernt liegenden, hausfernen Feldern ("bush fields") konzentriert wurden. Damit erhöhte sich auch die räumliche Variabilität von Pflanzennährstoffen und bodenorganischer Substanz.

Landnutzungsverläufe wurden mit Hilfe von Befragungen der Bauern (rural rapid appraisal) sowie mittels Satellitenbildauswertung klassifiziert. Der Einfluss von Landnutzung auf den Bodennährstoffvorrat wurde anschließend ermittelt. Die räumliche Verbreitung der Böden und Bodeneigenschaften und die beeinflussenden Faktoren wurden in einem Landschaftsausschnitt von 1.5 km^2 bestimmt. Die räumlichen Abhängigkeiten der bodenphysikalischen und -chemischen Parameter wurden geostatistisch berechnet. Das Pflanzenwachstumsmodell APSIM (= Agricultural Production Systems sIMulator) wurde für Sorghum (Sorghum bicolor (L.) Moench) angewendet. Anschließend wurde das angepasste Modell mit unabhängigen Daten von Versuchen in zwei Kleinbauernmanagementsystemen (hausnahen und -fernen Feldern) zum Wachstum von Sorghum in Abhängigkeit von gesteigerter Düngergabe (N und P) validiert.

Es zeigte sich, dass Landnutzung einen signifikanten Einfluss auf die Pflanzennährstoffvorräte der Böden in der Untersuchungsregion hatte. Die Bodenparameter waren räumlich ausgesprochen variabel. Obwohl nicht-parametrische Tests mehrere Bodentypen aufzeigen konnten, so fand sich im Hinblick auf physikalische und chemische Eigenschaften doch eine beachtliche Variabilität innerhalb der einzelnen Bodentypen. Diese Bodeneigenschaften wurden durch die ursprünglichen Böden, das Kleinbauernmanagement und durch die Topographie beeinflusst. Die Simulation des Einflusses von N und P Düngung auf den Ertrag von Sorghum mit Hilfe von APSIM erzielte insgesamt einen Effizienzkoeffizienten von 0.64. Im Laufe der Simulationsperiode von 29 Jahren nahmen die Erträge sowohl in den hausnahen als auch auf den hausfernen Flächen leicht ab. Wurde auf den hausnahen Flächen nur die Hälfte an Stickstoff gedüngt und zusätzlich Ernterückstände auf der Fläche belassen und in den Boden eingearbeitet, so glichen die Erträge ungefähr denen auf den hausfernen Flächen. Die zeitliche Variabilität der Ernteerträge war auf hausnahen und -fernen Flächen übereinstimmend höher, wenn Erntereste nicht auf dem Feld verblieben. APSIM gab den Einfluss von sowohl organische als auch anorganische Düngung wieder und unterstrich damit die Wichtigkeit dieser beiden Maßnahmen im Rahmen des gängigen Managements von Kleinbauern in der Region. Dies wird durch den starken Rückgang des bodenorganischen Kohlenstoffs sowie des Körnerertrages nach 29 Anbaujahren deutlich. Das Ausbringen von Mineraldünger als auch das Belassen von Ernteresten auf dem Feld sind unabdingbare Maßnahmen im Hinblick auf die nachhaltige Ernährungssicherung im semiariden Ghana.

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LIST OF ABREVIATIONS

AE_N	Agronomic use efficiency of Nitrogen
Al	Aluminium
ANOVA	Analysis of variance
APSIM	Agricultural Production Systems sIMulator
AS	Ammonium sulphate
asl	Above sea level
BD	Bulk density
BS	Base Saturation
C	Carbon
C/V	Cost to value ratio
Ca	Calcium
CEC	Cation exchange capacity
cm	Centimeters
CN	Carbon nitrogen ratio
CSM	Crop simulation model
CV	Coefficient of variation
DEM	Digital elevation model
DGPS	Differential global positioning system
DSSAT	Decision support system for agro-technological transfer
DUL	Field capacity
E_1	Modified internal model efficiency coefficient
FAO	Food and Agriculture Organization
fbiom	proportion of decomposable soil carbon in the more liable soil organic matter pool.
Fe	Iron
finert	proportion of soil carbon assumed not to decompose
GDD	Growing degree days
GHC	Ghanaian cedis
GIS	Geographical information systems
GLM	General linear model

GSS	Ghana statistical services
ha	hectare
KCl	murate of potash
Kg	Kilogram
Ks	Saturated hydraulic conductivity
LL15	Permanent wilting point
M	Meter
Max	Maximum
MdUAPE	Modified unbiased absolute percentage error
Mg	Magnesium
Min	Minimum
mm	Millimeter
MoFA	Ministry of Food and Agriculture
PF	partial factor productivity index
PRA	Participatory rural appraisal
r	Correlation coefficient
RMSE	Root mean square error
Rsq	Coefficient of determination
SARI	Savannah Agricultural Research Institute
SAT	Volumetric water content at saturation
SD	Standard deviation
SOC	Soil organic carbon
SoilN	Soil Nitrogen module
soilP	Soil Phosphorous module
soilWAT	Soil water module
SSA	Sub-Saharan Africa
TSP	Triple super phosphate
USDA	United States Development Agency
YR	year
ZEF	Zentrum für Entwicklungsforschung

1 GENERAL INTRODUCTION

1.1 Problem setting

The decline in soil productivity in the tropics and particularly in dryland areas continues to be a major concern to scientists and policy makers alike due to its direct implication for food security. Sub-Saharan Africa is one of the areas most affected by degrading soil fertility, and this is further aggravated by an agricultural system characterized by low input subsistent farming (Sanchez et al., 1997). This is also in part as a result of increasing pressure on agricultural land resulting in negative nutrient balances (Stoorvogel et al., 1993; Stoorvogel et al., 1998; Wopereis et al., 2006) and has translated into low crop yields over decades. For instance, a drastic decline in maize yield from 3 to 0.7 t ha^{-1} was reported for low input systems in Benin, where fallow periods have been reduced from 6 to 2 years (Wopereis et al., 2006). Moreover, the region is characterized by inherently poor soils. In most parts they are sandy in nature with a characteristically low capacity to store soil organic carbon (SOC) (Six et al., 2002). Also, SOC declines at faster rates in cultivated soils compared to forest soils due to their low biomass production capacity. This poses a major constraint to crop production, as in low external input systems SOC serves as the main source of nutrients in the soil.

Prominent among soil nutrients limiting crop production are phosphorous (P) and nitrogen (N). Unlike nitrogen, phosphorous is mainly lost from the soil through crop (grain) harvest and only little is left in residues for recycling (Rhodes, 1995; Vlek et al., 1997). Most efforts towards addressing soil fertility are, however, directed to only soil N deficiencies. It is also, however, evident that deficiency of soil P reduces the efficiency of N applied to crops. Abekoe and Tiessen (1998) and Owusu-Bennoah et al. (1991) have shown that soil available P content of soils in this area is limiting crop yield through (i) low availability due to low P content of underlying parent rock material, (ii) moderate to low sorption capacities of the soils and (iii) the presence of ferralitic concretions that serve as sinks (trap) to available P. These factors together contribute to the low values of available soil P (Bray 1) of below 10 mg kg^{-1} recorded for the region.

While recognizing the importance of regional studies and the above analysis, it is also important to consider spatial variations in terms of changes in soil fertility in smallholder farming systems (Scoones and Toulmin, 1999). More fertile soils are typically located close to the homesteads and fertility reduces with increasing distances from the homestead (Tittonell et al., 2005). Variation in soil fertility could be a result of natural factors such as underlying soil types (geology) (Decker, 2002), location within a topography (Franzen et al., 2002) or due to dynamic processes such as land-use histories and/or management activities. In spite of the influence of the soils and topography on spatial variation in soil fertility, farmers' management practices have been shown to have generated gradients in soil carbon and nutrient stocks (Prudencio, 1993; Deckers, 2002; Rowe et al., 2006) through the diferential allocation of organic inputs and the export of crop residues from the bush farms to farms closer to the homesteads (Hilhorst and Muchena, 2000). More so, most resources are allocated to the homestead fields (e.g. labor, manure) resulting in wide variations in crop yield.

About a 25 % of the increases in crop yield over the decade's world wide have been credited to improved technologies such as mineral fertilizer use (Bindraban et al., 2000). In spite of the major contributions of mineral fertilizer use to crop production in the developed world as well as the success of the "Green Revolution" in Asia, the use of mineral fertilizers in Sub-Saharan Africa (SSA) is very low. Among the reasons are the high prices for fertilizer, which are beyond the means of smallholder farmers (Kaizzi 2002). Farmers, however, use fertilizer on vegetable cultivation with a ready market, which indicates the possibility of its use in grain production if it is proven to be a profitable venture. Another, maybe more important reason, relates to the variable responses with the use of fertilizer due to varied soil fertility conditions and seasonal differences in yield resulting from erratic rainfall patterns (Nandwa et al., 1998). This is because environment is an important biophysical yield-limiting factor, especially in the semi-arid regions of West Africa where crop failure is a normal occurrence due to very low and/or erratic rainfall (Hengsdijk and Van Keulen, 2002).

To capture the interactive soil-atmosphere effect on crop yield, crop simulation models have proven to provide an excellent approach. The Agricultural Production Systems sIMulator (APSIM), which was developed for and has widely been used in smallholder farming systems in semi-arid regions, was selected to simulate sorghum grain yield in this study. It has a unique capability of tracking long-term dynamics of soil properties in response to farm management and weather conditions and their effects on crop yield. It also has an additional advantage of containing a routine to simulate the impact of soil P deficiency on crop growth and yield.

1.2 Research objectives

The overall aim of the study was to explore causes of variability in soil properties in the study area and to model the grain yield response of sorghum (*Sorghum bicolor* (L) Moench) – important crop in the study area - to inorganic fertilizer application on two distinct farm types. Based on these studies, the sustainability of farmers' management practices (crop residue management) and their implication for food sufficiency in the region were evaluated.

The specific objectives were to:

i. Assess the impact of land-use history (trajectories) on soil nutrient status,
ii. Assess variability of soil properties and soil types in selected landscape,
iii. Assess the agronomic and economic feasibility of inorganic fertilizer use in two distinct farm types,
iv. Calibrate and evaluate the APSIM crop simulation model for the study area,
v. Assess the sustainability of farmers' management practices in two farm types and the spatial variability of crop yield within the landscape.

1.3 Outline of thesis

The thesis is structured into seven main chapters. After the general introduction, chapter 2 reviews pertinent literature. Chapter 3 gives a general description of the study area and the materials and methods employed in the thesis. The results and discussions are presented in three main chapters: Chapter 4, discusses the impact of land-use trajectories (history) on soil nutrient stocks and the redistribution phenomenon that characterizes farmers' management practices. Chapter 5 describes and discusses the distribution of soils and soil properties, looking also at the spatial dependency of selected soil parameters at a landscape scale and their implications for precision management. Chapter 6, which is central to the thesis, discusses the agronomic and economic feasibility of inorganic fertilizer use in two farm types and soils, calibrates and evaluates the APSIM crop simulation model, and evaluates the sustainability of farmers' management practices under the given scenario analysis. The thesis concludes with a summary of the major findings their related policy implications and recommendations for further study.

2 LITERATURE REVIEW

2.1 Land degradation

Land degradation is a phenomenon characterised by loss of the production capacity of land due to decline in soil fertility and biodiversity and the degradation of natural resources (FAO, 2002). Another definition describes it as the aggregate diminution of the productive capacity of the land, which includes its major uses (rain-fed, arable, irrigated, rangeland and forest), its farming systems (e.g. smallholder subsistence) and the value of its economic resource. It is a composite term that portrays how one or more of the land resources (soil, water, vegetation, rocks, air, climate, relief) have changed for the worse. Central to all definitions is the link made between degradation and its subsequent effect on land use (Oldeman et al., 1991; Lynden, 1995).

The condition of soil is one of the best indicators of land degradation, as it integrates a variety of important processes involving vegetation growth, overland flow of water, infiltration, land use and land management practices. Consequently, soil degradation is, in itself, an indicator of land degradation.

The degradation of land resources, particularly soils, poses a great threat to food production, food security and the conservation of natural resources. In Table 2.1, the extensive nature of the process of agricultural land degradation on the global stage based on data presented by Oldeman et al. (1992) and Scherr (1999) is illustrated. More than 50 % of the arable land in Africa has been degraded and crop yield loss due to this phenomenon is estimated to range from a 2 % to 50 % decline over several decades (Scherr, 1999). Annual nutrient mining rates of 30 kg ha^{-1} of N P K were reported for 85 % of farmlands during the 2002 – 2004 cropping seasons. Of this figure, 40 % of the farms had nutrient mining rates exceeding 60 kg of N K P per ha yearly, rates that are considered to be severe (Bationo et al., 2006).

Unless concrete steps are taken to curb this phenomenon, particularly in Sub Sahara Africa where agriculture is characterized by low external inputs, attaining food security in the near future remains a myth.

Table 2.1: Degraded agricultural lands world wide

Region	Total land area (ha)	Degraded land (ha)	Proportion of degraded land (%)
Africa	187	121	65
Asia	536	206	38
South America	142	64	45
Central America	142	64	45
North America	236	63	26
Europe	287	72	25
Oceania	49	8	16
World	1,475	562	38

Source: Scherr 1999; Oldeman et al., 1992.

2.1.1 Soil fertility status of agricultural lands in Africa

Soil nutrient depletion is rapidly increasing and affecting a growing area of farmlands in Africa. This has a particularly negative effect on agricultural production as most of the soils of the continent are inherently poor. On the basis of soil quality and prevailing climatic conditions, it is estimated that about 55 % of agricultural lands are fragile and easily degradable and requiring high external inputs for optimum crop production (Figure 2.1).

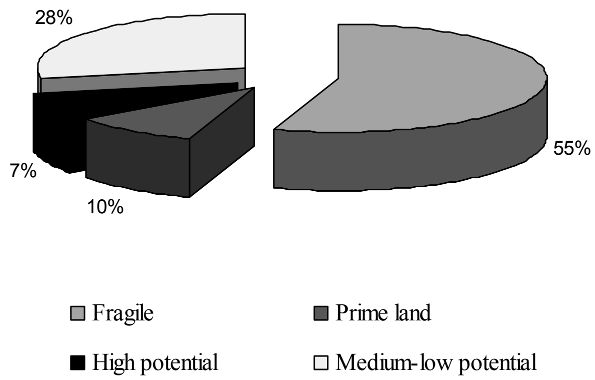


Figure 2.1: Classification of agricultural lands in Africa (Source: African Fertilizer Summit, 2006)

Medium to low potential lands constitute 28 % of the agricultural lands. These are lands with major soil constraints plus one or more minor constraint that can be remedied through management. They are largely found in West and Central Africa. Prime land is characterized by soils with deep, permeable layers, adequate supply of nutrients and limited periods of moisture stress. High potential lands are similar to prime lands but with some minor limitations such as extended periods of moisture stress and sandy or gravelly soils. Based on the proportion of the different classes of agricultural lands that characterizes the SSA, the use of mineral fertilizer is a prerequisite to increasing soil productivity.

2.1.2 Soil spatial variability

Soil fertility or quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, to maintain or enhance water and air quality, and to support human health and habitation (Arshad and Coen, 1992).

There are two types of soil spatial variability, one which can be described as dynamic and the other as inherent. Inherent soil spatial distribution is the result of natural soil forming processes. The deterministic components of soil spatial distribution are influenced by the soil forming factors such as: climate, plants, time, geological parent materials and topography. For example, finer textured soils occur in valley bottom areas whereas coarser textured soils occur on the upslopes. As a key feature, soils also vary with depth due to their horizontal development, and each horizon is characterised by distinct soil properties.

Dynamic soil spatial variation, on the other hand occurs as a result of human influences (management activities). Management choices affect the amount of soil organic matter, soil structure, soil depth, water and nutrient holding capacity, among others (Davidson and Nilsson, 2000). Soils, however, respond differently to management depending on the inherent properties of the soil and its surrounding landscape. It is also necessary to mention that soil spatial variation is scale dependent. On a regional scale, variation in soils can occur due to their relative positions within the landscape and their responses to variations in climate and parent materials. At the field scale, soil variability is due to the effects of human management activities and hill-slope position. Attempts by smallholder farmers at addressing the negative impact of soil degradation results in a phenomenon described as "redistribution" (Breman et al., 2005) of soil nutrients and organic matter.

2.1.3 Redistribution of organic matter and soil nutrients

Redistribution is a component of the process of soil fertility depletion (Breman et al., 2005). It involves removing soil organic matter and nutrients from an area and concentrating them in another. Stoorvogel and Smaling (1990) reported on this phenomenon of soil fertility depletion in Sub Saharan Africa in their study on the evaluation of the national agricultural nutrient balances. Farmers' management practices play an important role in this regard by moving sources of nutrients (e.g. crop residues) from, for example, bush farms to compound farms (Hilhorst and Muchena, 2000) through grazing of livestock (Haileslassie et al., 2005). This was further supported by Ramisch, (2005), who showed annual community-level nutrient balances in south Mali at plot and household levels of -9.2 kg ha^{-1} of N, +0.8 kg ha^{-1} of P and -3.4kg ha^{-1} of K. Together with other management practices, this has resulted in soils with deficiencies in the primary soil nutrients (N, P and K) with a consequent negative impact on crop yield.

2.1.4 Soil phosphorous dynamics

Soil P dynamics are characterized by interactions between physico-chemical and biological processes (Seeling and Zasoski, 1993). Soil P, like other soil nutrients undergoes two main transformations in the soil: the pedological, which is long term (Smeck 1985) and the biological, which is short term (Hedley et al., 1982). Apatite (Ca –P) is the main source of P in most parent materials; hence its proportion in the underlying parent material of a given soil influences the status of soil P. In the West African savannah soils, where soils have undergone progressive weathering, bases such as calcium (Ca), silicates and carbonates are leached out of reach of plants, resulting in the release of P into solution. Some of the P in solution is taken up by plants and other organisms, while the rest forms complexes with oxides of iron (Fe) and aluminium (Al), which serve as sinks to P. Hence, the more intense a soil is weathered, the lower is its Ca concentration, and the more complex oxides of Fe and Al are formed with P. These complexes additionally become occluded with time (Tiessen et al., 1984). In semi arid Ghana, low P contents are attributed to the low content of mineral apatite in the parent materials due to the great age and intensive weathering they have undergone (Nye and Bertheux, 1957; Abekoe, 1998). These losses and transformations have resulted in low and extremely low labile P concerntration of soils (Abekoe, 1998).

Biological transformation of P is governed by the bio-cycling of organic matter. During the process of transformation and losses of bases, carbonates and silicates, some of the P released into solution is taken up by soil biomass and plants.

Organic P is transformed to inorganic P through the process of mineralization, and the inorganic P in solution can again be transformed into organic P through the process of immobilization. Additionally, organic exudates released by soil microbes and plant roots or added organic materials may affect P sorption and the exchangeability of added P by competing for sorption sites (Le Mare et al., 1987; Nziguheba et al., 1998; Nziguheba et al., 2000). Soluble P is adsorbed on surfaces of secondary minerals and forms part of the pool referred to as labile P. This can be desorbed into solution and transformed into non-labile forms that are more stable thermodynamically and are not easily available to plants (Gijsman et al., 1996). In the semi-arid regions of Ghana, the annual burning of vegetation and the removal of crop residues from the fields is likely to negatively influence the short-term transformation of P. Organic P plays a major role in contributing to the P uptake (Gijsman et al., 1996) and short-term P fertility on highly weathered tropical soils (Tiessen et al., 1992).

Availability of soil P is governed by three factors, namely (i) the intensity factor, which is described by the activity of P ions ($H_2PO_4^-$; HPO_4^{2-}) in solution; (ii) the quantity factor, which is the amount of P ions that can be released into the soil solution from the solid phase during the growth period of the plant, and (iii) the buffer capacity, which describes the ability of the soil to maintain the intensity factor constant when quantity varies. Routine analysis of P availability in soils, however, describes only the quantity factor (Sinaj et al., 2001).

Factors influencing the distribution of phosphorous

The amount and distribution of P in tropical soils is determined by the type of parent material (Smeck, 1985), position in a landscape (Abekoe and Tiessen, 1998), extent of weathering (Gijsman et al., 1996) and type of land use (Sinaj et al., 2001; Hedley et al., 1982). These factors have resulted in a high variability of total P concentration in tropical soils. In Brazil, total P values ranged from 7 to 272 mg kg^{-1} (Caiado, 2005). Nwoke et al. (2004) reported values ranging from 90 to 198 mg kg^{-1} in topsoils of savannah zones of West Africa. Total P values of between 91 to 280 mg kg^{-1} were reported for topsoils of the Guinea savannah zone (Kanabo et al., 1978) while Hoffmann et al. (2001) reported 40 mg kg^{-1} in northwest Nigeria.

2.1.5 Trends in fertilizer use in Sub-Saharan Africa (SSA)

In SSA, a little more than 50 % of all fertilizer is used on cereals, particularly on maize. Although the area of land cultivated for sorghum and millet are large, very little of this area is fertilized and if fertilized, application rates are very low (Gerner and Harris, 1993). An average value of 9 kg ha-^{1} fertilizer in Sub-Saharan Africa is very low compared to Latin America, South Asia and Southeast Asia (Table 2.2). In 1990, the amount of fertilizer used per hectare of cultivated arable land in SSA was 8.4 kg compared to a world average of 93 kg and 81 kg for developing countries (Gerner and Harris, 1993). These levels of fertilizer input do not compensate for nutrients lost through crop harvests resulting in negative nutrient balances (Vlek, 1993; Smaling, 1993; Stoorvogel, 1993; Rhode, 1995). Mwangi (1997) indicated that grain yields averaged about a 30 % of those in East Asia, which is not only due to differences in land quality, but also to the low use of fertilizer, which is less than 20 % of the East Asian average.

Table 2.2: Fertilizer use on arable land in Sub-Saharan Africa compared to other regions (kg ha^{-1})

Region	2000-2001	2002-2003
Sub-Saharan Africa	9	9
South Asia	109	100
East and Southeast Asia	149	135
Latin America	99	73

Source: FAO 2004

For Ghana it was estimated that the use of fertilizer averaged about 11,000 nutrient tons as against 90,000 tons of nutrients removed through crop harvests. This means that large amounts of additional fertilizer are required to maintain soil fertility (Bumb et al., 1994). Since the 1980´s, fertilizer use in smallholder systems in Sub-Saharan Africa increased only marginally by 17 % representing 1.09 million tons in the

1980's to 1.26 million tons in 2000. Over the same period, the amount of fertilizer consumed per hectare of cultivated land rose by 5 %. The main reasons for low adoption of this technology are (i) high cost of fertilizer in Africa compared to other countries and (ii) lower proportion of irrigated land in the sub region hence lower fertilizer efficiency under erratic rainfall events. According to Sanchez (2002), the prices of mineral fertilizers are in the range of 2 – 6 times those in Europe, North America, or Asia, increasing several times through their transport from abroad to the towns and villages where they are needed. Despite the low fertilizer use in SSA, a number of countries have attained impressive growth trends per unit of cultivated land in the past decade (Crawford et al., 2006). This trend needs to be sustained, increased and expanded geographically over the next decades in order to stimulate crop production to levels that assure food sufficiency.

2.1.6 Implications of poor soil fertility for food security

African's annual population growth of 2.4 % is about the highest in the world and is negatively impacting on food security and is leading to soil nutrient depletion on the continent, lowering the per capita food availability, even in food-sufficient countries (Eilitta, 2006). Significant challenges in many parts of the world are the achievement of better soil nutrient and water management practices to improve low crop yields, the reduction of natural resource degradation, the selection and breeding of crops that give higher yields and nutritional value, and the control of insect pests that threaten livelihoods, food security and economic development. Although improving crop yields may not be a priority for many developed countries, it remains an important task for small-scale farms of the developing world. This requires that the fundamental bio-physical causes of the gap between potential and real yields be identified (Eilitta, 2006) in order to tackle the problem holistically.

In SSA, more challenges remain, as agricultural productivity is low and the future for food security is bleak. The low agricultural productivity is the result of the poor resource base, low inputs use and returns and the rapid population increases. Inherently poor soils and unfavourable climatic conditions are further reasons for the low productivity. Breman and Debrah (2003) stated that "Soils in SSA are not in the first place poor through depletion by farmers, but farmers deplete soils because their soils are poor by nature." This fertility status translates into low economic returns on mineral fertilizer use (Kaizzi 2002), a factor which has contributed to the fact that Sub-Saharan Africa has not benefited from the “Green Revolution”. Moreover, the socio-economic and policy environment are not favourable to resolving the low agricultural productivity (Bationo et al., 2006).

2.2 Sorghum

Sorghum (*Sorghum biocolor* (L.) Moench) is a drought resistant C-4 crop originating in the north-eastern part of Africa, where the greatest variability in wild and cultivated species is found. It is an extremely important commodity that provides food and feeds millions of people living in semi-arid environments worldwide. It is adapted to a wide range of environmental conditions, particularly to drought. It has a number of morphological and physiological characteristics that contribute to its adaptation to dry conditions, including an extensive root system, waxy bloom on the leaves that reduces water loss, and the ability to stop growth in periods of drought and resume it again when conditions become favorable. It is also tolerant to water-logging and can be grown in high rainfall areas. It is, however, primarily a crop of hot, semi-arid tropical environments with 400 – 600 mm rainfall that are too dry for maize. It is also widely grown in temperate regions and at altitudes of up to 2300 m in the tropics.

In West Africa, it is also known as 'Guinea corn'. In Ghana, it is cultivated from the Brong Ahafo region (forest – savannah transitional zone) to the hot dry Sudan Savannah zone of the extreme northern part of the country (Schipprack and Abdulai, 1992). It is mainly grown alone or intercropped with millet. Most of the varieties grown are late maturing (4 – 6 months) and have tall stalks of 2.5 – 4 m length. The plant has multiple uses. The grains are grounded into flour or paste and processed into local dishes (Koko and tuwo). It is also used for brewing a local beer called “pito”. The stalks are used as building material and also as fuel in the homes. Yields are often low, ranging from 1 to 3 t ha^{-1}.

2.3 Modeling crop growth and yield

Crop growth is an extremely complex process in both time and space. Changes in climatic conditions influence soil moisture availability, plant root uptake of soil nutrients and water. It also affects crop phenology and, depending on the growth stage of a plant, unfavorable climate conditions can result in large losses in crop yield or total crop failure.

In recent years, the crop growth model has become increasingly important as the main component of agriculture-related decision-support systems (Jame and Cutforth, 1996; Stephens and Middleton, 2002). Crop models serve as a research tool for evaluating optimum management of cultural practices, fertilizer use, and water use. There are two main different approaches to Modeling crop yields response to management options and prevailing environmental conditions. These are either the empirical and process-based (simulation) models, and each approach has its merits and limitations (Park et al., 2005).

2.3.1 Empirical approach

Empirical models are based on empirical datasets and driving variables, and the use statistical analyses such as correlation or regression analysis to derive patterns of crop yield responses, without explaining the underlying crop growth and yield processes. They are relatively simple to build and their predictive capability depends on the quality and range of the empirical data sets. However, ecological processes that define crop yield dynamics are often not well explained by pure empirical functions. Unlike process-based models, they are less, or even not at all, capable of extrapolating yield beyond the range of the data set. They are widely used in optimizing agricultural inputs with the aim of maximizing inputs use efficiency of crops (Zhang and Evans, 2003; Belanger et al., 2000, Prendagast, 1992).

2.3.2 Simulation models

The process-based Modeling approach primarily employs the knowledge or understanding of the crop yield through mathematical relations that are based on plant physiology, agro-climatic and plant-soil-atmosphere interactions (physiological and biochemical processes). Hence, these models arise primarily from the understanding of processes rather than from statistical relationships (Willmott 1996). They can be used to quantify potential yield gaps between prevailing management options and potential yields of different crops. They also provide a means of evaluating possible dynamics in crop yield responses over a given time within a given location. In contrast, traditional methods of analysis in agronomic research usually produce results that are site and season specific. They hence lack an in-depth framework for explaining the processes underlying yield formation, and their outputs provide inadequate insight into crop responses to management options and prevailing environmental conditions. The models provide a means of evaluating possible causes for changes in yield over time within a given location (Keating and McCown, 2001). Similarly, they serve as a research tool to evaluate optimum management of cultural practices, fertilizer use and water use. Finally, crop growth models can be used to evaluate consequences of global climate change on agricultural production, regional economies, etc.

To carry the analysis of yield formation beyond traditional agronomic research, predictive models of crop growth and yield are required. Since process models explicitly include plant-physiology, agro-climatic conditions, and biochemical processes, these models are supposed to be able to simulate both temporal and spatial dynamics of crop yields. Consequently, the ability to include temporal changes of crop yields and extrapolation potentials are much higher than in the case of empirical models (Jame and Cutforth, 1996).

As underlying processes of crop growth, grain yield and the temporal changes in grain as a consequence of farmers' management practices are the basis of this study, a process-based approach is preferred to the empirical approach.

3 STUDY AREA, GENERAL MATERIALS AND METHODS

3.1 Study area

The study area is located in Navrongo (Pungu) in the Upper East region of Ghana (Figure 3.1), one of the three most densely populated districts in the region. The region lies between the latitudes 10° 30" and 11° 15" N and between the longitudes 0° and 1° 45" W. It is bordered in the north by Burkina Faso, in the west by the Upper West region, in the south by the Northern region and in the east by Togo. It covers an area of 8,842 km^2. The population density is 87 persons per km^2, which is well above the national average of 57 persons per km^2 (Ghana Statistical Service, 2002).

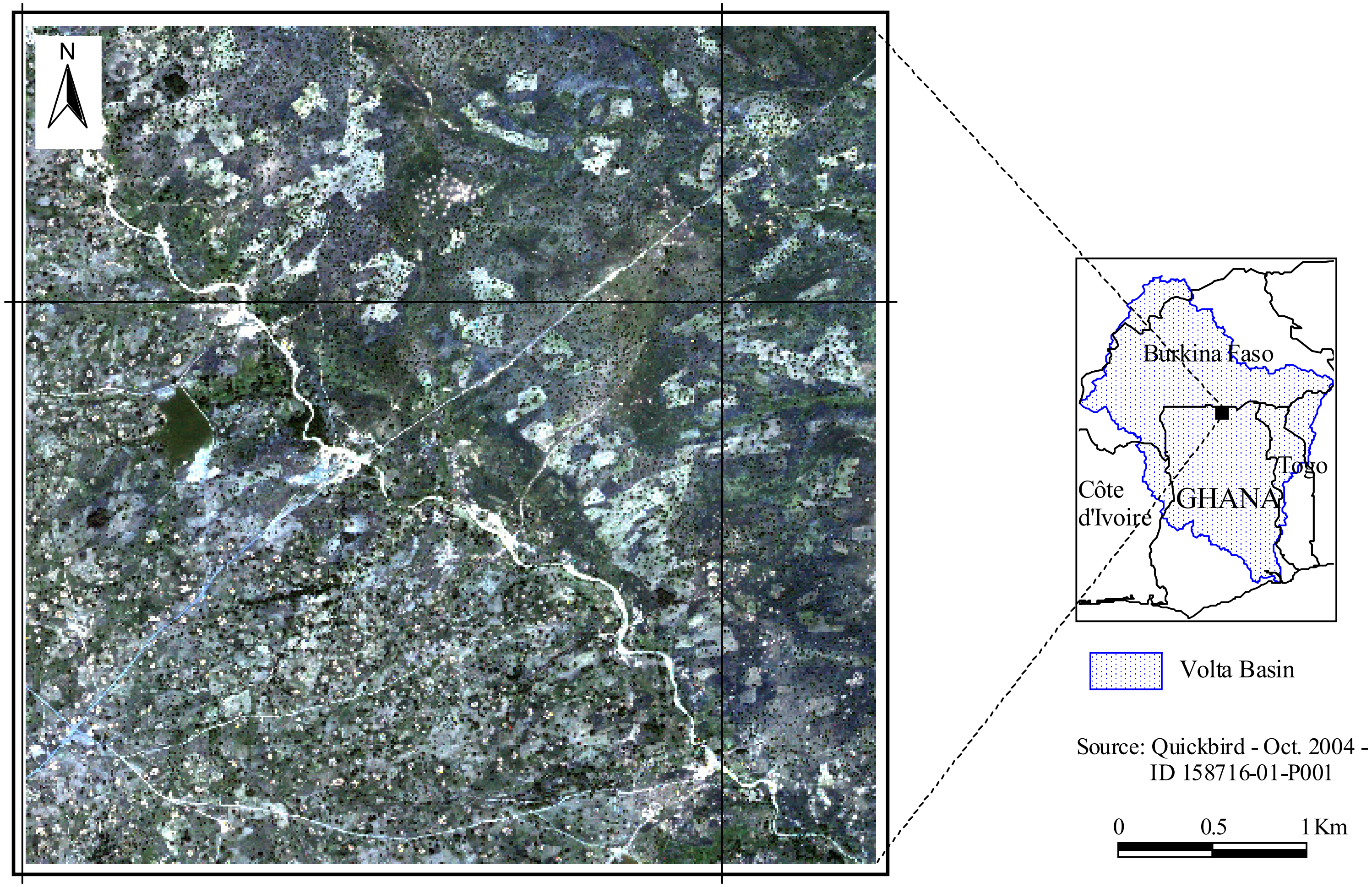


Figure 3.1: Study area shown within the Volta basin

3.1.1 Climate

The area falls within the transition of the Guinea and Sudan savannah agro-ecological zones and is characterized by pronounced wet and dry seasons. The two prevailing weather conditions are the result of two oscillating air masses, the harmattan air mass that blows in a north-easterly direction across the area from the Sahara, reaching its maximum south west extent across the Atlantic Ocean in January, and the monsoon air mass that passes over the area, reaching its maximum extent in August. The harmattan air is warm, dry and dust-laden, whereas the monsoon air is warm and humid. The movement of these two air masses determines the climatic conditions of the region.

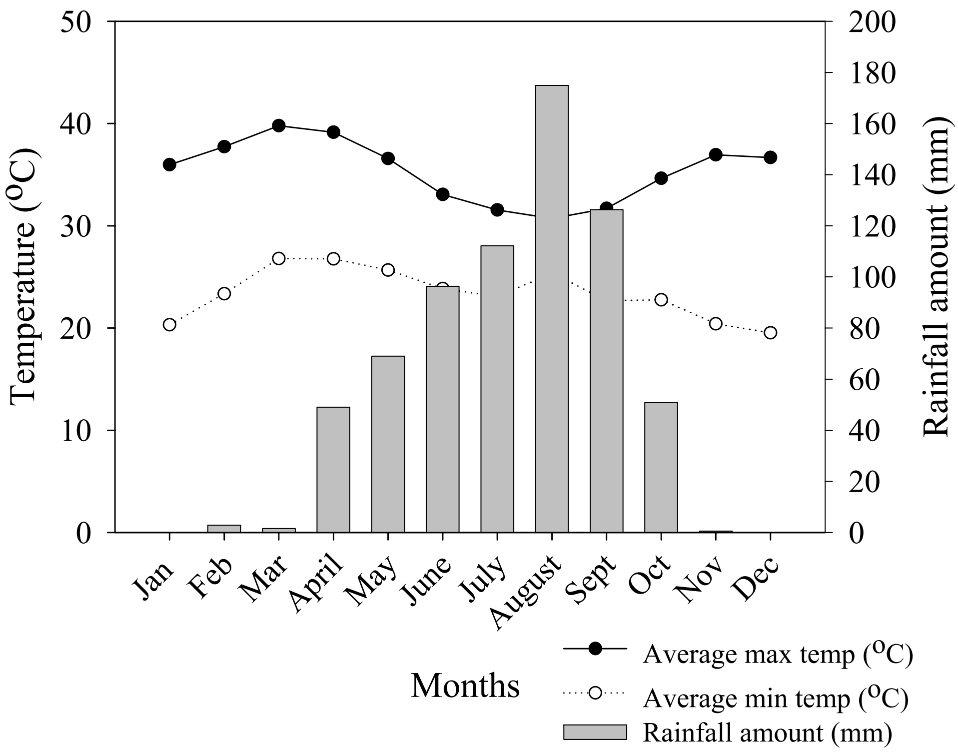


Figure 3.2: Average monthly temperature and rainfall distribution in Navrongo Upper East region, Ghana (1995-2005). Data source: Ghana meteorological services

The climate is characterized by a monomodal rainfall regime where monthly totals increase gradually from March till September, when rainfall peaks and then drops rather abruptly (Figure 3.2). Considerable variations exist between successive rainy seasons in time of onset, duration, and total rainfall amounts. The rainfall period is about five months and the remaining seven months remain hot and dry. Annual rainfall amounts lie between 900 and 1000 mm with an inter-annual variability of 20 – 30 % (Kasei, 1990). The onset and termination of the rains are usually characterized by violent thunder storms. The effective rainfall amounts are considerably low for agricultural purposes mainly due to high surface runoff during the rainy season (especially at the onset) and high evapotranspiration.

Average maximum temperatures occur in March and April. Minimum temperatures occur in December and are invariably associated with the harmattan. Average daily relative humidity is usually high in the rainy season, as high as 60 %, in particular from July to September, and as low as 12 % in the dry harmattan period from December to March. The Harmattan is a weather phenomenon that is characterized by cold wind during the night and hot dry wind during the day. These dusty winds are reported to contain aerosol concentrations from 15 - 20 mg cm^{-3}, but these can be as high as 100 mg cm^{-3} with visibility less than a kilometer.

3.1.2 Relief and drainage

The area is characterized by a gently rolling and undulating topography in a peneplain landscape. Decker (1996) identified five interrelated terrain units, namely, denudated rocky areas, iron-capped hills and remnants, stream beds and valley slopes. Contour heights range from 190 to 220 m above sea level (asl), with slopes rarely exceeding 4 % (Asiamah et al., 1996).

The drainage system consists of several tributaries and sub-tributaries. The White Volta is the major river flowing south of Navrongo, flowing from the north east then taking a sharp south west turn at the Gambaga escarpment before heading south east. Then there are the Red Volta, which flows in the north-south direction to the east of Navrongo and several other tributaries and sub-tributaries such as the Tono river, Nakambe River, Atankudi and Asebelika. Also peculiar to this area are disconnected pools of isolated water or river beds during the dry season. There are numerous small dams in the area for watering of livestock and dry season cultivation of vegetables and rice. There are also hand-dug wells and boreholes from which water is drawn for drinking and other domestic uses.

3.1.3 Soils and geology

There are three main types of rocks in the Upper East region; Voltaian, Birrimian and granitic rocks. The Voltaian rocks consist of sand-stones and shales and are confined to the southern part of the area lying unconformably on the granitic and Birrimian rocks. Birrimian rocks are associated with granites. They are composed of steeply dipping metamorphosed sediments and volcanics. Granitic rocks constitute the oldest of the three. They consist mainly of coarse and fine grained biotite granodiorites and gneisses. Some soil series formed from these are the Pu, Tenchera and Bongo soils.

The alternate clear-cut wet and dry seasons have a direct influence on soil forming processes in the area. The prevailing climatic conditions also permit accelerated chemical decomposition and deep weathering of rocks. However, the sudden and torrential rainfall following a prolonged dry season, during which the grass cover is burnt, induces topsoil erosion, which also leads to the irreversible hardening (laterisation) of the subsoil when this is exposed to the dry harmattan winds.

The soils formed over the granites and sandstones are light topsoils varying in texture from coarse sandy loams and heavier subsoils varying from coarse sandy loams to clays with varying amounts of gravel. Soils in the valley bottoms have heavier topsoils and subsoils including the Brenyasi and Kupela soil series. Soils located on the gently undulating to gently rolling terrain are more vulnerable to erosion than those occurring on the more strongly rolling relief of the forest regions in Ghana. Erosion is particularly evident and extensive along lower slopes of major and minor valley sides resulting in shallow, stony and rocky soils. These soils are generally suitable for the cultivation of sorghum (also known as Guinea corn), millet, and legumes.

3.1.4 Vegetation

The vegetation of the study region has been described by Taylor (1952). The original vegetation of this region was classified as Sudan savannah (mid-dry savannah, Figure 3.3) consisting of short deciduous trees that are widely scattered and a ground flora composed of different species of grasses and shrubs of varied heights.

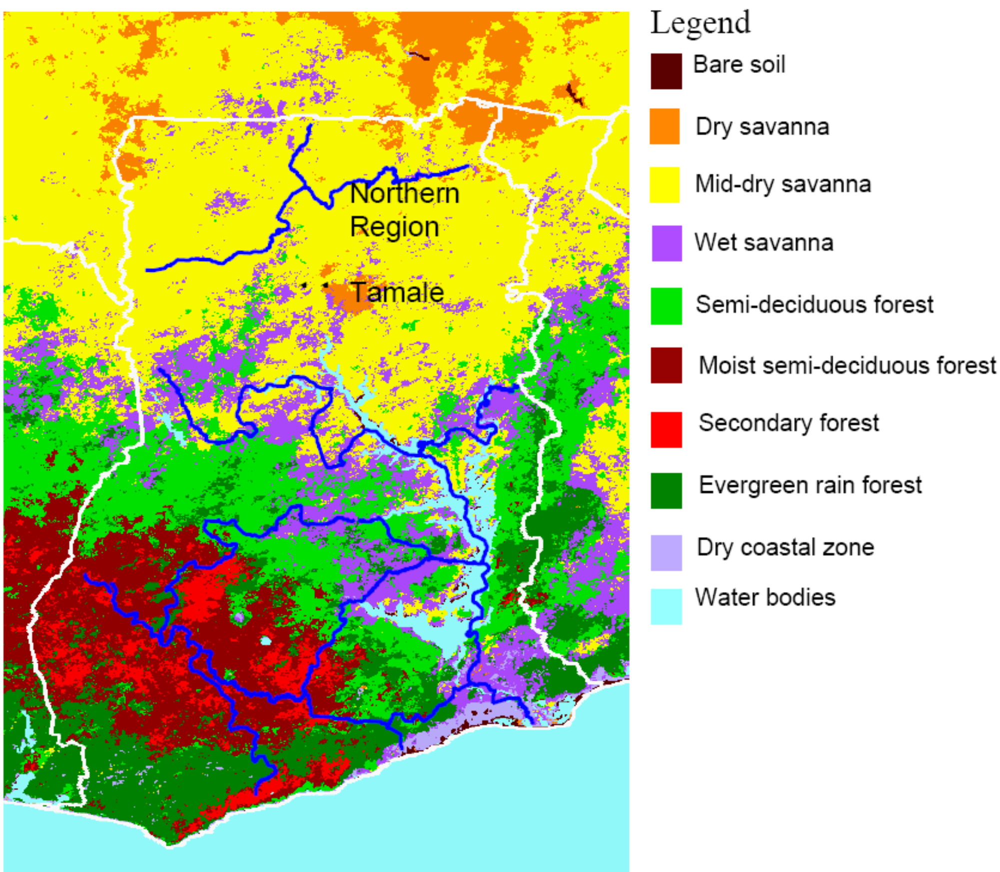


Figure 3.3: Vegetation map of Ghana (Menz and Bethke, 2000)

The vegetation has, however, been degraded mainly due to annual and periodic bush fires, long settlement and over-population. It is prone to erratic climatic conditions that are dominated by inter-annual rainfall variability (Nicholson et al., 1996; Nicholson et al., 2000). Native trees are usually to some extent drought and fire resistant. The grasses get burnt or scorched by the sun during the long dry season. Marked differences can be seen in the vegetation during the dry and wet seasons.

In the wet season, trees blossom and grasses become green. In the dry season, plants dry up and are usually burnt down by the annual bushfires. Trees typical to this region are *Butyrospermum parkii, Adansonia digitata, Parkia clappertoniana, Anogeissus leiocarpus, Detarium microcarpum, Mangifera indica, Accacia albida* and *Vitellaria paradoxa*. The common grass species in the region include Andropogon gayanus, Hyperhemia subphimosa and Imperata cylindrica.

3.1.5 Land tenure

The land tenure and ownership system in the area is entrenched in the traditional common property system with land administration vested in chiefs with heads of clans acting as custodians. The system evolved from the initial and subsequent settlement patterns. The first clan to settle on a given piece of land claims ownership of this land together with areas immediately surrounding it. The boundaries of neighboring settlements are delineated by natural geographic features such as rivers and rock outcrops. Land for each clan is held in trust by landlords (Tindana) who act as custodians but not owners. The landlords allocate lands to family members as well as to strangers for the purpose of settlement building or farming. Elders of families have the right to reallocate land within the family members. Once an individual establishes a right over a piece of land, he may not be disposed of the usufruct, i.e., right of usage of land is heritable patrilinealy (Overseas Development Institute, 1999). Hence, every adult male has entitlement to farmland in his settlement. The communal land holding system is largely responsible for poor land management leading to degradation, as individuals do not see these lands as their own (Appiah, 1996).

3.1.6 Agriculture and land-use systems

Subsistence agriculture is the main source of livelihood for the people in this region. About 64 % of the household income is derived from domestic agricultural income. There are two main types of farms: the compound farm, which is located within the homestead, and the bush farm which is out side of the homestead. The compound farms are characterized by a more or less permanent cultivation, and the fertility of the soil is maintained through the application of livestock droppings and household refuse. On the bush farm, land rotation and fallow are practised to maintain restore the fertility of the land.

Land immediately around the houses is usually fertile due to the dumping of household and farm waste and is normally planted with vegetables. Further away, sorghum (*Sorghum bicolor* (L) Moench), pearl millet (*Pennisetum glaucum*), cowpea (*Vigna unguiculata*), peanuts (*Arachis hypogaea*) and bambara beans (*Vigna subterranean*) are cultivated. These crops are grown in well to moderately drained upper and middle slope soils. In the densely populated settlements in the vicinities of

Bawku, Navrongo, Zuarungu, Bolgatanga and Sandema, farms around the dispersed compound houses are contiguous due to the heavy demand for land. Planting usually begins in the homestead with the first heavy rains. The bush farms are cropped subsequently. Crops are ready to be harvested early in the dry season. This is usually followed by land preparation for dry season farming. These farms are normally located in valley bottoms where groundwater is accessed from hand-dug wells. Water from these wells is used to irrigate the crops - normally vegetables. Manure and inorganic fertilizers are applied and the produce from these farms are mainly for sale.

Livestock population is higher in this Upper East Region than in the south of the country. Livestock are usually individually owned by residents or by a family. Cattle are held either for security reasons, to be able to make more expensive investments, or for dowries. Grazing lands are poor, especially during the dry season, and fodder production is non-existent, hence livestock grazes on available dried vegetation and frequently stray into vegetable gardens.

3.2 Overview of APSIM crop simulation model

Crop simulation models can be described as a state-of-the-art technology that provides the possibilities for users to estimate the development and yield of crops using environmental factors and management strategies as input parameters (Mavromatis et al 2001). The models provide an environment/framework that utilizes a range of component modules (Table 3.1). These modules can be biological, economical, environmental or managerial and are plugged into one main model (e.g., APSIM and DSSAT) engine (Jones et al., 2001). Crop simulation models utilize in-built algorithms that express the relationship between plant growth processes (photosynthesis, transpiration, phenological developments, plant water uptake and biomass growth and partitioning) and environmental driving forces (e.g., soil water availability, daily temperature and photoperiod). Also peculiar to these models is the integration of factors that are cultivar-specific “genetic coefficients” to estimate daily growth and response of plants to environmental factors such as weather, soil and management practices (Boote et al., 1998).

Crop simulation models have the capability of simulating the yield of a range of crops in response to crop rotation sequence. For example, they have been used for optimizing wheat productivity in rain fed systems (Heng et al., 2004), climate forecast applications (Meinke et al., 1996), simulating water and nutrient dynamics in fallows systems (Probert et al., 1998) on a short- and long-term basis, thereby providing insights into the impact of management strategies on the productivity due to soil fertility losses and erosion (Nelson et al., 1999).

APSIM provides a flexible working environment where users can configure their specific model by choosing from a set of modules from a suite of crop, soil and utility modules (Table 3.1). It was built based on the strengths (crop yield in relation to management factors) and weaknesses (system aspect of cropping) of earlier models such as CERES and GRO (Jones and Kiniry, 1986; Godwin and Singh, 1998; Ritches 1998; Ritche et al., 1998) now DSSAT. It also relied on the NTRM (Shaffer et al., 1983), CENTURY (Parton et al., 1987) and EPIC (Willaims, 1983) in dealing with the long-term dynamics of soil resources while recognizing the limited sensitivity of their generic crop models to weather input (Steiner et al., 1987).

Table 3.1: Major modules in APSIM

Module type	Module name
Biological	maize, wheat, barley, sorghum, millet, sunflower, canola, chickpea, mungbean, cowpea, soyabean, peanut, navybean, fababean, stylo pasture, lucerne, cotton (OzCot)[a], native pasture (GRASP), hemp, pigeonpea[b], FOREST[c]
Environmental	soilN, soilP, soilWat, solutes, soil pH, residue, manure[b], erosion, SWIM[c]
Management	manager, fertilizer, irrigate, accumulate, operations, canopy, micromet, clock, report, input, met

[a] *In association with CSIRO Plant Industry.*
[b] *In association with ICRISAT.*
[c] *In association with CSIRO Land and Water*
Source: Adapted from Jones et al., 2001

Important modules are the soilN, soilP and soilWAT modules. SoilN deals with the dynamics of both carbon (C) and N in the soil and their transformation which are considered on a layer basis. Soil organic C is differentiated in two pools, "biom" the more labile and "hum" the less labile. Flows between pools are calculated in terms of C, whilst the corresponding N is determined by the CN ratio of the receiving pool. The soilWAT module handles the water balance and solute movements within APSIM. It is a cascading layer model, which owes much of its precursors to CERES and PERFECT

(Littleboy et al., 1989, 1992) as well as to the algorithms for redistributing water within the soil profile. It operates on daily time steps and water characteristics specified in terms of wilting point, (LL15), drained upper limit (DUL) and saturated volumetric water contents of each soil layer. Processes adopted from PERFECT include the influence of crop residues and crop cover on runoff and potential evaporation.

The incorporation of a P routine in crop modules was motivated by the fact that many soils on which subsistence crops are grown are deficient in both N and P with potential sources of N and P being compost and manure. Hence, for models to be useful in these environments, they need to cope with the supply of both N and P. This was achieved by incorporating a routine into the crop modules that limits growth under P limiting conditions with a soilP module specifying P supply from the soil. Details of the above-mentioned modules and others are reported in Keating et al., (2003).

3.3 Experimental set up

3.3.1 Plant material

The test crop used for the study was 'ICSV III' Sorghum (*Sorghum bicolor* (L.) Moench). It is a pure-line cultivar developed at ICRISAT Asia Centre through a pedigree selection in a three-way cross [(SPV 35 x E35-1) x CS 3541]. The parents, SPV 35 and CS 3541, are converted, photo-insensitive, three-gene, dwarf types originating from Ethiopia and Sudan, respectively. E35-1 also originates from Ethiopia. It was released in the semi-arid regions of Ghana by the Savannah Agricultural Research Institute of Ghana, SARI, in 1996 (Murty et al., 1998). It is an improvement upon the traditional varieties, which are low yielding and have a low response to inorganic fertilizer.

3.3.2 Data for model calibration

For the purpose of calibrating the APSIM crop simulation model for that area, experimental plots of 4 m x 10 m were established with three replicates on two different planting dates (12th and 26th July, 2005) in two different locations in the homestead fields. The trials were provided with optimum conditions, thus each trial was provided with supplementary irrigation and adequate manure and fertilizer applied (no nutrient or water limitation).

Initial soil sampling was done on the day of planting. A profile pit was also dug and the following parameters were taken:

Soil surface information:

- slope
- color

Soil profile data (per soil horizon):

- soil texture
- soil organic carbon
- bulk density
- wilting point (LL = lower limit)
- soil water content and field capacity (DUL = drainage upper limit)
- Initial nutrients (N,P)
- ammonium and nitrate concentration
- initial soil water content
- cation exchange capacity (CEC)

The plots were monitored and sampled weekly for aboveground biomass accumulation. Other information collected included:

- Date of emergence
- Date of flowering
- Date of physiological maturity
- Grain dry weight
- Above-ground dry weight at harvest or harvest index
- Weight per grain
- Number of leaves produced on main stem

3.3.3 Data for model evaluation

Two categories of trajectories within an area of 1.5 km x 1 km were selected for the experimental trials. The selected window encompassed the homestead where continuous cropping of cereals was practiced, and the bush farms where peanuts were cropped. The homestead farms were permanently cultivated fields. Cultivation on the bush farm had not been practiced for more than six years, intermitted by annual bush burning. Farmers' fields in the homestead were used for the study with sorghum as a test crop.

Pit profiles were dug in each of the fields in the homestead and the bush farms. Initial pre-soil sampling was done as for the model calibration (see above). There were 13 treatments in all. Each treatment was replicated four and three times in each of the bush farm trials (Eutric-stagnic Plinthosol and Eutric-Gleyic Regosol, respectively) for two planting date (12th and 26th June). In the homestead fields, same experiments were established on Eutric-Gleyic Regosol with seven replicates on only one sowing date (12th July 2005). An equal amount of potash (K) was applied in all treatments, with three levels of N and two levels of P. The 13 different application rates of inorganic fertilizer (treatments) are presented in Table 3.2. The N source applied was ammonium-sulphate (AS), K as murate of potash (KCI) and P as triple-super-phosphate (TSP). The amount of each of K, P and N needed were calculated as described in Appendix 8.1.

Table 3.2: Treatments (inorganic fertilizer rates) used in the study

Treatment	N (Kg ha^{-1})	P (Kg ha^{-1})	K (Kg ha^{-1})
T_1 (control)	0	0	0
T_2	0	30	60
T_3	40	30	60
T_4	80	30	60
T_5	120	30	60
T_6	0	60	60
T_7	40	60	60
T_8	80	60	60
T_9	120	60	60
T_{10}	40	0	60
T_{11}	0	0	60
T_{12}	80	0	60
T_{13}	120	0	60

Each treatment plot was 5 m x 6 m (30 m^2) in size with spacing of 55 cm between rows (inter-row) and 30 cm within rows (intra-row). The plots were laid out in a randomized complete block design. Seeds were sown at a depth of about 5 cm. The chronology of the crop management activities carried out over the experimental period is given in Table 3.3.

Table 3.3: Chronology of management activities for cultivating sorghum

Date		Management operation
1st planting	2nd planting	
10/06/2005	24/06/2005	Land preparation
12/06/2005	26/06/2005	Sowing
26/06/2005	10/07/2005	Thinning
30/06/ 2005	16/07/2005	1st weeding
02/07/2005	18/07/2005	1st fertilizer application
25/07/2005	10/08/2005	2nd weeding
26/07/2005	14/08/2005	2nd fertilizer application
18/08/2005	18/08/2005	Spraying insecticides (Karate)
24-30/09/2005	3-5/10/2005	Harvesting

Sampling of plant material

An area of 3 m x 3 m was sampled in all plots for determining potential grain and aboveground biomass of sorghum and mean yields extrapolated over the total cultivated area. Plants were harvested at physiological maturity and panicles were separated from the plant (aboveground biomass) and the fresh weight of both taken. Three plants representative of each plot were selected and separated into leaves, stem, weighed and sub-samples taken, and dried at 70°C till constant weight. Dry weights were then taken.

3.4 Mapping of study area

3.4.1 Transect creation

In order to carry out a spatial analysis of the soil types and their chemical and physical attributes, transects in a 1.5 km^2 area created were, subsequently divided into grids and soils sampled at the vertex of the grids. A baseline of 1.5 km was created in the center of the landscape. This was then divided into strips by running parallel traverses at right angels to the baseline at 100 m intervals. Pegs were then put at 100 m intervals along the traverses up to 500 m on each side of the baseline resulting in square grids of 100 m x 100 m.

3.4.2 Generation of digital elevation model (DEM)

A field campaign was carried out and a differential global positioning system (DGPS; Ashtech equipment; Ashtech, 1998a) was used to generate point measurements. The data collected during the field campaign were processed with a Locus processor 1.2

(Aschteck, 1998b). All site data with high standard errors or that failed the quality assurance test of the software were excluded from further analysis.

A semivariogram analysis was carried out with the data in S-plus software and the selected model functions used in "Surfer 7" (Golden software Inc., 1999), and data points interpolated at a grid resolution of 30 m. The grid data were then saved as ASCII files and imported into Arcview 3.2 for generation of a DEM.

3.4.3 Soil mapping

At each vertex of the 100 m x 100 m grid cells, mini profiles were dug and described to identify the soil type. Data collected from each diagnostic soil horizon included: thickness of horizon, texture, structure, presence of iron and magnesium concretions, chroma, hue, value, transition of horizon and presence or absence of roots.

3.4.4 Soil sampling

Disturbed and undisturbed soil samples were taken at each of the pegs at 0-15 cm and 15-30 cm depth. Undisturbed soil samples were taken for bulk density using cylindrical 100 cm^3 metal cores.

3.5 Laboratory analysis

Soil samples were analyzed for their chemical and physical properties as follows and more detail description are in Appendix 2.

3.5.1 Soil chemical properties

The undisturbed samples were used for the analyses of bulk density. The disturbed samples were air-dried and passed through a 2 mm sieve, and subsequently analyzed for pH, N, K, P, cation exchange capacity (CEC), organic carbon, gravel content and particle size distribution. Soil samples collected for nitrate and ammonium analysis were transported in cooled boxes from the field and kept frozen until analyzed (Page et al., 1982).

Labile P

The labile P concentrations of the soils were determined following modified procedures Hedley soil P fractionation scheme described by Tiessen and Moir, 1993. The freely plant available P fractions were extracted with resins and $NaHCO_3$ (0.5 M, pH of 8.5).

P sorption capacity

Soil P sorption was obtained through optimization. The model was first calibrated using only the N module in the APSIM CSM. The P module was then plugged in and the P sorption values used were based on P sorption studies carried out in the region (Owusu-Bennoah et al, 1991). The values were varied until minimum variation in yield was observed between "P aware and non P aware (only N simulated)" simulations.

Carbon fractionation

Soil carbon fractionation as described by Tirol-Padre A. and J.K. Ladha (2004) was employed in fractionating total soil carbon into inert and labile fractions.

3.5.2 Soil physical analysis

Bulk density

Bulk density was determined after oven drying the undisturbed (cylinder) samples at 105°C for 24 hours and weighing the soil samples. The bulk density was then determined by dividing the weight of oven dry soil by volume of cylinder (Landon, 1991).

Particle size distribution

The proportions of primary soil particles (sand, silt and clay) were determined by their settling rates in an aqueous solution using a hydrometer. The hydrometer method of estimating particle size analysis is based on the dispersion of soil aggregates using a sodium hexa-meta-phosphate solution and subsequent measurement based on changes in suspension density (Landon, 1991). The soils were then classified into the different textural classes using a computer program (Gerikis and Baer, 1999).

Saturated hydraulic conductivity

Saturated hydraulic conductivity was determined for soil samples taken with metal cores of 10 cm length and 8.3 cm diameter using the falling-head permeameter method (Hillel, 1998). With this method, the hydraulic head at the upper end of the sample is allowed to decline with time. Soil samples in the sampling units were covered with fine nylon cloth and a rubber band used to hold it in place. The samples were then soaked in water for a minimum of 24 hours to allow them to become saturated.

A cylinder of the same diameter as the soil core and 20 cm long was erected on the saturated core samples. The unit was then gently placed in a metal box containing gravels. Water was then gently poured into the extended part of the unit to provide a hydraulic head on the soil core.

The saturated hydraulic conductivity was calculated based on the standard falling head equation:

$$\ln\left(\frac{h_0}{h_t}\right) = \frac{Ks \cdot A \cdot t}{a \cdot L} \tag{3.1}$$

where the gradient head at time t = 0 (before flow starts) is h_0. The gradient at some time, t, after the start is h_t. A and a are the surface area of the soil core and the extended cylinder, respectively (i.e., in this case A=a). Ks is the saturated hydraulic conductivity and L is the length of the soil core. Monitoring the water level h with time, a plot of $\ln(h_0/h_t)$ against t was made. The resulting slope (s) is Ks/L, from which the value of Ks can be determined (Ks = sL).

3.5.3 Plants and manure analysis

Plants and cattle manure were analysed for N, C, and P as indicated in Hoogenboom et al. (1999).

3.6 Data analysis

Descriptive statistics

Summary descriptive statistics of all data were performed using SPSS 11.0 (SPSS Inc., 1999). Statistics generated with this software includes means, minimum, maximum, standard deviations and coefficient of variation.

Correlation analysis

Where necessary, Pearson's correlation matrix was constructed after transforming the data set on a min-max transformation into a zero-one range for normalized data. This is a standardization method that that gives a minimum value of zero to the least value and maximum of one to the highest value. It allows assessing the existence and degree of association among parameters. The non-parametric Kruskal-Wallis test was used to differentiate between different soil types and the Mann-Whitney test for pairwise comparison.

Statistical comparisons

Analysis of variance (ANOVA) was used to compare yield and total biomass data from the different treatments and also between management zones and soil types. The Tukey t-test for pairwise comparison of means was used to identify significant differences between means.

Economic feasibility of fertilizer use

Partial budgets for the different treatments (under each of the trajectories) were done according to the methodology used by Kaizzi (2002) to determine the economic benefits. A cost-benefit ratio of 1 implies full cost recovery. A ratio of > 1 implies that profit has been made by the farmer whilst a ratio < 1 implies that loss have been incurred by the farmer.

Agronomic efficiency of fertilizer use

This is an index used to determine nutrient use efficiency of crops. Agronomic N and P use efficiency is described as grain (economic part) produced per kg N or P applied.

Evaluation of crop simulation models

Statistical methods were employed in assessing the performance of the crop simulation models in comparison with field measured/observed data. Methods used included Tukey test of pair wise comparison (Mann Whitney test for data not normally distributed), correlation coefficient (r), root mean square error (RMSE), modified unbiased absolute percentage error (MdUAPE) and modified internal model efficiency coefficient (E_1).

4 IMPACT OF LAND-USE TRAJECTORIES AND FARMERS' MANAGEMENT PRACTICES ON SOIL NUTRIENT STATUS

4.1 Introduction

Land-use activities such as agriculture, mining and settlement generate economic benefits for the sustenance of man. However, changes in land use, reflecting in changes in land cover inevitably have an effect on the productivity of the soil. The extent to which this occurs depends on the land-use type and management practices, soil/land characteristics, as well as the intensity of the land-use activity. In many parts of the world, particularly in the tropics, soil productivity (quality) is threatened by environmental degradation associated with increasing land-use and land-cover change (Vitousek et al., 1997; Smalberger et al., 2006).

In Ghana, conversion of land under natural vegetation to agricultural land increased by 10 % from 1970 to 1995 (FAO, 1998). The area of closed forest is estimated to be declining at an annual rate of 0.4% and for the savannah woodland it is 0.5% (Forestry Department, Ghana. 1998). The expansion of agricultural land is mainly a response to an increasing demand for food. Soils in the study area are described as fragile, easily degradable and have been reported to be deteriorating at an alarming rate in most parts of the subregion (Vlek et al., 1997). This is supported by findings of Abatania and Albert (1993) stating that soil fertility in northern Ghana has been on the decline for the last two decades. The causes are mainly burning of standing vegetation, continuous cropping, mono-cropping and overgrazing. Declining soil fertility is a major concern for communities in the savannah and transitional zones of Ghana. To counteract this and to increase productivity of the soil, animal manure is applied to fields in the homestead. Additionally, crop residues are carried from the bush farms for fodder and beddings for animals, which eventually end up in the homestead fields.

The conversion and modification of landcover (vegetation) through landuse activities and the intensity of the activities therefore have the potential to interrupt the ecological services provided by the soil ecosystem. These include its ability to support soil micro-organisms, capability to store soil organic matter and recycle soil nutrients (Monreal et al., 1998). In studying strategies (nutrient and water use efficiency) for improved crop productivity in the Volta Basin it is necessary to investigate the possible impacts of landuse and landcover change on soil productivity in the study area. To achieve this, the following objectives were set:

(i) Assessment of the impact of landuse trajectories on soil productivity (nutrient stocks),

(ii) Assessment of the impact of management practices (redistribution phenomenon) on soil nutrients stocks.

4.2 Materials and methods

4.2.1 Land-use trajectory of the study area

Land-use trajectory (history) determination of an area can be achieved through the use of participatory rural appraisal techniques (Rücker et al., 2003) or by remote sensing (multi-temporal satellite images) and GIS techniques (Braimoh and Vlek 2005; Amissah-Aurthur et al., 2000). To assess the impact of the land-use history on soil quality (nutrient status), a participatory rural appraisal technique was employed in this study. A quick bird image of 2.4 m x 2.4 m resolution was acquired. The raw image was registered (geo-referenced) with ground truth data collected from the study area. With the aid of the resulting image, a participatory rural appraisal (PRA) approach was employed with farmers for the mapping (identification) of the various land-use trajectories. Information gathered during the exercise with the farmers includes number of years that fields had been under continuous cultivation and number of years under fallow. The responses were then used to determine the land-use trajectories (land-use history) of the area. Land or vegetation not cultivated for the previous 15 years was taken as land under permanent vegetation. Cultivated fields were categorized based on their land-use history (Table 4.1).

Table 4.1: Land-use change trajectories

Trajectory	Description
Permanently cultivated	Land under cultivation for the past 15 years
Old fallow	Land not cultivated for the past 15 years
Recent fallow	Cropland that reverted to natural vegetation in the past 2 years
Medium fallow	Cropland that reverted to natural vegetation in the past 3 or 4 years
Recent cropland	Natural vegetation converted to cropland in the past 1 or 2 years
Crop land	Natural vegetation converted to cropland in the past 5 to 10 years

4.2.2 Soil sampling

Soil samples of the top 15 cm were collected from the study area in a stratified sampling design with at least 30 samples from each land-use trajectory. The soil samples were air dried, sieved and analyzed for total N, available P, available K, CEC, Ca, Mg, K, pH and base saturation as described in Chapter 3.

4.2.3 Data analysis

Statistics applied included, descriptive statistics, Pearson's product moments correlation, and analysis of variance (ANOVA) which was performed using the general linear model (GLM) procedure. Data sets were first tested for normal distribution using Kolmogorov – Simirnov test statistics and those failing the test were log-, square-, root- or reciprocal-transformed to normality. Linear regression was used to show the strength of the relationship between organic matter and selected soil properties in both farm types (homestead fields and bushfarms).

4.3 Results and discussion

4.3.1 Nutrient stocks in the study area

Soils in the study site were generally moderately acidic with a mean pH value of 5.65 (Table 4.2). Soil organic matter contents of the soils were low, resulting in a poor soil structure with a subsequently low water holding capacity. The soils were generally very poor in total N, available P and K. The low level as well as the very high variability of available P in the study area is consistent with results from other studies carried out in the savannah zone of Ghana (Abeoko and Tiessen, 1998). This is in parts attributed to the low mineral P content of the soils as a result of the intensive weathering they have undergone and also the low organic P as a result of the low soil organic matter content of the soils.

Table 4.2: Soil attributes in Pungu

Soil attribute	Min	Max	Mean	SD	CV*	Rsq
pH	4.66	8.15	5.65	0.56	10	0.46
SOC (mg g^{-1})	0.40	21.80	5.70	4.00	70	0.35
Total N (mg g^{-1})	0.10	2.30	0.60	0.30	50	0.30
C-N ratio	2.70	19.30	8.80	3.60	41	0.14
Ca (cmol (+) kg^{-1})	0.08	17.81	2.62	2.00	77	0.41
Mg (cmol (+) kg^{-1})	0.20	4.02	0.81	0.70	81	0.44
K (cmol (+) kg^{-1})	0.06	3.01	0.33	0.30	104	0.34
CEC (cmol (+) kg^{-1})	0.50	23.12	4.02	2.80	72	0.44
$P_{available}$ (mg kg^{-1})	0.11	140.02	7.72	14.60	189	0.37
$K_{available}$ (mg kg^{-1})	32.93	592.63	109.03	95.60	88	0.36
Base saturation (%)	70.33	99.84	94.23	4.90	5	0.24

** Coefficient of variation (CV) expressed in percentage. SD: standard deviation, Rsq: coefficient of determination, SOC: soil organic carbon.*

An average CN ratio of 8.8 recorded in this study favors a rapid release (mineralization) of nutrients from organic carbon. The fraction of available carbon required by soil microbes for decomposition is, however, more critical than the absolute CN ratio. The soil CECs were also lower than the critical level required for optimum crop production, a phenomenon related to clay mineralogy (predominantly kaolinitic 1:1 minerals) of the soils (Nye and Stephens, 1962). The dominant exchangeable cation was Ca, with a high mean base saturation of 94.23 % (ranging between 77.33 and 99.84 %). The coefficient of variation (CV) of the soil chemical attributes ranged from 5 for base saturation to 189 % in soil available P. With the exception of pH and base saturation, all soil chemical attributes in the study sites were highly variable with CVs more than 50 %.

4.3.2 Impact of land-use trajectories on soil chemical attributes

In Table 4.3, the soil chemical attributes of the different land-use histories in the study area are given. Permanently cultivated fields had higher levels of organic carbon, N, CEC, available P and K compared to the other land-use trajectories. The fields under permanent cultivation were located within settlements where animal manure as well as crop residues from the bush farms was applied regularly to maintain soil productivity. All land-use trajectories showed deficient soil total N with mean values less than 0.80 mg g^{-1}, including the permanently cultivated field on the homestead, which showed a very high coefficient of variation (49 %). The Tukey's mean separation procedure was used to differentiate between pairs of land-use trajectories. No significant differences were observed among the other land-use trajectories (with the exception of permanently cultivated fields) with respect to CEC, available P and K, and all recorded values were below critical values required for optimum crop production. The mean value of total N recorded for all the land use trajectories were in decreasing order: permanent cultivation > new cropland > old fallow > new fallow > old cropland > medium fallow. The total N level in old fallow lands (located in the bush farms) was significantly higher than that in old cropland and medium fallow.

Table 4.3: Classification of land-use trajectories based on soil chemical attributes

Land-use trajectories	pH	SOC ($mg\ g^{-1}$)	N ($mg\ g^{-1}$)	CEC ($cmol\ kg^{-1}$)	Avail. P ($mg\ kg^{-1}$)	Avail. K ($mg\ kg^{-1}$)	Ca ($cmol\ (+)\ kg^{-1}$)	Mg ($cmol(+)\ kg^{-1}$)	K ($cmol\ (+)\ kg^{-1}$)	BS (%)
New fallow (1)	5.33 (6)*	3.60 (31)	0.50 (30)	2.51 (30)	3.76 (15)	71.72 (28)	1.59 (32)	0.51 (50)	0.16 (35.1)	93.5 (4.2)
New cropland (2)	5.60 (4)	6.10 (51)	0.70 (36)	3.20 (5)	3.04 (52)	77.66 (30)	2.14 (51)	0.73 (55)	0.20 (49)	93.9 (4.3)
Permanent Cultivation (3)	6.39 (12)	8.00 (76)	0.80 (49)	7.15 (64)	28.11 (103)	204.29 (64)	4.96 (67)	1.38 (64)	0.56 (92)	98.0 (2)
Old fallow (4)	5.21 (6)	6.30 (25)	0.60 (28)	3.21 (27)	1.84 (60)	100.72 (56)	1.98 (32)	0.67 (51)	0.19 (40)	92.0 (6)
Old cropland (5)	5.50 (5)	3.80 (34)	0.40 (31)	2.44 (26)	3.44 (92)	59.01 (50)	1.57 (33)	0.47 (36)	0.13 (39)	91.7 (7)
Medium fallow (6)	5.56 (6)	3.20 (88)	0.40 (50)	2.90 (36)	4.07 (81)	70.69 (28)	1.94 (42)	0.50 (52)	0.20 (36)	93.3 (5)
ANOVA	0.00^{a} 36.74^{b}	0.00^{a} 23.00^{b}	0.00^{a} 18.04^{b}	0.00^{a} 33.94^{b}	0.00^{a} 25.07^{b}	0.00^{a} 22.90^{b}	0.00^{a} 29.96^{b}	0.00^{a} 34.03^{b}	0.00^{a} 21.46^{b}	0.00^{a} 13.19^{b}
Tukey HSD mean separation (p= 0.05)	1#2, 1#3 2#3, 2#4, 3#1,3#4, 3#5,3#6, 4#5, 4#6	1#2,1#3, 1#4, 2#5, 2#6,3#4, 3#5, 3#6, 4#5, 4#6	1#3, 2#3, 2#5, 3#4, 3#5, 3#6, 4#5, 4#6	1#3, 2#3, 3#4, 3#5, 3#6	1#3, 2#3, 3#4, 3#5, 3#6	1#3, 2#3, 3#4, 3#5, 3#6	1#2, 2#3, 3#4, 3#5, 3#6	1#2, 2#3, 3#4, 3#5, 3#6	1#2, 2#3, 3#4, 3#5, 3#6	1#2, 2#3, 3#4, 3#5, 3#6

[a] probability, [b] F-statistics, #: significantly different; p<0.05, SOC: Soil organic carbon, Avail.: Available, ( ) coefficient of variation in parenthesis.*

The main soil chemical attributes of interest to this study are N, P, K, CEC and soil organic matter, as these attributes mostly impact on crop production. Based on these soil attributes, the sites were reclassified into two management zones (Table 4.4): (i) the homestead for the fields under permanent cultivation, which were located within the settlements, and (ii) the bush farms comprising the remaining the land-use trajectories, as these did not differ in the main soil attributes (CEC, P, K and N) that are critical for optimum crop production.

In general, decreasing trends were observed in the values of soil nutrients with increasing cultivation except for those permanently cultivated fields where crop residues and animal manure were applied. This finding is comparable with those from similar studies in the savannah zone of Ghana (Braimoh and Vlek, 2004). The ANOVA revealed the influence of land-use trajectory (history) on soil nutrient stocks. This is underlined by the high explanatory power for land-use trajectories on the variation in soil chemical attributes (Table 4.2). The coefficients of determinations of the impact of land-use trajectories on the various soil chemical parameters were generally moderate (Table 4.2). Percentage base saturation of the soils was the least influenced by land-use histories with a coefficient of determination of 0.24. The pH showed the highest impact with a value of 0.46, and CEC and SOC contents with the values, 0.44 and 0.35, respectively. The impact of land-use histories decreased in the order: pH>Mg=CEC>Ca>$P_{available}$>$K_{available}$>C_{org}>K>total N>base saturation.

4.3.3 Impact of management practices on soil nutrient status

Assessment of the differences between the two farm types (bush and homestead farm types) was done using the Tukey's mean separation procedure. Both, the homestead and bush farms were located on the same soil type (Eutric-Gleyic Regosol) with an average sand content of 75 %. However, the homestead fields had higher contents of soil organic carbon, total N, available K and P than the bush farms due to manure inputs. Also, smallholders typically remove crop residues (mainly peanuts and bambara beans) harvested from the bush farms for use as fodder. Similar observations were reported in a smallholder farming community in Zimbabwe (Zingore et al, 2007). "Moreso", the annual burning of the standing vegetation on the bush farms, which is accompanied by the displacement of the plant nutrients in the ash (Bagamsah, 2005), resulted in further nutrient losses.

The CEC of the soil was also higher in the homestead fields than in the bush farms, a condition that can be explained by the contribution of soil organic matter, which is the prime contributing factor to CEC and soil buffering capacities on sandy soils (Mapfumo and Giller, 2001; Bationo and Mokwunye, 1991). Land management practices had significant influences on the nutrient status of soils. The management practice may not be a deliberate form of management but rather the consequence of limited availability of animal manure (Vanlauwe and Giller, 2006) and the quest to increase crop production levels. For instance, mean values of available P were 28.1 and 3.24 mg kg^{-1} in the homestead and bush farms respectively. Thus, available soil P in the homestead was more than 8-fold that of the bush farms (Table 4.4). Similar trends were reported by Breman et al., 2005 in the synthesis of three other studies in Sub-Saharan Africa.

Table 4.4: Soil chemical attributes in two land management zones at Pungu, Navrongo

Soil attribute	Min	Max	Mean	SD	Min	Max	Mean	SD	T-test
	Homestead fields				Bush farms				
pH	5.21	8.15	6.39	0.77	4.66	6.34	5.45	0.33	-7.60*
SOC (mg g^{-1})	4.00	21.8	8.2	6.1	0.5	13.3	4.5	2.4	-6.20*
Total N (mg g^{-1})	0.3	2.3	0.9	0.4	0.1	1.4	0.5	0.2	-4.88*
Ca (cmol (+) kg^{-1})	1.44	17.7	4.96	3.33	0.08	5.60	1.83	0.76	-11.7*
Mg (cmol(+) kg^{-1})	0.32	3.84	1.38	0.89	0.16	1.76	0.57	0.31	-10.1*
K (cmol(+) kg^{-1})	0.16	3.01	0.56	0.51	0.06	0.46	0.17	0.07	-9.98*
CEC (cmol(+) kg^{-1})	2.69	23.0	7.15	4.54	0.54	8.04	2.84	1.05	-5.98*
$P_{available}$ (mg kg^{-1})	4.80	140	28.11	23.87	0.10	18.9	3.24	2.36	-11.8*
BS (%)	92.6	99.8	98.0	1.7	70.3	99.0	92.9	4.95	-6.47*
$K_{available}$ (mgkg^{-1})	32.9	560	204.3	131.3	32.9	398	75.9	35.7	-6.14*

The correlations among soil attributes from the bush farms were lower in magnitude than those for the homestead fields. This suggests that, as soil fertility deteriorates, relationships between the soil attributes; soil organic carbon and total N, available P and CEC become weak (Figure 4.1). There was a significant correlation between soil organic carbon and P in the homestead field soils while this relationship in the bush farm soils was not significant. Soil pH correlated significantly with all soil attributes in the homesteads. In the bush farm soils, it related to all soil attributes except for SOC and Ca.

Land-use management had significant impacts on the relationship between soil properties. This is evident from the weaker correlation between SOC and CEC, total N, available P and K in the bush farms soils as compared to those of the homestead fields (Table 4.5a and 4.5b). In the bush farm soils, available P showed a consistent lack of correlation with all soil attributes except pH. This suggests that the main source of P in highly weathered soils (organic carbon) was lacking. More so, P was exported from fields by the harvest of crops (Rhodes, 1995) and residues were carried into the homestead. Phosphorous was therefore not compensated for by nutrient recycling which is crucial in these environments for soil P nutrition of crops (Gijsman et al., 1996). Phosphorous was additionally lost through over-grazing on the bush farms to the homestead fields through cow dung. This implies that optimum crop production on the bush farms cannot be attained or maintained without the use of inorganic fertilizer (Vanlauwe and Giller, 2006). Moreover, the application of more organic manure or the use of cover crops is necessary to increase the efficiency of fertilizer use.

Table 4.5: Correlation between soil attributes under two farm types

a) Bush farm

Soil attribute	pH	SOC	N	Ca	Mg	K	CEC	Avail. P	Avail. K	Base sat.
pH	1									
SOC	ns	1								
N	ns	**	1							
Ca	**	**	**	1						
Mg	**	**	**	**	1					
K	**	**	**	**	**	1				
CEC	**	**	**	**	**	**	1			
$P_{available}$	**	ns	ns	ns	ns	Ns	ns	1		
$K_{available}$	ns	**	**	**	**	**	**	ns	1	
Base Sat	**	**	*	**	**	**	**	*	**	1

(b) Homestead fields

Soil attribute	pH	SOC	N	Ca	Mg	K	CEC	Avail. P	Avail. K	Base sat.
pH	1									
SOC	**	1								
Total N	**	**	1							
Ca	**	**	**	1						
Mg	**	**	**	**	1					
K	**	**	**	**	**	1				
CEC	**	**	**	**	**	**	1			
$P_{available}$	**	**	**	**	**	**	**	1		
$K_{available}$	**	**	**	**	**	**	**	**	1	
Base sat.	**	**	**	**	**	**	**	**	**	1

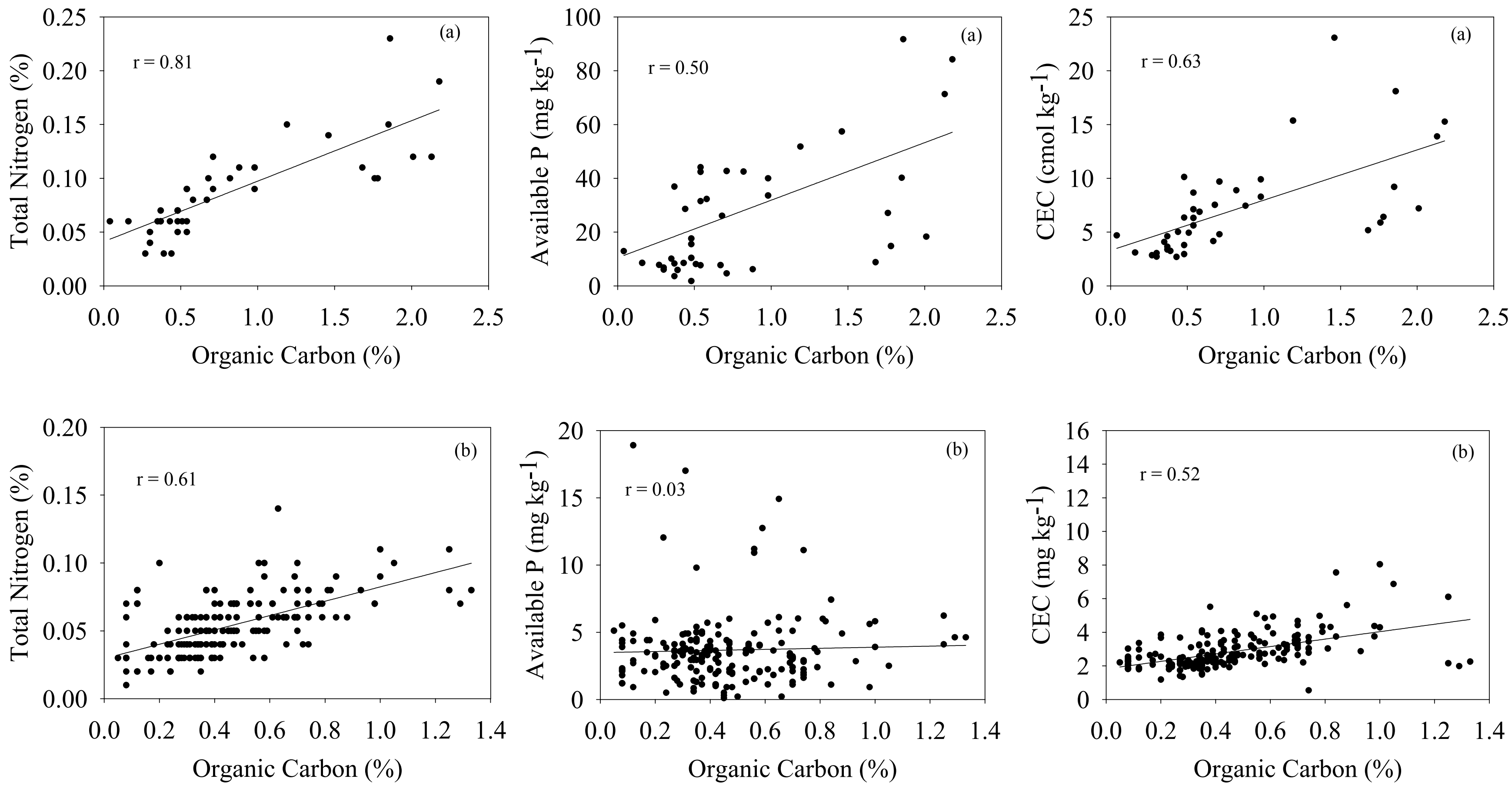


Figure 4.1: Relationship between percentage soil organic matter and total N, available P and CEC in soils with different nutrient status, a = Homestead, b = bush farms

4.4 General discussion

Soils in the subregion have been described as inherently poor in nutrient and soil organic carbon stocks. This is consistent with the results of the present study where values of important nutrient such as total soil N, available P, CEC and soil organic carbon were 0.6 mg g^{-1}, 7.7 mg kg^{-1}, 4.4 $cmol^{+}$ kg^{-1} and 5.7 mg g^{-1}, respectively. Land management practices further contribute to soil deterioration. This is reflected in the decline in soil nutrient stocks with increasing number of years the land was put under cultivation except for permanently cultivated fields around the homestead that benefited from nutrient imports from the bush farms. The impact land-use trajectories had on the various soil nutrients are shown by the high coefficients of determination as revealed by ANOVA. In the soils of old fallows (not cultivated for more than 15 years), higher soil nutrients were expected than those measured in this study. This can be explained by the annual vegetation burning that characterizes the study area, which is normally accompanied by nutrient losses (Bagamsah 2005). The effectiveness of fallow (restoration of soil nutrients) is likely reduced by the annual bush fires.

Unless practices that contribute to declining soil nutrients are checked, severe soil and land degradation and extremely low crop yields are unavoidable. To reverse the continuous decline in soil nutrients witnessed in this study, soil management practices that help to restore soil organic matter and soil nutrients are necessary. The use of mineral fertilizer is indispensable for attaining adequate crop yields. However, this has to be economically feasibile and its use in the study area should be based on appropriate recommendations. Economic feasibility studies therefore need to be carried out to determine the profitability of fertilizer use and the appropriate application rates, taking into account the heterogeneity of soil nutrient supply as illustrated in their high coefficients of variation. Efforts to increase soil organic matter content are also necessary to minimize loss of nutrients through leaching, a phenomenon that is characteristic of the sandy soils in the area. The amount of manure applied is very biased as seen in the wide ranges in soil nutrients measured in the homestead fields which can be attributed to accessibility of manure.

In spite of the significant differences observed in soil nutrients between the homestead and bush farms, the values reported here are well below those reported by other studies. Wopereis et al. (2006) reported 13.4 and 6.3 g kg^{-1} for the homestead and bush farms, respectively, in a smallholder farmer community in Togo. This brings to light the complexity of the redistribution phenomenon, which is unique for each environment and is based on the socio-economic settings among other factors. The results of this study provide a basis to distinguish between the two farm types in modeling sorghum yields (Chapter 6).

5 DISTRIBUTION OF SOIL PROPERTIES AND SOILS IN A LANDSCAPE

5.1 Introduction

The soils in the semi-arid regions of West Africa are highly weathered, well-drained and low in P and organic matter (Zougmore, 2003). Consequently, increased crop production on these soils is only possible with appropriate soil amendments and crop management practices. The increasing pressure on land has necessitated continuous cropping, which has exposed the soils to nutrient deficiencies especially N and P (Bationo et al., 2003). This is being aggravated by the negative nutrient balances of most cropping systems (Vlek et al., 1997). The annual bush fires are also reported to be detrimental to soil fertility, as they result in reduction of soil organic matter and losses of other soil nutrients (Bagamsah, 2005).

Whereas fertilizer use has been reported to contribute as much as 30 % of the total food production increase in developed countries, in developing countries it has increased production by less than 15 % (Halm, and Dartey, 1991). This is partly due to low fertilizer use for various reasons including the high cost of fertilizers. A sustainable increase in crop productivity to feed the increasing population can only be acheived with, the use of inorganic fertilizers.

Variability in soil characteristics in space has been reported by several studies conducted in both temperate (e.g. Blackmore et al., 2003; Lopez-Granados et al., 2002) and tropical (Atsivor et al., 2001; Haefele and Wopereis, 2005) regions. These show the difficulties involved in soil surveys and their interpretation, which ignores within-field spatial variation of nutrients. This makes it difficult to interprete crop yield data. The spatial variability of nutrients results from spatial variation in the underlying soils (parent rock materials), topography and, in some cases, from management practices of farmers. This in turn may be reflected in the variations in crop yield in space. Knowledge of the spatial distribution and dependency of nutrients in soils and the soil parameters that affect crop yield are necessary for a better nutrient management planning at a landscape level. The objectives of this part of the study are therefore to:

i. Assess variability in soil parameters at a landscape level
ii. Identify factors influencing the spatial distribution of soil parameters
iii. Identify and classify soils within the landscape.

5.2 Materials and methods

5.2.1 Data collection

An initial, reconnaissance survey of an area of about 6 km^2 (see Chapter 4) was carried out to assess the possible soil types present and thus to determine the soil boundaries of the study landscape.The location of profile pits for each soil series were identified. This was followed by a detailed soil survey. The study site was divided into square grids as described in Chapter 3. Soils at each of these vertex or grid points were classified into soil series using mini-pits, a common soil survey practice in Ghana (Agyare, 2004).

At each of these grid points, mini-pits of 70 cm in depth and 30 cm in diameter were dug. The profiles were described to support the mapping of the spatial distribution of the soils within the area. From each mini-pit profile, the soil diagnostic horizons and their corresponding boundaries, texture, structure, color, mottles, concretional fractions and root density (or abundance) were determined. The landuse types and position in the topography were also noted. Soil series are defined as soils with similar profile morphology derived from similar parent materials under similar conditions with respect to vegetation, relief, climate and drainage. Thus each soil series has a distinct characteristic soil diagnostic horizon and is therefore found in similar locations within the topography has similar drainage, texture and structure, among others. In Ghana, mapping soil series over large areas is impractical as the soils rarely cover a sufficient area in an individual expanse. This study, however, was carried out at a landscape scale, where soil series were more relevant and hence employed as the unit for mapping.

5.2.2 Data analysis

The Kolmogorov-Smirnov-Test statistics was used to assess the soil variables for normal distribution. Soil variables that failed the normality test were transformed to normal or near normal distribution, which is a necessary pre-requisite for most statistical analyses (Table 5.1).

Table 5.1: Transformations for changing distributions of data sets

Transformation	Name	Effect
X^3	Cube	Reduces extreme negative skewness
X^2	Square	Reduces negative skewness
$X^{1/2}$	Square root	Reduces mild positive skewness
Log10(X)	Log	Reduces positive skewness
$X^{-1/2} = 1/SQRT(X)$	Positive reciprocal root	Reduces extreme positive skewness
$-(X^{-1}) = -1/X$	Negative reciprocal	Reduces very extreme positive skewness

Source: Adapted from Hamilton, 1990

To describe the data collected within the landscape, a descriptive analysis was carried out in SPSS version 11. The statistics derived included mean, maximum, minimum, standard deviation and coefficient of variation.

Table 5.2: Soil Parameters and transformations used to convert them to normal distribution

Soil variable	Transformation	
	Topsoil	Subsoil
pH	Log	Log
Soil organic carbon (SOC)	Log	Log
Total N	Log	Log
$P_{available}$	Log	Raw
$K_{available}$	Log	Reciprocal
Cation exchange capacity	Log	Log
Silt	Log	Raw
Clay	Log	Log
Sand	Raw	Standardize
Bulk density	square root	Raw
Hydraulic conductivity	Log	Log

To access the possible relations between the soil parameters, the transformed values were standardized to enable comparison of the parameters with different transformation. The following z-score transformation was used to standardize all parameters, with the resulting output having a mean of 0 and a standard deviation of 1 (Sokal & Rohlf, 1995):

$$Xt = \frac{Xi - X}{S}$$

where Xt is the standardized value of the sample, Xi is the sample, X is the mean and S is the standard deviation. The Kruskal-Wallis non-parametric test was used to assess differences in soil series because most of the variables within the various soil types were not normally distributed and also lacked equal variance, not permitting the application of an ANOVA, which requires normal distribution. The Kruskal-Wallis test was preferred to the median test for the analysis first, because of the variation in the sample size of the various soils and second, because it takes into account the size of each sample rather than just the above-below dichotomy employed by the median test.

Kolmogorov-Smirnov normality test statistics and their respective significant values are presented in Appendix 3. Most of the soil properties within the various soil types failed the normality test ($P < 0.05$). The Kruskal-Wallis mean rank was then used to analyze the soil properties of the various soils. Criterion variables with significant differences within the soils were noted and the non-parametric Mann-Whitney rank sum test used for the pairwise comparison of the different soils for parameters with significant differences.

Geostatistical analysis

The spatial dependency of selected soil parameters was analyzed using semi-variogram analysis with normalized data. Semi variogram analysis has been proven as an excellent approach to exploring the structure of spatial variation in agricultural soils (Webster and Oliver, 1990; Geypeus et al., 1999; Mulla and McBratney, 2000). A semivariogram was calculated for each soil property (Isaaks and Srivastava, 1989; Journel and Huijbregts, 1978):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=i}^{N(h)} \left[z(x_i + h) - z(x_i) \right]^2$$

where γ(h) is the experimental semivariogram value at a distance interval h, N(h) is number of sample value pairs within the distance interval h, $z(x_i)$, $z(x_i+h)$ are sample values at two points separated by the distance h. It has three main statistics: nugget, sill and range. The nugget, which is also known as a stochastic variance, is a measure of the variance due to sampling, and measurement errors or other unexplained sources of variation. The sill is the variance of sampled populations at large separation distances if data has no trend. The range is described as the average maximum distance at which two samples are spatially correlated. The parameters of the best-fit empirical model were used to interpolate the respective point soil parameters values in space using ordinary kriging. Ordinary kriging was used for data interpolation, as it has the additional advantage of minimizing the influence of outliers (Odeh et al., 1994, Triantafilis et al., 2001).

5.3 Results and discussion

5.3.1 Soil characteristics

Analysis of the soil samples collected in the landscape included mean, minimum and maximum values of the soil parameters for both the topsoil and the subsoil (Table 5.3) it gives an overview of the soils within the landscape in terms of their physical and chemical attributes.

Table 5.3: Descriptive statistics of top- and subsoil parameters taken at grid scale (100 m x 100 m) in the semi arid region of the Volta Basin (Navrongo, Ghana)

	Topsoil (0 – 15 cm)				Subsoil (15 – 30 cm)			
Parameter	Mean	Max	Min	CV (%)	Mean	Max	Min	CV (%)
pH	5.46	8.12	4.48	10	5.46	8.38	4.59	13
SOC (mg g^{-1})	4.0	11.6	0.7	56	0.27	1.32	0.07	56
Nitrogen (mg g^{-1})	0.61	11.0	0.11	245	0.02	0.12	0.01	61
$P_{available}$ (mg kg^{-1})	6.32	44.2	0.93	89	5.9	31.4	1.1	65
$K_{available}$ (mg kg^{-1})	73.6	230	8.22	52	71.5	165	29.1	35
CEC (cmol(+) kg^{-1}	4.94	21.4	1.51	60	6.30	35.2	2.05	67
Sand (%)	70.9	91.7	18.1	17	64.9	92.4	23.0	20
Silt (%)	24.3	63.6	3.5	36	24.0	63.0	0.2	42
Clay (%)	6.9	32.0	1.2	58	11.1	34.0	0.9	55
BD (g cm^{-3})	1.63	1.78	1.40	5	1.67	1.93	1.36	5
Ks (cm day^{-1})	23	363	0.3	227	25	487	0.03	296

The soils in the area are on average sandy loams with a mean sand content of 70.9 and 64.9 % in the top and subsoils, respectively. The high sand content of the soils can be attributed to the granite parent material over which they are formed. In the topsoil, SOC content ranged from 11.6 to 0.7 mg g^{-1} with a mean of 4.0 mg g^{-1}, and in the subsoil from 13.2 to 0.7 mg g^{-1} with a mean of 2.7 mg g^{-1}. The low organic carbon content is the result of the high temperatures resulting in rapid organic matter decomposition in combination with a generally low input of organic material. The annual burning of the vegetation throughout the area further reduces the available aboveground organic matter that could potentially contribute to soil organic carbon. Organic matter is closely associated with the nutrient status of soils for two main reasons. First, it has a high CEC (150 -200 cmol kg^{-1}) compared to 9 cmol kg^{-1} of clay (silt and sand have even lower CECs). Secondly, it constitutes the major reserve of available soil N and P. Thus, soil organic matter is directly linked to soil fertility. The mean organic carbon content of the topsoils of 4.0 mg g^{-1} is very low and well below the recommended level of 17.0 mg g^{-1} necessary for adequate crop production (Okalebo et al., 1992). The clay content is also low with a mean of 6.9 % in the topsoil and 11.1 % in the subsoil. This may be attributed to the translocation of clay minerals to lower soil profile depths.

Due to the sandy nature of the soils and their low organic carbon content, water infiltration is high and water holding capacity is low as indicated by the high (saturated) hydraulic conductivity (Ks). This is not conducive to crop production, particularly in light of the low and erratic rainfall and the frequent dry spells in the region. Total soil N content is also very low and well below the value of 2.0 mg g^{-1}, which is required for adequate crop production. The soils are on average moderately acidic with a mean pH of 5.5. Available P of the soils at both sampling depths was 6.3 mg kg^{-1} in the topsoil and 5.9 mg kg^{-1} in the subsoil. This was again less than the 11 mg kg^{-1} that is considered the lower limit for viable crop production. Available K was on average within the recommended range (50 – 100 mg kg^{-1}) for adequate plant growth (73.6 mg kg^{-1} in the topsoil and 71.5 mg kg^{-1} in the subsoil). The low mean CEC values of 4.9 and 6.3 cmol (+) kg^{-1} in the top- and subsoil, respectively, are low for crop growth. These low values are due to the highly weathered soils left with only single-layered clay minerals (kaolinites), which have a notoriously low CEC due to the small surface area for charge attraction (Nye and Stephen, 1962; Dowuona et al., 1998). All soil chemical variables had higher mean values in the topsoil than in the subsoil, except for soil CEC. The higher CEC in the subsoil is caused by the higher content of clay.

In summary, the soils were low in N and P, which are critical for crop production, low in organic carbon, clay and CEC but had adequate K levels. The use of inorganic fertilizer is therefore indispensable for production. This has to be complemented with organic amendments to increase the efficiency of the inorganic fertilizer, which could otherwise be rapidly lost from the rooting zone through leaching (due to the sandy nature of the soils).

Soil pH correlated positively with most of the other soil chemical parameters except available K (Tables 5.4 and 5.5). As expected, soil organic carbon was negatively correlated with sand content and bulk density and a very highly positively correlated (87 %) with total soil N. The latter is not a new finding but was already pointed out by Nye and Stephen (1962) who stated that soil carbon is an important reserve for soil N.

Soil CEC correlated significantly with most of the soil parameters in both depths. However, only in the topsoil was it negatively correlated with sand content and bulk density. There was no significant correlation between available P and any of the other chemical properties in both sampling depths, most probably due to its generally low content in the soils sampled.

Table 5.4: Correlation matrix of soil variables in the topsoils (0 – 15 cm) from Navrongo, Ghana

Soil parameter	pH	SOC (mg g^{-1})	Total N (mg g^{-1})	$P_{available}$ (mg kg^{-1})	$K_{available}$ (mg kg^{-1})	CEC (Cmol(+)kg^{-1})	Silt (%)	Sand (%)	Clay (%)	BD (g cm^{-3})	Ks (cm day^{-1})
pH											
SOC (mgg^{-1})	0.32**										
N (mgg^{-1})	0.30**	0.87**									
$P_{available}$(mg g^{-1})	0.31**	0.14*	0.13								
$K_{available}$(mg g^{-1})	0.07	0.01	0.08	0.01							
CEC (Cmol(+)kg^{-1})	0.37**	0.40**	0.40**	0.07	0.08						
Silt (%)	0.09	0.36**	0.28**	-0.21	0.09	0.41**					
Sand (%)	-0.14	-0.45**	-0.35**	0.12	-0.11	-0.42**	-0.89**				
Clay (%)	0.16*	0.45**	0.40**	0.05	0.02	0.31**	0.35**	-0.63**			
BD (g cm^{-3})	-0.16	-0.31**	-0.28**	-0.37**	-0.04	-0.18*	-0.05	-0.04	-0.13		
Ks (cm day^{-1})	0.04	0.09	-0.08	-0.17	-0.13	-0.03	0.11	-0.13	-0.05	-0.05	

*N = 176; significance level: * p< 0.05, ** p < 0.01, SOC: Soil organic carbon, BD: Bulk density, CEC: cation exchange capacity (cmol (+)kg^{-1}, Ks: saturated hydraulic conductivity.*

Table 5.5: Correlation matrix of soil variables in the subsoils (15– 30 cm) from Navrongo, Ghana

Soil parameter	pH	SOC (mg g^{-1})	N (mg g^{-1})	$P_{available}$ (mg kg^{-1})	$K_{available}$ (mg kg^{-1})	CEC (Cmol(+) kg^{-1})	Silt (%)	Sand (%)	Clay (%)	BD (gcm^{-3})	Ks ($cmday^{-1}$)
pH	1										
SOC (mg g^{-1})	0.00	1									
N (mg g^{-1})	0.00	0.90**	1								
$P_{available}$ (mg kg^{-1})	0.00	0.28**	0.23**	1							
$K_{available}$ (mg kg^{-1})	-0.14	0.00	0.02	0.02	1						
CEC (Cmol(+)kg^{-1})	0.44**	0.28**	0.25**	-0.01	0.03	1					
Silt (%)	0.29**	0.31**	0.26**	-0.09	0.17*	0.55**	1				
Sand (%)	-0.17*	-0.05	-0.03	0.05	-0.29**	-0.06	-0.11	1			
Clay (%)	0.19*	0.09	0.11	-0.07	0.00	0.26**	0.34**	-0.36**	1		
BD (gcm^{-3})	-0.15*	-0.07	-0.07	-0.07	0.12	-0.05	-0.03	0.20**	0.18*	1	
Ks ($cmday^{-1}$)	-0.17	0.11	0.11	-0.02	0.33**	-0.14	0.02	0.33**	-0.07	0.20	1

*N = 176 ; significance level: * p < 0.05, ** p < 0.01 SOC: Soil organic carbon, BD: Bulk density, CEC: cation exchange capacity (cmol (+)kg^{-1}, Ks: saturated hydraulic conductivity.*

5.3.2 Spatial variation in soil properties

Knowledge of the spatial structure plays an important role in the understanding and managing of ecological processes, with 'gradients' and 'patches' as the two most common in nature (Fortin and Dale, 2005; Legendre et al 2002). Understanding the spatial pattern of soil attributes, which influence soil productivity, is critical for appropriate management and planning of sustainable crop production.

Spatial dependency of soil properties

Soil available K, CEC, pH and sand in the topsoil were best fitted with variogram functions that did not sill at distances considered for the study (Table 5.6), thus exhibiting a trend pattern.

Table 5.6: Semivariogram parameter models for top- and subsoils of the selected landscape in Navrongo, Ghana

Parameter	Function	Range (m)	Sill (m)	Nugget	Slope
		Topsoil			
SOC	Exponential	712	2.78	3.62	-
N	Spherical	436	0.00	1.2E-2	-
$P_{available}$	Exponential	225	15.89	17.28	-
$K_{available}$	Linear	-	-	1480	96.89
CEC	Linear	-	-	6.23	4.5E-3
pH	Linear	-	-	0.29	4.5E-5
Sand	Linear	-	-	83.01	8.4E-2
Silt	Gaussian	774	54	63.00	-
Clay	Gaussian	688.9	4.61	13.73	-
BD	Exponential	1.08E+3	3.6E-3	4.03E-3	-
Ks	Gaussian	274.49	10.24	22.00	-
		Subsoil			
SOC	Exponential	2.24E+6	3.61E+2	2.15E-2	-
N	Spherical	486	9.5E-6	1.97E-4	-
$P_{available}$	Exponential	1.29E+6	3.60	8.07	-
$K_{available}$	Spherical	706	213.06	459.6	-
CEC	Spherical	664	9.30	11.19	-
pH	Exponential	354	2.98E-1	2.62E-1	-
Sand	Spherical	810	126	91.09	-
Silt	Spherical	1.28E+3	86.53	52.94	-
Clay	Spherical	483.46	15.48	26.20	-
BD	Exponential	216.41	4.0E-3	3.22E-3	-
Ks	Gaussian	2.7 E-4	6.2 E+3	8.65E-3	-

The soil properties showed spatial dependency in the subsoil, implying other factors such as land use and management activities could be reasons for the lack of spatial dependency in the topsoil. The remaining soil parameters were fitted with Gaussian, exponential and spherical models. Total N in the topsoil was best fitted with a spherical model, while available soil P, SOC, silt, clay, bulk density and Ks were fitted best with an exponential empirical model. The spatial correlation (range) of soil parameters varied from 2.7 E-4 (Ks in subsoil) to 1.29 E+6 (SOC in subsoil). At distances beyond that range, the respective soil parameters did not autocorrelate.

The nugget, which is an indication of micro-variability, was highest for available K in the topsoil. Except for available K, sand, silt and clay content showed the highest micro-variability, a phenomenon that might be attributed to measurement error. They also exhibited a high semivariance as indicated by high objective values. This is consistent with results from Rücker (2005) and Agyare (2004), who also observed soil physical parameters to have higher micro-variability than chemical attributes. The exceptionally high nugget values for available K contradict results from other studies in Spain (Pierce and Nowak, 1999; Lopez-Granados et al., 2002) based on which the prospects for the precise management of K were concluded to be high. It also implies that selected sampling distance did not capture spatial dependencies.

Spatial distribution of soil properties

To visualize the spatial pattern or distribution of soil parameters within the landscape, soil parameter data within the landscape were interpolated and draped on a DEM generated for the landscape. The homestead fields are located to the south of terrian diagrams (Figure 5.1 and 5.2) and are separated from the bush farms by a stream channel (lowland evident in diagrams). The influence of terrain on the distribution of SOC, CEC, available P and pH within the selected landscape is illustrated in Figure 5.1.

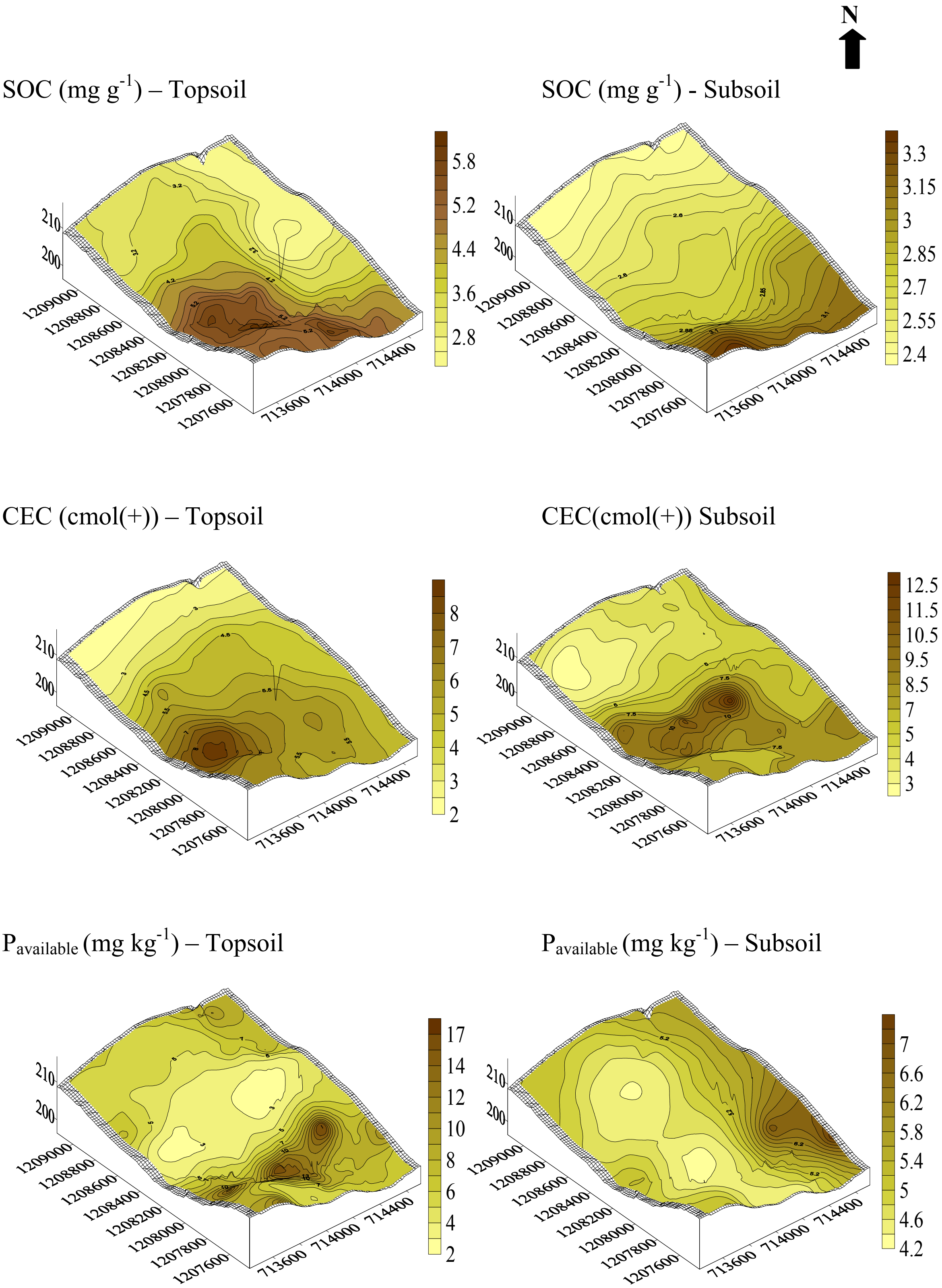
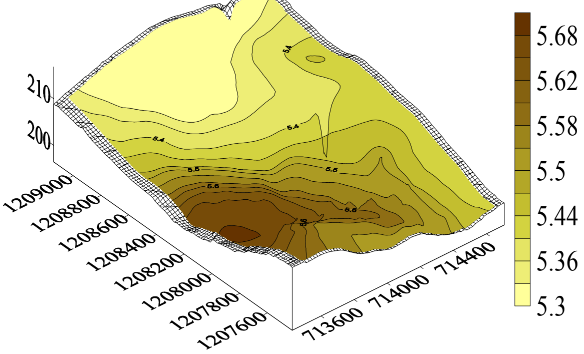


Figure 5.1: Spatial distribution of selected soil chemical properties within the landscape at Navrongo, Ghana. x-axis is easting, y – axis is northing and z – axis is height (m)

pH – Topsoil



pH – Subsoil

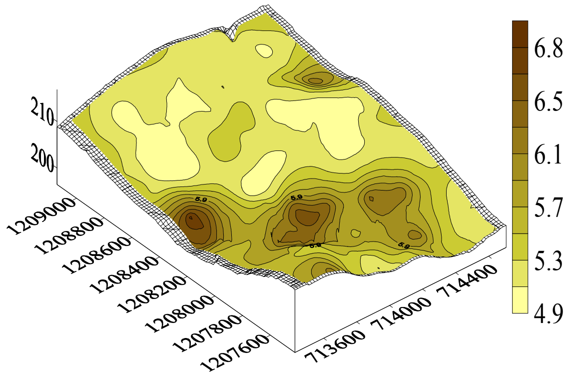


Figure 5.1 continued

SOC in the topsoil was distributed along gradients, increasing from upslope north of the stream channel to the lowlands along the stream channel. The south to the stream channel, which falls in the homestead, also showed a high SOC content despite its upslope position, a phenomenon that can only be attributed to human management activities. It can therefore be concluded that intrinsic variations in soils play an important role in the spatial dependency of soil parameter and that the level of the impact varies among soil parameters.

Similar trends for SOC were observed in the subsoils. The spatial pattern of SOC thus was (i) influenced by location within the terrain, (ii) the type of soil present at a location (Eutric Gleysols – lowland soil with the highest SOC content as mentioned in the previous Chapter) and (iii) lastly by farmers' management witnessed by higher SOC contents recorded in the homestead (upslope south of stream channel) as compared to locations north of the stream channel. The distribution pattern of SOC and available P in the topsoils were noisier (patchy) than those in the subsoil, again explainable by the impact of human activities.

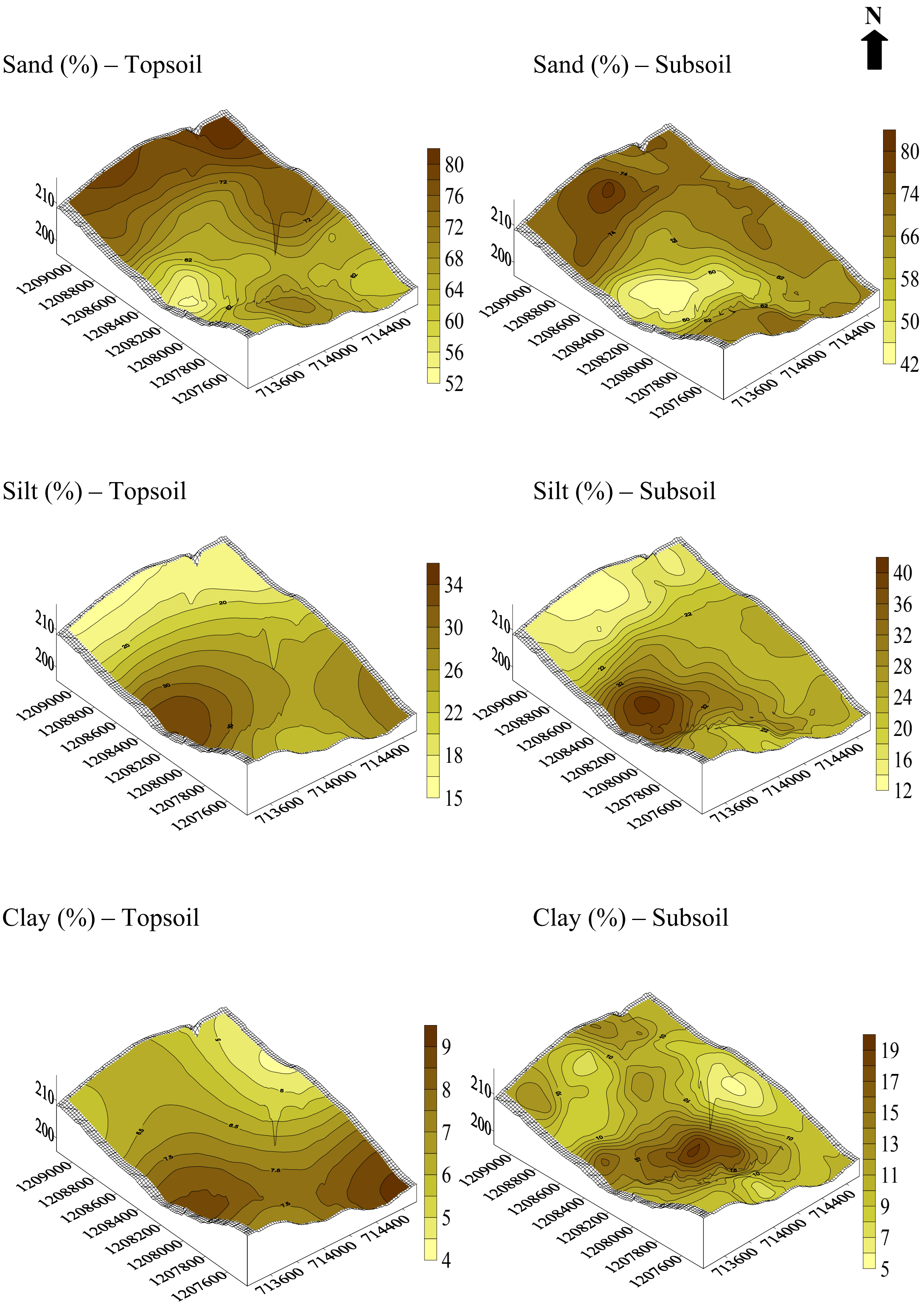


Figure 5.2: Spatial distribution of selected soil physical properties within the landscape at Navrongo, Ghana. x-axis is easting, y – axis is northing and z – axis is height (m)

Bulk density (g cm^{-3}) – Topsoil   Bulk density (g cm^{-3}) – Subsoil

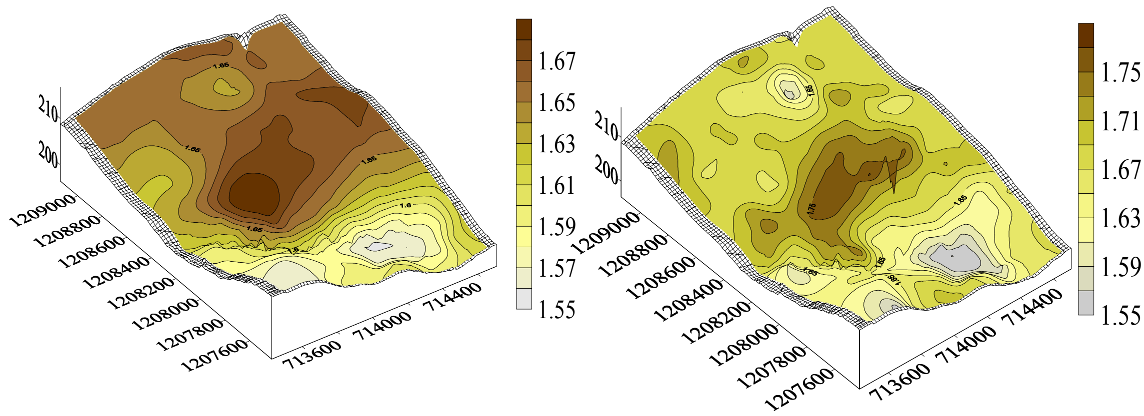


Figure 5.2 continued

Soil pH was highest along the stream channel and in the homestead-upslope (south of the stream channel), whilst upslope soil acidity increased with increasing distance from the stream channel. Similar observations were made by Annan-Afful and Wakatsuki (2002) with higher pH values in lowland soils compared with those of the upland in their study on toposequence as influenced by landuse in an inland valley in the Ashanti region of Ghana. The application of organic manure and household waste such as ash accounted for the high pH in the homestead through addition of K and Ca. The pattern was however much noisier in the subsoils. The high mobility of cations was illustrated by higher values in the lowlands that decreased with increasing distance upslope, except in the homestead. This phenomenon was described by Park and Vlek (2002) to be a characteristic of mobile soil attribute that change rapidly over space and time.

Contrary to observations made with SOC and available P, soil physical properties exhibited clearer spatial gradients in both sampling depths which were distinct in the topsoil than in the subsoil. Lopez-Granados et al. (2002) and Cambardella and Karlen (1999) reported a similar phenomenon in the spatial structure of soil properties at different depths. Movement of clay particles from the upland to the lowland is evident in the increasing clay content with increasing proximity to the lowlands (Figure 5.2). The distribution in the subsoil showed patchy patterns. This lateral movement of finer soil particles (silt and clay) from the highlands to the low lying areas has resulted in the highest sand content in the uplands, decreasing with increasing distances to the lowlands.

5.3.3 Soil type identification and mapping

In Ghana, soil series are commonly named based on two criteria. Soils located in lower slopes are named after the rivers within the area they were first identified. Soils on upper slopes are named after the town close to which they were first identified. In this study, following this method, five soils were identified: (i) Brenyasi (Gleyic Arenosol) and (ii) Kupela (Eutric Gleysol) located on the lower slopes, (iii) Pu (**E**utric **G**leyic Regosol) on the mid slopes, and (iv) Tanchera (**E**ndoeutric-**s**tagnic Plinthosol) and (v) Puga (Eutric Plinthosol) located at the summit and the upper slopes. Coordinates of each of the 176 mini-pits were recorded in order to derive a soil map. The coordinates were imported into Arc View 3.2 software. A soil map was then generated, employing the interpolation and digitizing tools of the software. This map provided a broad overview for the selection of the location of the profile pits for each soil. The profile pits were 1.5 m and 1.5 m x 1 m wide. In all, five pit profiles were dug within the study area.

Spatial distribution of soil types

Information on the location, altitude, relative occurrence and position in the topography of profile pits are provided in Appendix 4. The two main soil types of importance to this study were the E-G Regosol and E-S Plinthosol covering 60.2 % and 18.2 % of the area, respectively (Figure 5.3). The Eutric Plinthosols covered 11.9 %, most of which usually remained uncultivated due to its coarse soil texture and high concretional fractions (iron and magnesium oxides). Eutric Gleysol and Gleyic Arenosol, both lowland soils, covered merely 4.5 and 5.1 %, respectively. They are used mainly for rice and dry season irrigated vegetables. Brief descriptions of the soil profile of each soil are presented in Appendix 5.

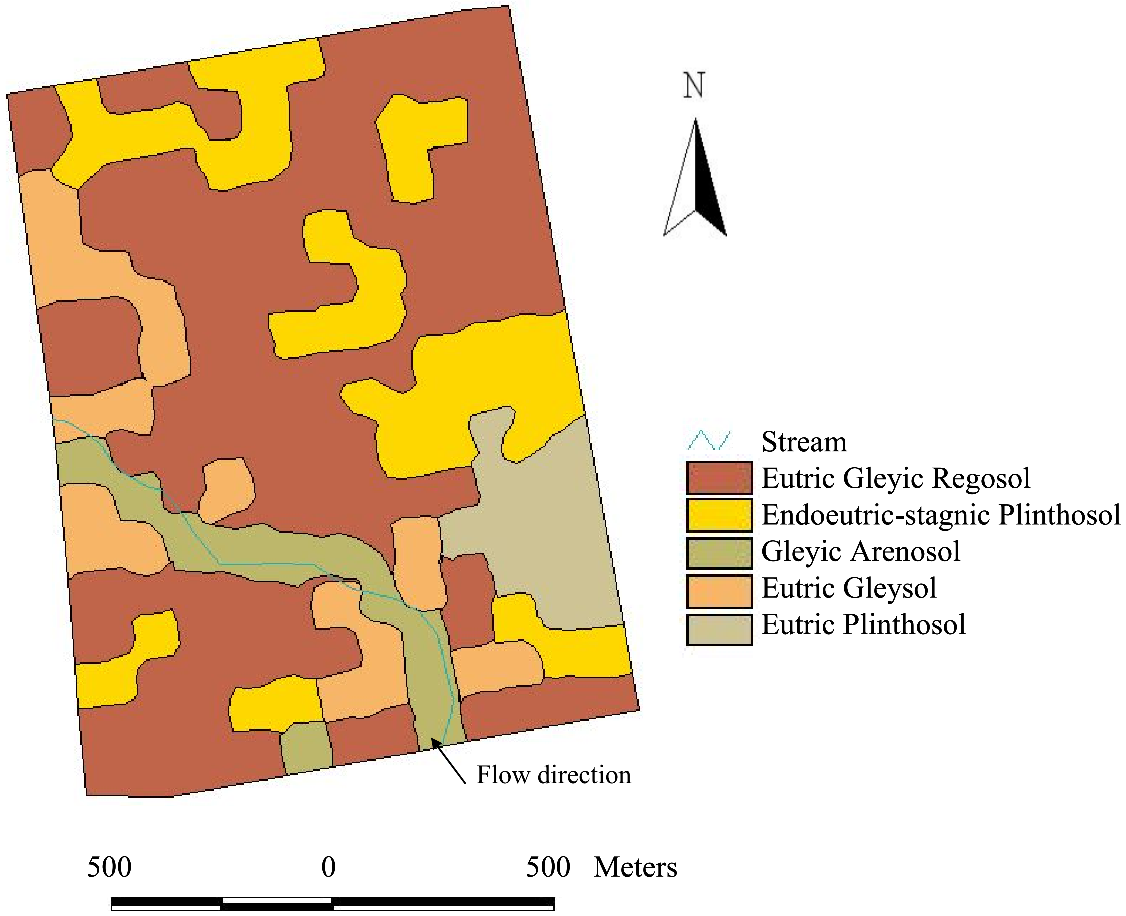


Figure 5.3: Spatial distribution of soils in study area, Navrongo (Ghana)

Eutric Gleyic Regosol (Pu soil type)

These are soils that are usually shallow and occur on the mid-slopes. They are derived from hornblende granites and are highly eroded with partially weathered rock close to the surface. The topsoils usually contain coarse sand with medium-size quartz and feldspar fragments. They have a low water retention capacity due to their sandy nature. They are, however, not well drained the underlying partially weathered rock, which acts as a water barrier.

Endoeutric-stagnic Plintosol (Tanchera)

These soils were found on slopes of between 2 and 3 %. They are also derived from hornblende granites. They were located on the upper slopes over E-G Regosol. They are imperfectly drained soils consisting of pale gritty sandy loam and underlined by concretions of iron and magnesium oxides. They are formed over decomposed granite. The topsoils are loose and coarse textured to a depth of about 33 cm. Underneath is mainly gravels or oxides of iron and magnesium.

Eutric Plintosol (Puga)

The Eutric Plinthosol soils were found at the summit or on upslope sites, and are also derived from hornblende granites. The profile showed a clear differentiation of topsoil, subsoil and decomposed substratum. The soils are shallow and poorly drained with massive ironstone. The topsoils were about 25 cm in depth, brown to brownish black, light-textured sandy loam with single grain in the top 8 cm depth and a few quartz concretions. They have low water retention capacity due to their coarse nature. They have massive iron and magnesium concretions than the E-S Plinthosol.

Eutric Gleysol (Kupela)

The Eutric Gleysols are found in the lowlands. They are poorly drained and formed from mixed local alluvium of clayey sand in the narrow valley bottoms. The profile consists of 8 cm humus topsoil over gray, slightly mottled brown, clay loam or clay to a depth of about 40 cm. The profile below was brownish grey, mottled brown or yellow to a depth of about 120 cm and below.

Gleyic Arenosol (Brenyasi)

These soils were located along the stream (Budunga) on the site which runs from the north to south eastern direction. The topsoil (~12 cm) soil were brown, fine sandy loam with a considerable humus content overlaying a more loose and sandy soil with less humus. The deeper profile consisted of yellowish-brown loose medium to coarse sand to a depth of about 150 cm and below.

Properties of soil series

The variations in the soil attributes for the various soil series are presented in Tables 5.7 and 5.8.

Table 5.7: Chemical properties of soil series at two sampling depths at Navrongo, Ghana

Soil Series	Number of soil pits	SOC ($mg\ g^{-1}$) Mean (CV)	pH Mean(CV)	Nitrogen ($mg\ g^{-1}$) Mean (CV)	$P_{available}$ ($mg\ kg^{-1}$) Mean (CV)	$K_{available}$ ($mg\ kg^{-1}$) Mean (CV)	CEC ($cmol(+)kg^{-1}$) Mean (CV)
0 – 15 cm							
Eutric Gleyic Regosol (1)	106	4.3 (51)	5.4 (10)	0.7 (245)	6.2 (85)	76.9 (50)	5.0 (63)
Endoeutric-stagnic Plintosol (2)	32	2.6 (46)	5.3 (9)	0.2 (58)	4.9 (61)	71.1 (58)	3.4 (45)
Eutric Gleysol (3)	21	4.9 (59)	5.7 (13)	0.5 (57)	6.7 (69)	77.2 (52)	6.9 (47)
Gleyic Arenosol (4)	8	4.2 (51)	5.8 (6)	0.4 (45)	8.0 (64)	65.2 (21)	5.2 (34)
Eutric Plintosols (5)	9	3.1 (45)	5.6 (14)	0.3 (46)	9.4 (143)	43.4 (73)	4.5 (40)
15 – 30 cm							
Eutric Gleyic Regosol (1)	106	2.7 (56)	5.5 (12)	0.24 (61)	4.6 (34)	71.7 (38)	6.14 (74)
Endoeutric-stagnic Plintosol (2)	32	2.3 (40)	5.0 (5)	0.23 (49)	5.6 (85)	148.1 (36)	4.73 (56)
Eutric Gleysol (3)	21	3.0 (40)	5.9 (14)	0.26 (37)	4.4 (28)	82.4 (28)	9.08 (44)
Gleyic Arenosol (4)	8	2.1 (53)	6.1 (14)	0.18 (59)	5.4 (76)	74.3 (29)	8.53 (46)
Eutric Plintosols (5)	9	4.1 (87)	5.2 (4)	0.37 (89)	8.3 (104)	66.6 (14)	5.24 (27)

CV: Coefficient of variation, SOC: soil organic carbon, CEC: cation exchange capacity

Table 5.8: Physical properties of the different soil types at two sampling depths at Navrongo, Ghana

Soil Series	N	Sand (%) Mean (CV)	Silt (%) Mean (CV)	Clay (%) Mean (CV)	Bulk density ($g\ cm^{-3}$) Mean (CV)	Ks ($cm\ day^{-1}$) Mean (CV)
0 – 15 cm						
Eutric Gleyic Regosol (1)	106	69.7 (13)	23.7 (31)	6.6 (49)	1.64 (5)	19.5 (216)
Endoeutric-stagnic Plintosol (2)	32	75.1 (9)	19.4 (32)	5.6 (49)	1.65 (3)	17.8 (101)
Eutric Gleysol (3)	21	58.2 (25)	33.2 (38)	8.6 (62)	1.62 (6)	12.5 (146)
Gleyic Arenosol (4)	8	64.7 (32)	24.5 (52)	10.9 (80)	1.52 (6)	87.6 (139)
Eutric Plintosols (5)	9	66.1 (29)	26.5 (56)	5.4 (60)	1.65 (2)	80.8 (27)
15 – 30 cm						
Eutric Gleyic Regosol (1)	106	64.5 (20)	40.1 (23)	12.5 (50)	1.68 (4)	21.6 (325)
Endoeutric-stagnic Plintosol (2)	32	71.0 (12)	20.9 (30)	8.1 (68)	1.69 (5)	18.2 (111)
Eutric Gleysol (3)	21	52.4 (30)	35.9 (36)	11.7 (46)	1.66 (5)	38.2 (338)
Gleyic Arenosol (4)	8	75.0 (19)	18.3 (61)	6.7 (55)	1.57 (6)	87.7 (139)
Eutric Plintosols (5)	9	67.7 (6)	24.9 (13)	5.9 (36)	1.69 (4)	26.8 (91)

(CV): Coefficient of variation in parenthesis, Ks: Saturated hydraulic conductivity.

Mean soil organic carbon content of the soils varied from 2.6 mg g^{-1} (Endoeutric-stagnic Plintosol) to 4.9 mg g^{-1} (Eutric Gleysol) in the top 15 cm of the soil profile, and 2.1 mg g^{-1} (Gleyic Arenosol) to 4.1 mg g^{-1} (Eutric Plintosol) in the subsoil (15-30 cm). Consequently, these values were below 20 mg g^{-1}, the threshold for reasonable crop production as set by Landon (1991). Soil pH was the least variable soil chemical property with a CV less than 15 % (6-14 % in the topsoil and 4-14 % in the subsoil). All other chemical properties, in both the top and subsoil were generally highly variable with CVs of more than 35 %. Variations were, however, higher in the topsoils than in the subsoils for all soil types. Soil CECs were slightly above the critical limit of 5 cmol (+) kg^{-1} except for the Endoeutric-stagnic Plintosol and Eutric Plintosol soils, where values were 3.4 and 4.5 cmol (+) kg^{-1}, respectively. Subsoil mean CECs were generally higher than those in the topsoil, an indication of movement of clay particles from the topsoil to the lower layers. The highest mean CEC values of 6.9 and 9.1 cmol (+) kg^{-1} for the top- and subsoils respectively, were obtained from the Kupela soil type.

Bulk density showed the lowest CV with a range of 2 – 6 % in the topsoil and 4 – 6 % in the subsoil for the different soils. Mean bulk density of the soils ranged from 1.52 to 1.65 g cm^{-3} and 1.57 to 1.69 g cm^{-3} in the top and subsoils, respectively. The soils were generally sandy, with a high sand content with values ranging from 58 to 75 % in the topsoil and 52 to 71 % in the subsoil. Variability in soil physical properties increased in the order of bulk density < sand < silt < clay. Percentage clay content was the most variable (CV of 49 – 80 % in the topsoil and 36 – 68 % in the subsoil) physical properties with mean values of 5 – 11 % and 6 – 13 % in the topsoil and subsoil respectively. Mean values were higher in the subsoil than the topsoil, implying the translocation of clay particles to lower soil profiles a pattern that directly affected the CEC.

The high variability of most of the soil properties within the soil series of the study site is an indication of the heterogeneity of the soil parameters in both physical and chemical attributes, which may translate into variations in yield over the landscape. Soil variability, therefore, needs to be taken into account when predicting crop yields on a given landscape.

5.3.4 Classification of soil types based on soil physical and chemical properties

Comparisons of the different soils

The aim of this section is to distinguish the different soil types identified in the study area based on the chemical and physical properties that are relevant to crop production. A non-parametric test (Kruskal-Wallis test) revealed differences between soils in the study site.

In Table 5.9a – 5.9d, the median of each parameter for each soil type, Kruskal-Wallis median test values (chi-square values and their respective significance levels), mean ranks and pairwise comparisons of soil types for parameters with significant differences are given. The highest chi-square value was 37.3 for soil pH in the subsoil and the lower was 2.75 for available P in the topsoil. In the topsoil, significant differences were obtained for pH, organic carbon, CEC, total N and available K. In the subsoil, only pH, available K and CEC differed between the soil types.

Table 5.9a: Differentiating soil types using Kruskal-Wallis mean rank test statistics of chemical properties of the topsoils at Navrongo, Ghana

Soils	n	pH Median(R)	SOC (mgg^{-1}) Median(R)	N (mgg^{-1}) Median(R)	$P_{available}$ (mg/kg) Median(R)	$K_{available}$ (mg/kg) Median(R)	CEC (cmol(+)kg) Median(R)
Eutric Gleyic Regosol (1)	106	5.4 (87)	3.8 (97)	0.40 (98)	4.5 (88)	72.3 (95)	3.9 (89)
Endoeutric-stagnic Plintosol (2)	32	5.2 (69)	2.3 (52)	0.20 (50)	4.5 (82)	57.6 (81)	3.2 (58)
Eutric Gleysol (3)	21	5.5 (110)	4.7 (104)	0.40 (108)	4.4 (93)	69.1 (93)	6.9 (123)
Gleyic Arenosol (4)	8	5.7 (129)	3.8 (97)	0.35 (97)	5.8 (113)	65.8 (84)	5.6 (109)
Eutric Plintosols (5)	9	5.5 (88)	2.6 (67)	0.30 (66)	4.2 (87)	32.9 (41)	3.9 (90)
Total	176	5.4	3.5	0.30	4.5	68.3	3.9
Median test		13.4^{c} (0.01)	24.2^{c} (0.00)	27.1^{c} (0.00)	2.8^{c} (0.60)	10.5^{c} (0.03)	22.9^{c} (0.00)
Pair-wise comparison ($p < 0.05$)		1≠4, 2≠3, 2≠4	1≠2, 2≠3, 2≠4	1≠2, 2≠3, 2≠4, 3≠5		1≠4, 1≠5, 2≠5, 3≠5, 4≠5	1≠2, 1≠3, 2≠3, 2≠4

R: mean rank, c: chi square value

Table 5.9b: Differentiating soil types using Kruskal-Wallis mean rank test statistics the chemical properties of the subsoils at Navrongo, Ghana

Soils	N	pH Median(R)	SOC (mgg^{-1}) Median(R)	N (mgg^{-1}) Median(R)	$P_{available}$ (mg/kg) Median(R)	$K_{available}$ (mg/kg) Median(R)	CEC (cmol(+)kg) Median(R)
Eutric Gleyic Regosol (1)	105	5.5 (91)	2.4 (86)	0.20 (85)	4.5 (85)	65.8 (87)	5.1 (85)
Endoeutric-stagnic Plintosol (2)	32	5.0 (48)	2.4 (85)	0.20 (91)	4.8 (98)	56.8 (70)	3.9 (65)
Eutric Gleysol (3)	21	5.6 (124)	2.8 (109)	0.30 (104)	4.1 (76)	77.4 (117)	8.6 (131)
Gleyic Arenosol (4)	8	5.7 (130)	1.8 (59)	0.15 (59)	4.1 (74)	72.4 (103)	7.0 (125)
Eutric Plintosols (5)	9	5.1 (71)	2.8 (116)	0.30 (112)	5.3 (135)	65.8 (92)	5.3 (86)
Total	175	5.3	2.5	0.2	4.6	65.8	5.3
Median test		37.3 (0.00)	9.22 (0.06)	7.96 (0.09)	11.1 (0.03)	11.70 (0.02)	26.52 (0.00)
Pair-wise comparison ($p < 0.05$)		1≠2, 1≠3, 1≠4, 2≠3, 2≠4, 3≠5, 4≠5			1≠5, 3≠5, 4≠5	1≠3, 2≠3	1≠3, 1≠4, 2≠3, 2≠4, 3≠5, 4≠5

Table 5.9c: Differentiating soil types using Kruskal – Wallis mean rank test statistics of the physical properties of topsoils at Navrongo, Ghana

Soils	n	Sand (%) Median(R)	Silt (%) Median(R)	Clay (%) Median(R)	Bulk density (mg/kg) Median(R)	Ks Median(R)
Eutric Gleyic Regosol (1)	106	71.1 (88)	22.3 (89)	6.4 (87)	1.64 (92)	11.6 (42)
Endoeutric-stagnic Plintosol (2)	32	76.4 (116)	19.6 (63)	4.8 (68)	1.66 (97)	7.0 (50)
Eutric Gleysol (3)	21	63.4 (48)	32.1 (129)	7.4 (110)	1.61 (77)	3.5 (34)
Gleyic Arenosol (4)	8	72.0 (85)	18.6 (79)	8.2 (129)	1.52 (27)	87.6 (48)
Eutric Plintosols (5)	9	74.5 (94)	20.7 (87)	4.8 (92)	1.65 (97)	10.8 (53)
Total	176	67.7	22.9	10.3	1.68	3.6
Median test		23.3 (0.00)	21.5 (0.00)	13.9 (0.01)	14.3 (0.01)	4.2 (0.38)
Pair-wise comparison ($p < 0.05$)		1≠2, 1≠3, 2≠3	1≠2, 1≠3, 1≠4, 2≠3	1≠4, 2≠3, 2≠4	1≠4, 2≠4, 3≠4, 4≠5	

Table 5.9d: Differentiating soil types using Kruskal–Wallis means rank test statistics of the physical properties of subsoil at Navrongo, Ghana

Soil types	n	Sand (%) Median(P)	Silt (%) Median(P)	Clay (%) Median(P)	Bulk density (mg/kg) Median(P)	Ks Median(P)
Eutric Gleyic Regosol (1)	106	66.5 (86)	21.9 (84)	12.0 (102)	1.67 (90)	2.5 (38)
Endoeutric-stagnic Plintosol (2)	32	70.8 (113)	22.3 (75)	6.5 (57)	1.68 (101)	12.7 (54)
Eutric Gleysol (3)	21	56.8 (47)	33.6 (135)	10.8 (97)	1.67 (80)	3.1 (36)
Gleyic Arenosol (4)	8	78.8 (126)	14.9 (59)	6.0 (47)	1.55 (37)	87.7 (56)
Eutric Plintosols (5)	9	68.2 (93)	23.9 (102)	6.8 (55)	1.67 (95)	19.4 (65)
Total	176	71.7	22.1	6.3	1.64	9.6
Median test		25.95 (0.00)	23.91 (0.00)	29.68 (0.00)	10.82 (0.03)	10.32 (0.04)
Pair-wise comparison ($p < 0.05$)		1≠2, 1≠3, 1≠4, 2≠3, 3≠4, 3≠5	1≠3, 2≠3, 2≠4, 3≠4, 3≠5	1≠2, 1≠4, 1≠5, 2≠3, 3≠4, 3≠5	1≠2, 1≠5, 2≠3, 3≠5	1≠2, 1≠5, 2≠3, 3≠5

In general, the chi-square values were higher in the subsoil than in the topsoil; trends that can be attributed to the influence of land-use activities that naturally affect the topsoil more strongly. Soil CEC in the topsoil of the different soil types were in the decreasing order: Eutric Gleysol > Gleyic Arenosol > Eutric Plinthosol > E-G Regosol > E-S Plinthosol. A similar trend was also observed in the subsoils.

Eutric Gleysol, a lowland soil showed the highest SOC content with the highest mean rank of 104 and a median of 4.7 mg g^{-1}, while E-S Plinthosol showed the lowest mean rank of 51.6 and a median value of 2.3 mg g^{-1}. The SOC content of the topsoils of the soils were in decreasing order, Eutric Gleysol > E-G Regosol >Gleyic Arenosol > Eutric Plinthosol > E-S Plinthosol. A similar pattern was observed in the subsoils of the soils; however, there were no significant differences between their SOC values. Soil N was highest in Eutric Gleysol soil type with a Kruskal mean rank of 108 and a median of 0.4 mg g^{-1}, while the lowest N content was obtained in the E-S Plinthosol with a rank of 50.3 and a median of 2 mg g^{-1}. The E-G Regosol topsoil was higher in soil N than the E-S Plinthosol. In the subsoil however, the differences were not significant. In general, the lowland soils had higher mean rankings in almost all parameters.

Sand content ranged from a median value of 63.4 to 76.4 % for the topsoil. Kruskal-Wallis ranking gave a rank of 116 for Endoeutric-stagnic Plintosol and 47.5 for Eutric Gleysol. In the top 15 cm soil layer, the soils could be differentiated based on their sand, silt and clay content and bulk density. The lowland soils Eutric Gleysol and Gleyic Arenosol differentiated from the upslope Endoeutric-stagnic Plintosols based on their sand, silt and clay content.

5.4 General discussion and conclusions

The Kruskal Wallis test enabled the differentiation of the different soil types based on their chemical and physical properties. Though the Eutric Gleysol was revealed to be the best soil type for cultivation in terms of soil parameters desirable for adequate crop production, its low internal drainage (prone to water logging) does not favor sorghum cultivation. More so, it occupied merely about 5 % of the total landscape, and is hence not important for this study. The dominating soil types E-G Regosol and E-S Plinthosol are used for the cultivation of sorghum and other crops in spite of their low fertility status. This poor soil fertility is further worsened by the prolonged exposure to wind erosion (surfaces are left bare of vegetation) in the dry season and to high run-off particularly at the onset of the rains. Considering the sandy nature of these soils, soil management practices that positively impact on SOC content and the use of inorganic fertilizers need to be encouraged to ensure meaningful and sustainable food production. Due to the importance of these two soil types, they were selected to model crop yield. Also the economic feasibility of inorganic fertilizer use in the cultivation of sorghum needs to be assessed, as farm management has been cited to be synonymous to managing risks and its impact on food security, which leads to low adoption of new technologies (Walker and Ryan, 1990).

Assessment of variability in properties of agricultural soils is necessary to provide appropriate knowledge for effective management (Onofiok, 1993). The considerable variations observed within the various soils in this study put into question the use of only soil mapping units as homogeneous zones for crop management especially in precision farming. Three factors were identified to have influenced the spatial variations/distribution of soil parameters at the landscape scale namely, influence of farmers' management activities, farm location within the landscape and the underlying soil. The phenomena are indicative of the intrinsic variations in soil parameters, as reported in other studies (Mallarino et al., 1999; Haefele and Wopereis, 2005) and also the influence of other factors such as topography and farmers' management practices.

Though the classical statistics of the soil parameters indicate a high level of variability (coefficient of variation), geostatistical techniques go further and illustrate the spatial structure of these variations. Soil parameters were characterized by a wide range of spatial distribution models and level of dependencies within the landscape, a phenomenon that poses a challenge to the collective precise management of these parameters for agricultural purposes. The variations observed in the soil parameters were further exploited by modeling the distribution of sorghum grain yield in the landscape using point data (see Chapter 6). This was done to assess to what extent variability observed in soil parameters impacted on sorghum yield based on the assumption that small absolute differences in soil parameters such as clay and its associated parameters may result in relatively large differences in nutrient availability and consequently in large differences in plant yield (Manu et al., 1991), which normally translate into grain yield (Brouwer et al., 1993).

6 MODELING SORGHUM GROWTH AND GRAIN YIELD

6.1 Introduction

6.1.1 Background

Soil degradation poses a serious threat to crop production and consequently, food security in sub-Saharan Africa (de Jager et al., 2003). Cereal crops constitute a crucial part of the staple food in Ghana and other West African countries. Its production in the semi- arid areas of Ghana as in other West African savannahs is significantly influenced by inadequate and poor rainfall distribution, low levels of nitrogen (N) and phosphorous (P) contents in the soil (Bationo et al., 2003). The maintenance of soil quality for sustainable yields requires considerable investments in inorganic fertilizers (Vlek et al., 1997), as nutrient recycling does not compensate for the removal of P from the soil, mainly through crop harvests. However, mineral fertilizer use is notoriously low in these regions (de Jager et al., 2003). On average, merely 8 kg of mineral fertilizer are applied per hectare and year (Henao and Baanante, 1999).

Phosphorous deficiency is a widespread constraint to crop production in tropical soils. Worldwide, an estimated land area of over 20 million km^2 is affected (Fairhust et al., 1999). In the semi-arid region of Ghana, the soils are inherently low in plant available P (Owusu-Bennoah and Acquaye, 1989; Abekoe 1996). The mean available soil P (Bray 1) values measured in the top 0-15 cm of the soil types in the study area ranged from 4.38 to 9.43 mg kg^{-1} which is far below the required level needed for optimum crop production, and also below the 10 mg kg^{-1} reported by Okalebo et al., (1992), below which maize responded to the application of P fertilizer.

The low levels of available P have been attributed to the advanced weathering of the soils, their variable sorption, and poor organic matter content and recycling of the soils (Abekoe and Tiessen, 1998). Most studies on soils in the semi-arid region of Ghana described the sorption capacities of the soils as low to moderate (Kanabo et al., 1978, Owusu-Bennoah and Acquaye, 1989; Abekoe and Tiessen, 1998). Abekoe and Tiessen (1998) in their studies in Northern Ghana further established that the presence of lateritic nodules in the soils increases the sorption capacities for P. It also reduces available root space, hence limiting root growth for reaching available P within the soil profile.

Many studies have been conducted to assess the yield response of crops to mineral N fertilizers (Bowen and Baethgen, 1998; Godwin and Singh, 1998; Wolf and van Keulen, 1989). It is, however, evident that P deficiency reduces the crop yield response to mineral N (Smalberger et al., 2006) due to the absence of the synergistic effects between N and P. Finally, P deficiency results in the reduction in photosynthesis and thus directly reduces crop growth. Hence, under low-input agriculture, the low P supplies of soils in the tropics have a high potential of limiting crop production. Therefore, external inputs of inorganic P and N fertilizer are necessary for adequate crop production.

6.1.2 Conceptual framework of crop simulation models

Crop simulation models (CSM) such as Agricultural Production Systems sIMulator – APSIM (Keating et al., 2003) and Decision Support System for Agrotechnology Transfer-DSSAT (Jones et al., 2003) predict crop yield and growth dynamically, i.e. in daily time step intervals. Both models use data from soil, weather, crop management and site data. Grain yield is described through the daily capture and utilization of environmental resources such as water, soil nutrients and solar radiation. The response to these environmental factors (stimuli), are expressed in distinct phenological phases (development stages) in the growth cycle of plants. A seed is sown, it absorbs moisture from the soil to germinate, it emergers, a leaf canopy is produced, this intercepts incident light, and the absorbed light energy is converted into assimilates. These assimilates are then partitioned to various parts of the plant components. In APSIM, plant growth cycles are characterised by development stages, which are controlled by thermal time and photoperiod. The commencement of each of these development stages is determined by the accumulation of thermal time. It is, however, reduced by unfavorable conditions to plant growth such as water and nitrogen stress, resulting in delayed phenology under stressed conditions. The photoperiod mainly controls the onset of anthesis in plants. For instance, under short-day conditions a long-day plant will have a prolonged vegetative phase, which under extreme circumstances might result in a complete absence of flowering.

The development of the APSIM was initiated in 1990 in the semi arid tropics of Australia and East Africa (Keating and McCown, 2001). It has since witnessed a broad applicability to a wide range of systems management and has been extensively used (e.g. Nelson et al, 1998; Ludwig and Asseng, 2006; van Ittersum et al, 2003; Probert et al, 1998). The capability to simulate crop growth in response to low soil P is one of its more recent capabilities (Carberry et al., 2002), providing opportunity to simulate crop production in the tropics where soil P nutrition affects crop yield and efficient use of applied mineral fertilizers. This capability of APSIM to simulate crop growth in response to P limitations was first tested on maize experiments carried out in Kenya.

This section assesses the crop yield response of Sorghum to mineral fertilizer for different farm types and soils, using APSIM, the Agricultural Production Systems Simulator (Keating et al., 2003). To achieve these, the following objectives were set;

(i) Calibrate APSIM for Sorghum growth in the study area,
(ii) Evaluate the performance of the model for two different farm types and soils,
(iii) Assess the response of Sorghum (grain) to mineral fertilizer on two different farm types and soils,
(iv) Assess the agronomic efficiency and economic feasibility of mineral fertilizer use in the two farm types,
(v) Apply the model in analyzing selected farmers' management scenarios.

6.2 Materials and methods

6.2.1 Description of study area

This study was conducted in Navrongo in the Upper East region of Ghana, boarded by latitude 10° 15" and 11° 10" N and 0° and 1° 0" W. It lies in the semi-arid portion of the Volta Basin. The area is characterized by a uni-modal rainfall pattern with an annual average rainfall of 950 mm. The rainy season begins in May and ends in September/October, varying from year to year. The soils used in the study are Endoeutric-stagnic Plinthosol and Eutric Gleyic Regosol (FAO classification).

6.2.2 Model calibration

Crop (APSIM-sorghum), soilN2 (soil nitrogen), soilP (soil phosphorous), soilWat (soil water), manure and residue modules were linked with APSIM 4.0 for simulations. Also included were manager and weather (met) modules. The manager module deals with crop management module informations such as when to plant and date and amount of fertilizer applied. The met module had inputs of daily weather data for the study area and was used for both model calibration and evaluation. It is a key input parameter as all processes are driven by weather variables. Data included rainfall amount, minimum and maximum temperature and solar radiation.

Soil modules were calibrated mainly with measured data from experiments, and from related literature e.g. Fening et al., 2005; Owusu-Benoah and Acquaye, 1996). Though soil processes are central to simulations in APSIM (Nelson et al., 1998), simulating crop yield also requires adequate calibration for the phenology, biomass and grain yield. For this purpose, two different sets of data collected from two different planting dates (June 12 and 26, 2005) experiments were conducted. Each planting date experiment was replicated three times and grown under optimal growth conditions (supplementary irrigation and adequate inorganic fertilizer (80 kg NPK ha^{-1}) provided). Growth and yield data collected were used as input parameters to calibrate the sorghum module. Phenological data monitored included planting date, date of flowering, date for grain filling date of maturity and date of flag leaf appearance. Date of flowering and grain filling are intermediary development phases of crops that are critical data for calibration as priorities for partitioning of assimilates between the different plants organs change as plants developed through each of these development phases. Thermal time accumulations were derived using algorithm described in Jones and Kiniry (1986) with observed phenology and weather data. Each set of data was used to estimate genetic coefficient related to thermal time accumulations for the critical growth stages (Table 6.1) for the Sorghum cultivar; CSV III. APSIM's default base temperature of 5.7 °C was changed to 8 °C to comply with widely used standard settings. The factor controlling the effect of photoperiod was set to a minimum value of 0.01 to eliminate the effect of photoperiod from the cultivar as it is photoperiod insensitive. With the soil, weather and management data of each planting date, the model was run and predicted anthesis date, biomass and yield were compared to measured values.

Measurements and modeling "soil fertility"

Parameters influencing soil fertility are mainly represented in the SoilN2 and SoilP modules. Initial state variables (NO3, NH4, soil organic carbon, pH and CNR for soil and roots) were measured for each soil layer from each experimental site and used for simulations. Soil P module was parametization was achieved using measured labile p content of each soil layer (Tiessen and Moir, 1993). Also, the CP ratio of roots and residue of the sorghum plant were calculated using measured data field data. P sorption capacity of soils were determined through inverse modeling with values within the limites of known boundary for the study area (Abekoe and Tiessen, 1998; Owusu-Bennoah and Acquaye, 1989).

Table 6.1: Genetic coefficients used for modeling sorghum in APSIM

Coefficient	Definition
tt_emerg_to_endjuv	Thermal time accumulation from seedling emergence to end of juvenile phase (°C days)
tt_flower_to_maturity	Thermal time accumulation from flowering to maturity (°C days)
tt_flag_to_flower	Thermal time accumulation from flag stage to flowering (°C days)
tt_flower_to_start_grain	Thermal time accumulation from flowering to start of grain filling (°C days)
photo_crit 1	Critical photoperiod 1
photo_crit 2	Critical photoperiod 2
photo_slope	The extent to which growth is affected by photoperiod increases beyond photo_crit 1 and 2

6.2.3 Model evaluation

In order to evaluate the APSIM model, four levels of inorganic N (0, 40, 80 and 120 kg ha^{-1}) in the form of ammonium sulphate and three levels of P (0, 30 and 60 kg ha^{-1}) in the form of triple super phosphate (TSP) were applied. The experiments were conducted in homestead fields (Regosol) and bush farms (Regosol and Plinthosol) with the later being planted on two different dates (June 12 and 26, 2005). In the study area, farmers' attempt to improve crop production has created soil fertility gradient between the homestead fields (located within settlement) through application of organic manure and crop residues (mainly peanuts and cowpea) harvested from the bush farms are applied in the homestead fields annually to improve crop productivity in the homestead. The experiments were laid out in a randomised complete block design on each of the soil types and farm types. In the homestead, farmer's fields were used for the study. Treatments were replicated seven times in the homestead fields, three times on the Regosol and four times on the Plinthosol in the bush farms for each planting date.

For ease of reading, Endoeutric-stagnic Plinthosol and Eutric Gleyic Regosol will be referred to as Plinthosol and Regosol, respectively. Soil samples were collected from soil profiles dug on the experimental sites. They were air-dried, sieved and analyzed for organic carbon, pH, bulk density, plant wilting point and field capacity, and liable P. Ammonium and nitrate were also determined. Plant growth duration from emergence to flowering, total biomass as well as grain yield data was collected to evaluate the performance of model. Some of the soil parameters from the experimental trials used in evaluating the performance of the APSIM model are presented in Tables 6.2 and 6.3 and 6.4.

Table 6.2: Soil properties used for modeling sorghum yield on homestead farms (Regosol) in Navrongo, Ghana

Layer	1	2	3	4	5
Soil water parameter					
Layer thickness (mm)	150	300	200	250	250
BD (g cm^{-3})	1.54	1.53	1.62	1.63	1.64
SAT [cm cm^{-1}]	0.353	0.357	0.369	0.341	0.338
DUL [cm cm^{-1}]	0.131	0.139	0.162	0.359	0.127
Soil-C parameters					
Organic C (g 100 g^{-1})	0.58	0.56	0.45	0.37	0.32
finert[a]	0.35	0.40	0.50	0.80	0.80
fbiom[b]	0.02	0.02	0.01	0.01	0.01
Soil P parameter					
Labile P (mg/kg)	21	6.2	5.7	3.2	1
P sorption (mg/kg)	79	150	150	200	200

[a] proportion of soil carbon assumed not to decompose, [b] proportion of decomposable soil carbon in the more labile soil organic matter pool, BD: bulk density, SAT: volumetric water content at saturation.

Table 6.3: Soil properties used for Modeling sorghum yield on bush farms (Regosol) in Navrongo, Ghana

Layer	1	2	3	4	5
Soil water parameter					
Layer thickness (mm)	150	300	200	250	250
BD (g cm^{-3})	1.56	1.58	1.56	1.58	1.56
SAT	0.352	0.321	0.320	0.372	0.246
DUL	0.093	0.126	0.142	0.149	0.145
Soil-C parameters					
Organic C (g 100 g^{-1})	0.39	0.36	0.32	0.37	0.32
finert[a]	0.35	0.35	0.60	0.80	0.80
fbiom[b]	0.015	0.01	0.01	0.01	0.01
Soil P parameter					
Labile P (mg kg^{-1})	15.0	5.2	5.0	2.0	1.0
P sorption (mg/kg)	50	75	120	180	200

[a] proportion of soil carbon assumed not to decompose, [b] proportion of decomposable soil carbon in the more labile soil organic matter pool, BD: bulk density, SAT: volumetric water content at saturation.

Table 6.4: Soil properties used for modeling sorghum yield on the bush farms (Plinthosol) in Navrongo, Ghana

Layer	1	2	3	4	5
Soil water parameters					
Layer thickness (mm)	150	300	200	250	250
BD (g cm-3)	1.59	1.61	1.56	1.58	1.56
SAT	0.353	0.357	0.369	0.341	0.338
DUL	0.093	0.119	0.109	0.129	0.115
Soil-C parameters					
Organic C (g 100 g^{-1})	0.40	0.37	0.23	0.25	0.32
finert[a]	0.35	0.35	0.60	0.80	0.90
fbiom[b]	0.015	0.01	0.01	0.01	0.01
Soil P parameter					
Labile P (mg/kg)	11.5	5.8	5.0	2.0	1.0
P sorption (mg/kg)	50	75	120	180	200

[a] proportion of soil carbon assumed not to decompose, [b] proportion of decomposable soil carbon in the more labile soil organic matter pool, BD: bulk density, SAT: volumetric water content at saturation.

6.2.4 Data analysis

Descriptive statistics and one way analysis of variance (ANOVA) were performed using SPSS version 10.0. The Bonferroni mean separation method was used for pair-wise comparison of means. The dependent variables of selected groups were log-transformed to comply with normal distribution and equal variance, a requirement of ANOVA.

Agronomic efficiency of inorganic fertilizer use

Agronomic N or P use efficiency AEx was calculated as the amount (kg) of grain yield per kg of applied N or P fertilizer.

$$\mathbf{AEx} = \frac{Yx - Yo}{Fx} \qquad (6.1)$$

where Fx is amount of N or P applied in fertilizer, Yx is grain yield at a particular rate of N or P, Yo is grain yield under no N or P application, and x is N or P.

Economic feasibility of inorganic fertilizer use

The value to cost ratio of mineral fertilizer was calculated as

$$VCR = \frac{[PS * YI]}{CF} \qquad (6.2)$$

where VCR is value to cost ratio, PS is price of sorghum, YI is yield increase, and CF the cost of applied fertilizer.

Evaluation of model performance

The performance of the APSIM model in predicting grain yield was evaluated by determining the closeness of the relationship between observed and predicted values using the RMSE, the median unbiased absolute percentage error (MdUAPE), modified coefficient of efficiency (E_1) and the correlation coefficient (r) (Moore and McCabe, 1993). Simulated and observed values were also assessed for significant differences using the Tukey test and Mann-Whitney test.

$$\text{RMSE} = [n^{-1} \sum (Yield_{Calc} - Yield_{meas})^2]^{0.5} \qquad (6.3)$$

where n is the number of replicates in each planting date experiment, *calc* and *meas* denote simulated and measured yield for each replicate.

The MdUAPE is

$$MdUAPE = 100 * Median\left[\frac{|Simulated_i - observed_i|}{0.5(observed_i + simulated_i)}\right] \quad (6.4)$$

MdUAPE avoids problems such as bias in favor of lower prediction that occurs when using the regular MUdAPE in expressing goodness of fit between predictions and observations (Armstrong and Collopy, 1992; Makridakis, 1993).

The modified coefficient of efficiency E_1 is defined as

$$E_1 = 1 - \frac{\sum_{i=1}^{n}|Observed_i - Simulated_i|}{\sum_{i=1}^{n}|Observed_i - Mean_{obs}|} \quad (6.5)$$

It was originally defined by Nash and Sutcliffe (1970). E_1 values range from $-\infty$ to 1.0, with higher values indicating better agreement between model simulations and observations. An E_1 value of zero indicates model performance is as good as the mean observed value of treatments. $E_1 = 1$ implies a perfect fit for simulated and observed values. When $E_1 < 0.0$, then the observed mean value is a better predictor than the model. In the modified coefficient of internal efficiency, the squared difference terms are replaced by their respective absolute values, hence reducing the sensitivity of the coefficient to outliers as in the original coefficient (Willmot et al., 1985; Legates and McCabe, 1999; Evans et al., 2004). Unlike the coefficient of determination, the modified coefficient of internal efficiency is also sensitive to both additive and proportional differences between mode simulations and observations.

6.2.5 Scenario analysis

The APSIM model calibrated for the study area was used to simulate Sorghum grain yield in response to inorganic fertilizer (N and P) and also, crop residues management (seasonal removal of crop residues from the bush farms that eventually ends up in the homestead, while the homestead benefits from addition of organic manure). Relevant data (soil parameter, initial soil conditions and agronomic information) collected at all sites and used in evaluating the model were used as baseline information. The Sorghum cultivar calibrated for the study region was used as the test crop. To project (forecast) crop yield in the study area, based on current practices, a climate simulation model by the name of LARS-WG (Semenov and Brooks, 1999) was used to generate weather data by random re-sampling of 15-years historical weather data from the study site. The climatic inputs generated were daily solar radiation, maximum and minimum air temperatures and rainfall.

The normal practice of smallholders in this region is low input subsistence farming where no fertilizer are applied in cultivating Sorghum and crop residues are removed at the end of each season for domestic use (e.g. fuel). To assess the sustainability of food production in the region, the following management scenarios were formulated. Description of simulated management scenarios are listed as follows;

- Annual removal of crop residue – mineral fertilizer inputs
- Annual removal of crop residue + mineral fertilizer inputs
- Annual incorporation of crop residue – mineral fertilizer inputs
- Annual incorporation of crop residue + mineral fertilizer inputs

The model was applied in both farm types (homestead and bush farm) to simulate the long term effects of the removal of crop residue on sorghum grain production and soil organic carbon. Subsequently, the long term implications of no inorganic fertilizer inputs on sorghum grain yield in the study region were assessed. To contrast the zero-fertilizer input scenarios, a fertilization scheme of 80 (bush farm) and 40 (homestead) kg N ha^{-1} and 30 kg P ha^{-1} (both locations), which were the most economical fertilization practices, were simulated.

To model the spatial distribution of grain yield as a factor of soil parameters, point data on SOC, pH, and soil texture data (sand, clay and silt) (Chapter 5) were used to simulate the impact of spatially heterogeneous soil parameters on yield. Data on soil wilting point, field capacity available water and saturation were generated using a pedo-transfer function (Saxton et al., 1986) with the soil texture and SOC as input data. Two simulations were run, one with no organic and with inorganic input, and the other with 40 and 30 kg ha^{-1} N and P inorganic fertilizers respectively. Simulated grain yield at point locations were then interpolated over the landscape to illustrate the spatial distribution of yield as affected by the variability of input data.

6.3 Results and discussion

6.3.1 Field data

This section presents observed data from the two farm types (homestead and bush farms) as well as those from different soils (Regosol and Plinthosol). Phenology data is presented for all soils and farm types in one sub-section. Grain yield is presented under different headings for each management system and soils.

Phenology

The duration of sorghum growth from emergence to flowering in all experiments are presented in Table 6.5. The number of growing degree days (GDDs) taken from emergence to flowering on the bush farms (Regosol) varied from 1305 to 1567 GDDs between treatments in the first planting date experiment, corresponding to 23 August at the earliest and 6 September at the latest. In the homestead fields, it varied from 1227 and 1453 GDDs between treatments, corresponding to 19 August at the earliest and 31 August at the latest. On the Plinthosol in the bush farms, flowering ranged from the 21 August to 8 September in the first planting date experiment, corresponding to 1230 to 1604 GDDs, respectively. In general, there was a trend of delayed flowering under low levels of inorganic N and P fertilizer applications. Sorghum on the homestead fields flowered much earlier than on the bush farms, probably due to the relatively higher fertility of the soils in the homesteads. Similar observations were reported for silking in maize crowns in the semi-arid region of Nigeria by Dass et al. (1997) and by Sadler et al. (2000) in the southeastern USA coastal plains.

Table 6.5: Duration of sorghum (CSV III) growth from emergence to flowering date in two farm types and two soils expressed in growing degree days (GDD) in Narongo, Ghana

Amount of Fertilizer applied (kg ha^{-1})		GDD Emergence to flowering (°C days)				
P	N	H- R[1]	B-R[1]	B-R[2]	B-P[1]	B-P[2]
0	0	1453	1567	1589	1604	1649
30	0	1453	1567	1570	1604	1649
60	0	1453	1567	1570	1604	1649
0	40	1342	1362	1326	1400	1326
30	40	1381	1362	1326	1362	1326
60	40	1381	1362	1326	1362	1344
0	80	1246	1324	1307	1305	1326
30	80	1284	1305	1270	1284	1270
60	80	1284	1305	1270	1284	1270
0	120	1246	1324	1307	1305	1307
30	120	1227	1305	1230	1266	1249
60	120	1227	1305	1230	1266	1249

H-R: Homestead farms on Rogosol, B-P: Bush farms on Plinthosol, and B-R: Bush farms on Regosol.
[1, 2] 1st and 2nd planting dates respectively.

Sorghum grain yield

Sorghum grain yield on the bush farms (Regosol) ranged from 0.54 t ha^{-1} in the control to a maximum value of 3.77 t grains ha^{-1} with the application of 120 kg N ha^{-1} and 60 kg P ha^{-1} (Table 6.6). This represented an increase in yield of 3.23 t ha^{-1} compared to the control treatment, which is the normal practice by farmers. Significant differences in yield were observed between grain yields at 0 kg P ha^{-1} and the other two levels of P (30 and 60 kg P ha^{-1}) at all levels of N except for the zero-treatment (0 kg N ha^{-1}). There was, however, no difference in grain yields obtained with 30 or 60 kg P ha^{-1} applications ($p= 0.05$). Thus, beyond 30 kg P ha^{-1}, other factors (other soil nutrients, environment) were limiting crop yield. The response of grain yield to inorganic P fertilizer application was consistent with the general observations presented in the earlier chapter that available soil P was below the critical values for optimum crop production. The results are also in line with Abekoe and Tiessen (1998), who showed that P is one of the soil nutrients limiting optimal crop growth in the study region.

Table. 6.6: The response of Sorghum grain yields (t ha^{-1}) to P treatments with different levels of N in Navrongo, Ghana

N applied (kg ha^{-1})	P applied (kg ha^{-1})	B-R[1]	B-R[2]	H-R[1]	B-P[1]	B-P[2]
0	0	0.54	0.88	1.3	0.51	0.50
30	0	0.70	0.84	1.67	0.48	0.75
60	0	0.63	0.81	1.43	0.61	0.82
0	40	1.14	1.35	2.78	1.14	1.17
30	40	2.01	2.48	2.79	1.65	2.03
60	40	2.42	2.88	2.78	1.81	2.42
0	80	2.44	2.55	3.65	2.33	2.20
30	80	3.15	3.44	3.83	3.02	2.44
60	80	3.36	3.56	3.89	3.20	3.58
0	120	2.37	2.67	3.81	2.41	2.61
30	120	3.45	3.62	4.53	3.65	3.34
60	120	3.77	3.57	4.36	3.78	3.68
ANOVA		F - probability				
P treatment		0.000	0.000	0.000	0.000	0.000
N treatment		0.000	0.000	0.000	0.000	0.000
P*N interaction		0.000	0.000	0.020	0.001	0.041
Planting dates		0.000			0.007	

H-R: Homestead farms on Regosol, B-P: Bush farms on Plinthosol, and B-R: Bush farms on Regosol.
[1, 2] 1st and 2nd planting dates respectively.

The very low grain yield of 0.54 t ha^{-1} for sorghum in the absence of inorganic fertilizer application explains the reluctance of farmers to cultivate sorghum in these fields, as they lack the resources to purchase inorganic fertilizer. Instead, peanuts and bambara beans (legumes capable of fixing atmospheric N) are cultivated.

There were significant (p=0.001) grain yield increases with increasing levels of inorganic N and P applications on the homestead farms on Regosols (Table 6.7). Significant interactive effects on grain yield were also observed between inorganic N and P fertilizers. Grain yield of sorghum varied from 1.3 t ha^{-1} under the control condition to a mean value of 4.53 tons ha^{-1} with the application of 120 kg N ha^{-1} and 30 kg P ha^{-1} on the homestead farms. There were significant (p=0.001) increases in grain yield in response to inorganic P (at 30 and 60 kg ha^{-1}) applications over the level of no P application at all levels of inorganic N fertilizer application except for no N application. No significant increases were observed between 30 and 60 kg P ha^{-1}, an indication that 30 kg P suffices crop requirements on the homestead soils. This rather low level of sufficient inorganic P fertilization can be attributed to the addition of animal manure, which also contains phosphate.

Grain yield of sorghum on the Plinthosol on the bush farms ranged from a mean value of 0.51 in the control to a mean value of 3.78 t ha^{-1} under the treatment with 120 kg N ha^{-1} and 60 kg P ha^{-1} (Table 6.7). Grain yield response to inorganic N and P fertilizer applications on the Plinthosol were highly significant (0.001). There was also a highly significant (0.001) interactive effect on grain yield between N and P applications. This implies that both N and P limit grain yield on this soil. There were significant differences between mean grain yield from the control and those at 30 and 60 kg P ha^{-1} at all levels of N application except for grain yield under the control (no fertilizer input).

Grain yields on the homestead fields and bush farms

Significant (p=0.05) grain yield increases in sorghum were observed between the homestead and bush farms for all levels of inorganic P and N fertilizer application. Grain yields were higher at all levels of inorganic N and P applications on the homestead fields than on the bush farms. The yield gaps between the two sites were not compensated by the application of as much as 120 kg N ha^{-1} with 60 kg P ha^{-1}, an indication that inorganic P and N were not the only yield limiting factors. This means that inorganic fertilizer alone can not solve crop production problems on poor soils with low organic matter content. Yield differences can likely be attributed to the differences in the soil organic matter, which in turn affects soil structure and water holding capacity of the soils. The saturated soil hydraulic conductivity on the homestead farms was lower than that of the bush farms (Chapter 4). As illustrated earlier, the homestead fields had higher soil organic carbon, N, P and K than the bush farms. Consequently, the water holding capacity (which is very important in this area due to the erratic nature of rainfall pattern) was higher on the homestead fields than in the bush farms. Thus, for sustainable crop production on the bush farms, inorganic fertilizer must be complemented with measures to increase soil organic matter content.

On both the homestead and bush farms, 30 kg P ha^{-1} fullfilled crop requirements. In both management zones, significant interactive effects of N and P were observed. The interaction was stronger on the bush farms (p = 0.001) than on the homestead fields (p = 0.05).

Grain yields from Plinthosol and Regosol soils on the bush farms

Sorghum grain yield responded to both N and P inorganic fertilizer application on both the Plinthosol and Regosol soils on the bush farms. The response to inorganic N fertilizer was significant at all levels of N application on both soils. On the Plinthosol, significant grain yield increases were observed at all levels of P application, whilst on the Regosol, no significant grain yield increases were observed between 30 and 60 kg P ha^{-1} application, implying that the Plinthosol may be more deficient in P or has higher P sorption capacity due to the presence of feralitic nodules in its soil profile (Abeoko and Tiessen, 1998).

Grain yield was higher on the Regosol than on the Plinthosol. These differences, though significant ($p = 0.05$), were much lower than those between the homestead fields and the bush farms. The differences in grain yield between the two soils could be due to the lower water holding capacity of the Plinthosol compared to the Regosol. Also, the Plinthosol had abundant concretional fractions of iron and magnesium oxides from 30 cm and below in the soil profile, hence providing less space for root development. Grain yields on both soils showed highly significant ($p = 0.001$) positive interactive effects between inorganic N and P fertilizer applications.

Biomass response to mineral fertilizer

The ANOVA revealed a highly significant influence ($p = 0.001$) of mineral N and P fertilizer and their interactive effect on sorghum biomass production. The F statistics probability for the interactive effects was lower on the homestead fields ($p = 0.036$) than on the bush farms ($p = 0.018$, 0.010 for the Regosol and Plinthosols, respectively). This may be due to the additional P made available to the plants from manure application. The mean biomass produced under the two farm types were also different ($p = 0.001$). Mean biomass of sorghum produced on the homestead fields varied from 3.12 to 7.62 t ha^{-1} with no mineral fertilizer and the treatment with 120 kg N ha^{-1} with 60 kg P ha^{-1} mineral fertilizer application, respectively (Figure 6.1a). On the bush farms, biomass ranged from 1.28 (0 kg N ha^{-1} with 30 kg P ha^{-1}) to 6.42 t ha^{-1} (120 kg N ha-1 with 60 kg P ha^{-1}) on the Plinthosol and 1.60 to 6.60 t ha^{-1} on the Regosol. As with grain yield, biomass production increased generally with increasing amount of mineral N applied at all levels of mineral P application except for 80 and 120 kg N ha^{-1} rates, which were not different (p = 0.05). Application of 60 kg P ha^{-1} did not increase biomass yield over that of 30 kg P ha^{-1} for both farms. In general, sorghum biomass yield on the homestead compared to the bush farms reflects the trends that were observed for grain yield.

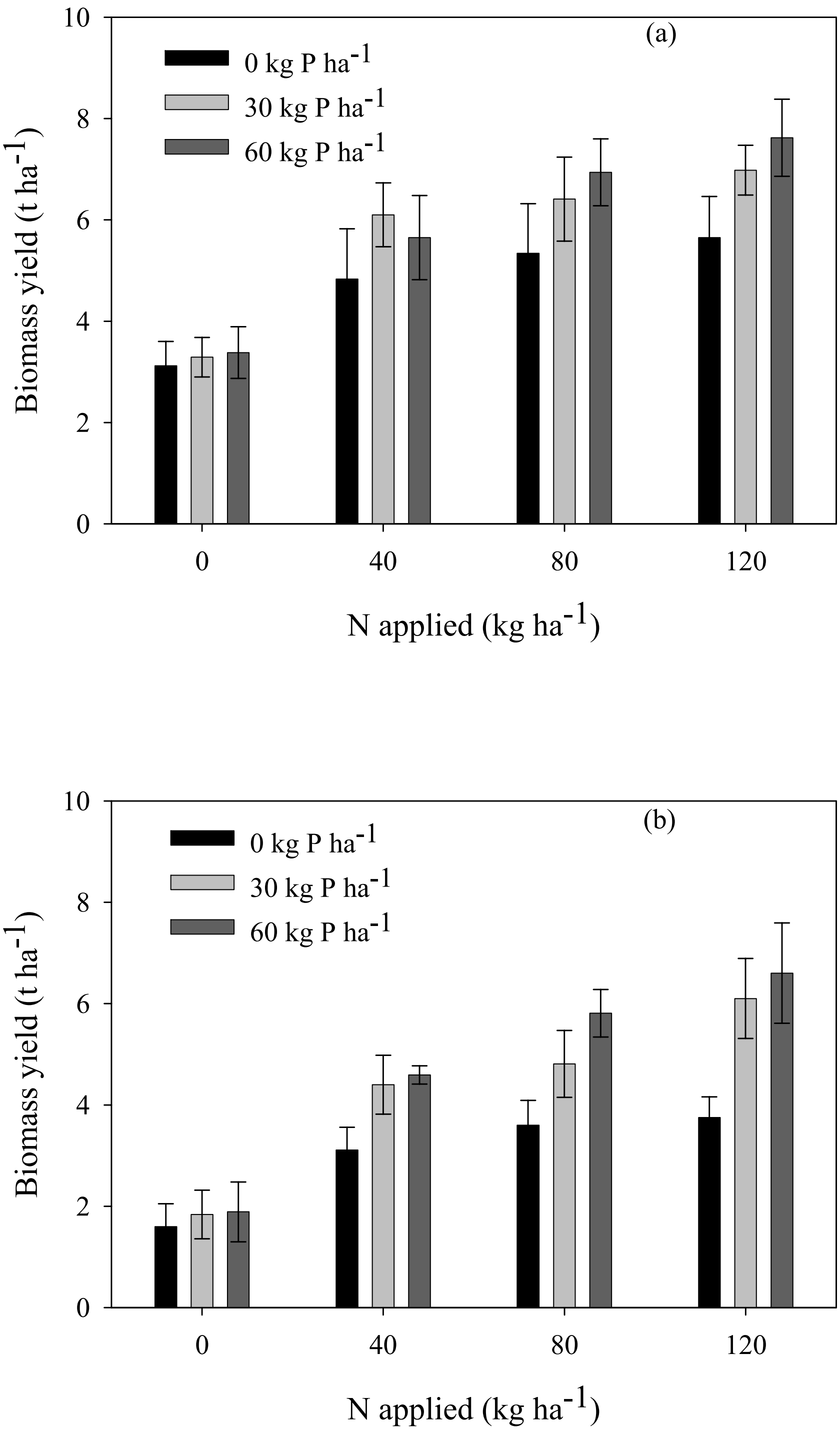


Figure 6.1: Biomass yield on the Regosols on the homestead (a) and bush farms (b) for first planting date in Navrongo, Ghana

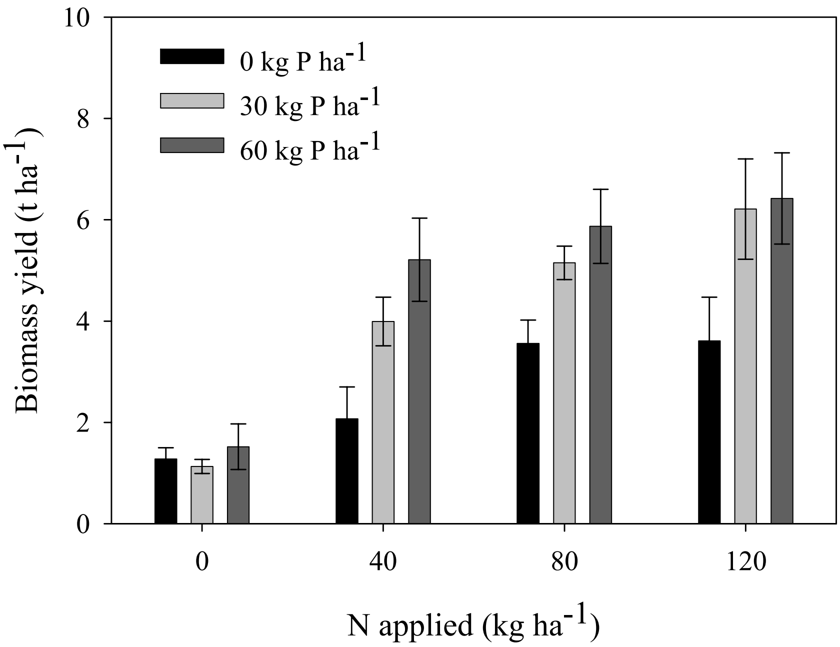


Figure 6.2: Biomass yield on the Plinthosols on the bush farm (first planting date experiments) in Navrongo, Ghana

6.3.2 Agronomic efficiency of mineral fertilizer use

Agronomic N use efficiency (AE_N) in the homestead fields Regosol ranged from 20.9 kg grains kg^{-1} N at 120 kg N ha^{-1} with no P application to 37.3 kg grains kg^{-1} N at 40 kg N ha^{-1} with 30 kg P ha^{-1} (Figure 6.3). On the Regosol on the bush farm, the AE_N by sorghum ranged from 15 kg grains kg^{-1} N at 40 kg N ha^{-1} without mineral P to 44.8 kg grains kg^{-1} N at 40 kg N ha^{-1} with 60 kg ha^{-1} P application. Thus, AE_N was generally highest at low N application rates on Regosol in both farm types, a trend which is comparable to that observed by Mushayi et al. (1999) and Zingore et al. (2006). In general, the homestead fields had higher AE_N compared to the bush farm, a situation reported to be typical of poorly managed and depleted sandy soils (Mushayi et al., 1999; Wopereis et al., 2006).

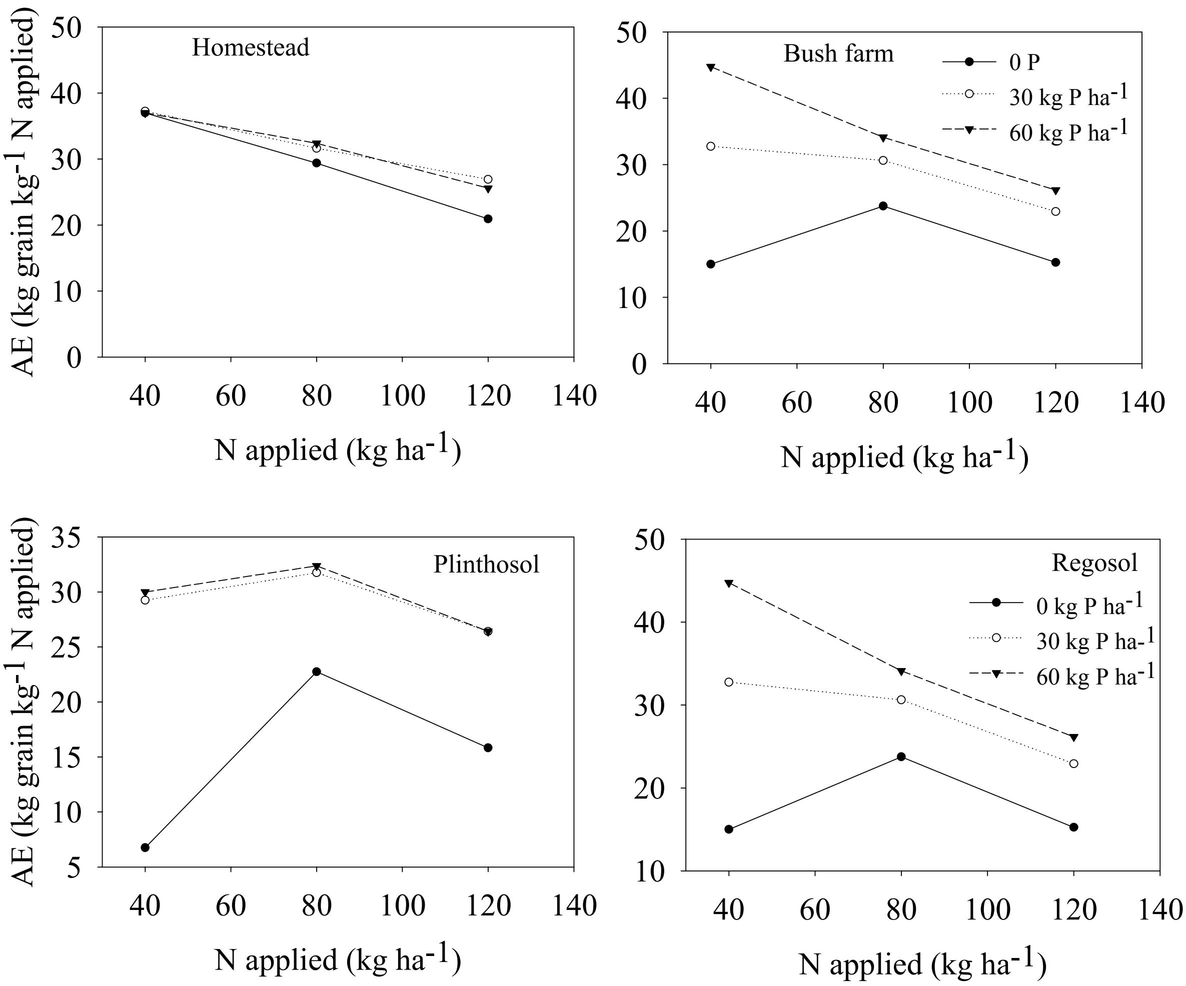


Figure 6.3: Average agronomic N use efficiency (AE) for sorghum yield as influenced by different levels of P application on two farm types and soils (Plinthosols and Regosols; data from 1st planting date) in Navrongo, Ghana

On the Plinthosols on the bush farm, average AE_N varied from 6.75 kg grains kg^{-1} N at 40 kg N ha^{-1} application with no P input to 32 kg grains kg^{-1} N at 80 kg N ha^{-1} application with 60 kg P ha^{-1}. Compared to the Regosols on the bush farms, the Plinthosols had a lower AE_N, most probably due to the coarser soil structure, predisposing it to higher amounts of N to be leached below the rooting zone of the plants. Unlike on the Regosols, AE_N increased at all levels of P application from 40 kg N ha^{-1} to 80 kg N ha^{-1} and then declined with further increases in applied N (Figure 6.3).

Agronomic N use efficiency increased with the addition of P, particularly on the bush farms. This suggests that the bush farm soils are more deficient in P than those of the homestead fields due to the different management. Additionally, the application of P may have improved the capture of N, probably due to the removal of P limitation and the interactive effects between N and P on improving root growth, which could have also improved N uptake (Zingore et al., 2006). The above results show that the current practice of "blanket" fertilizer recommendations are inappropriate in light of the variable soil fertility conditions and their variable responses to both N and P applications in terms of agronomic efficiency in the different farm types.

6.3.3 Economic feasibility of inorganic fertilizer use

Smallholders often produce on a subsistence scale to feed their families, and surpluses accrued are sold. The application of inorganic fertilizer adds to the total cost of producing grain sorghum. Smallholders are generally risk adverse, and risk has been cited for reluctance to adopt such technologies. In order to convince them to opt for any strategy that results in increasing total production costs, it is necessary to subject the grain yields obtained under each of the fertilizer applications to a value to cost ratio analysis to ascertain their economic feasibility.

Value to cost ratio (V/C) estimates and adds up the equivalent monetary value of the benefits and costs to one or more strategies in order to establish whether they are worthwhile. It is therefore, an indicator of the economic feasibility or profitability of a given strategy. A V/C ratio of 1 indicates farmers have recovered all costs associated with grain production. A V/C value less than 1 indicates farmers have incurred loss on adopting a given strategy, while a value more than 1 implies farmers have made gains on using a given fertilizer strategy.

The value/cost ratios were determined using Equation 6.2. Monthly market survey data for 2005 (MoFA, Ghana) showing the monthly variation in the selling price of sorghum is given in Appendix 7. For the purpose of this analysis, 90 % of the average selling price of sorghum for the months of October through to March was used and also the local market price for fertilizer was used.

Feasibility of inorganic fertilizer use in study area

The application of inorganic fertilizer on the homestead fields resulted in V/Cs above 1 in all application rates of inorganic N and P except for application of 60 kg P ha^{-1} without N application. This implies that farmers recovered all costs associated with the production of grain sorghum including the purchase of inorganic fertilizer in all fertilizer strategies except for 60 kg P ha^{-1}. The V/C ranged from a minimum value of 0.36 with the inorganic fertilizer rate of 60 kg ha^{-1} P and no N application to a value of 5.01 with the application of 40 kg N ha^{-1} with no P application. Thus, inorganic fertilizer application is a profitable strategy to increase sorghum grain production at all levels of N and P fertilizer. An increase in N application from 80 kg ha^{-1} with the application of 30 kg P ha^{-1} to 120 kg N ha^{-1} with 60 kg P ha^{-1} resulted in reduction of benefits to farmers due to the extra cost of the additional fertilizer. Benefits accrued to farmers generally decreased with the increasing application of mineral P except for the 120 kg N ha^{-1} level where V/C ratio increased at the 30 kg P application before declining below the value at 40 kg N ha^{-1}. This could be because the homestead farms benefited from added organic manure, hence the impact of mineral P was less in terms of grain produced.

Table 6.7: Economic feasibility of mineral fertilizer use on different management and different soils in Navrongo, Ghana

P applied(kg ha^{-1})	N applied (kg ha^{-1})			
	0	40	80	120
	Homestead (Regosol)			
0	-	5.01	4.79	3.65
30	1.62	3.51	4.08	3.96
60	**0.36**	2.67	3.45	3.28
	Bushfarm (Regosol)			
0	-	2.03	3.87	2.66
30	**0.70**	3.46	4.21	3.56
60	**0.25**	3.39	3.76	3.41
	Bush farm (Plinthosol)			
0	-	**0.92**	3.71	2.76
30	**0.13**	2.69	4.05	3.84
60	**0.28**	2.34	3.59	3.46

On the bush farms (Regosol), the value to cost ratio ranged from 0.25 with 60 kg ha^{-1} P and no N fertilizer application to 4.21 with the application of 80 and 30 kg ha^{-1} N and P, respectively. Application of inorganic P fertilizer increased benefits to farmers at 30 and 60 kg P ha^{-1}, with the 30 kg P ha^{-1} application generating the highest returns at all levels of N application. This was in contrast to the situation in the homestead fields, indicating that mineral P is necessary to increase benefits from mineral N applications. This is illustrated in the high V/C associated with its application (Table 6.8). Additionally, V/Cs increased with increasing application of inorganic N fertilizer applications up to 80 kg ha^{-1}, beyond which the ratio declined at all levels of P and the benefits of the farmers decreased. With no N fertilizer application, the addition of inorganic P fertilizer only added to production cost and hence reduced the V/C ratio, resulting in losses to the farmers (0.70 at 30 kg P ha^{-1} and 0.25 at 60 kg P ha^{-1}).

On the Plinthosol soil (bush farm), the V/C ratio increased with increasing N application at 30 and 60 kg ha^{-1} levels of P applications till 80 kg N ha^{-1} and then declined, a trend similar to that on the Regosol bush farms. In the absence of P application, the V/C ratio declined after 80 kg ha^{-1} N from 3.71 to a value of 2.76 at 120 kg N ha^{-1} application. The V/C ratios were less than 1 in the absence of N application at all levels of P as was the case on the Regosols bush farms and farmers would incur losses. This is also the case with no P applications 40 kg N ha^{-1} applied. Farmers are however faced with limited credit facilities, hence unable to purchase fertilizers. Also, most of the sorghum cultivars used are local varieties with low response to mineral fertilizer but are preferred by farmers because they perform better under unfavourable weather conditions.

6.3.4 Modeling sorghum growth and grain yield

Model calibration

The genetic coefficients (Table 6.1) were calibrated with data collected from experiments conducted in 2005 under optimum growth conditions (no nutrient and water limitation) and with actual weather data. RMSE between observed and predicted values were calculated using equation 6.3. The genetic coefficients of the planting date experiment that achieved the lowest RMSE for the measured parameters was assumed most appropriate for the cultivar and used for further modeling (Table 6.9).

Table 6.8: Comparison of predicted and measured growth parameters using two planting date data sets

Parameter set	Grain [t ha^{-1}]	Biomass [t ha^{-1}]	Anthesis date (GDD °C days)
1st planting date	0.213*	284	13.81
2nd planting date	0.281	297	14.04

** RMSE values, GDD: Growing degree days*

Evaluation of model performance

The performance of the model to reproduce observed crop phenology (anthesis), grain yield and total biomass was tested under different levels of mineral N and P and organic manure treatments on the homestead and bush farm soils.

Phenology

Similar observations were reported by Gungula et al. (2003) for other models in simulating maize phenology under N-stress in Nigeria. The general trend of the growth duration of sorghum in response to the different treatment of N and P fertilizer was reasonably well predicted by the model (Figure 6.1). The model exaggerated the impact of nutrient stress in delaying crop phenology, expressed by the deviations between observations and predictions of GDDs at lower levels of input.

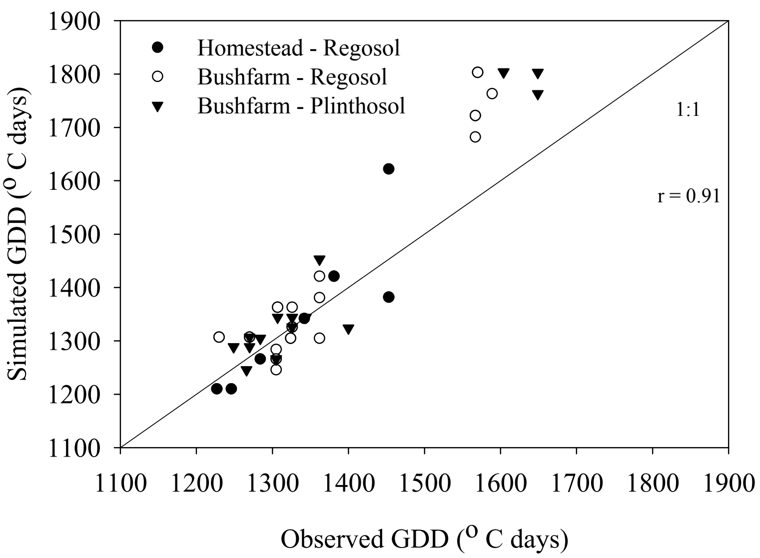


Figure 6.4: Comparison of observed and simulated duration of sorghum growth from emergence to flowering expressed in growing degree days (GDD), Navrongo, Ghana

Total aboveground biomass and grain yield

In general, the model predicted the trend of biomass production under the various N and P fertilizer treatment combinations rather well (Figure 6.5). There was a good correlation between the observed and predicted total dry biomass values with an r value of 0.86 and an overall RMSE between observed and predicted values of 1.17 t ha^{-1} and with an internal model efficiency coefficient of 0.50.

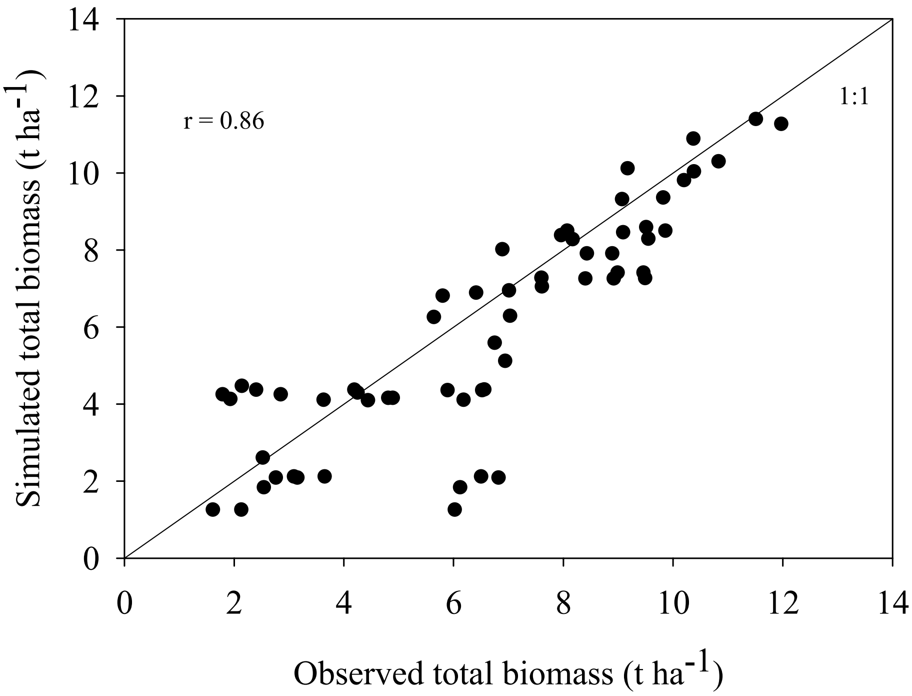


Figure 6.5: Comparison of mean of measured and predicted grain yield of sorghum grown in Navrongo, Ghana

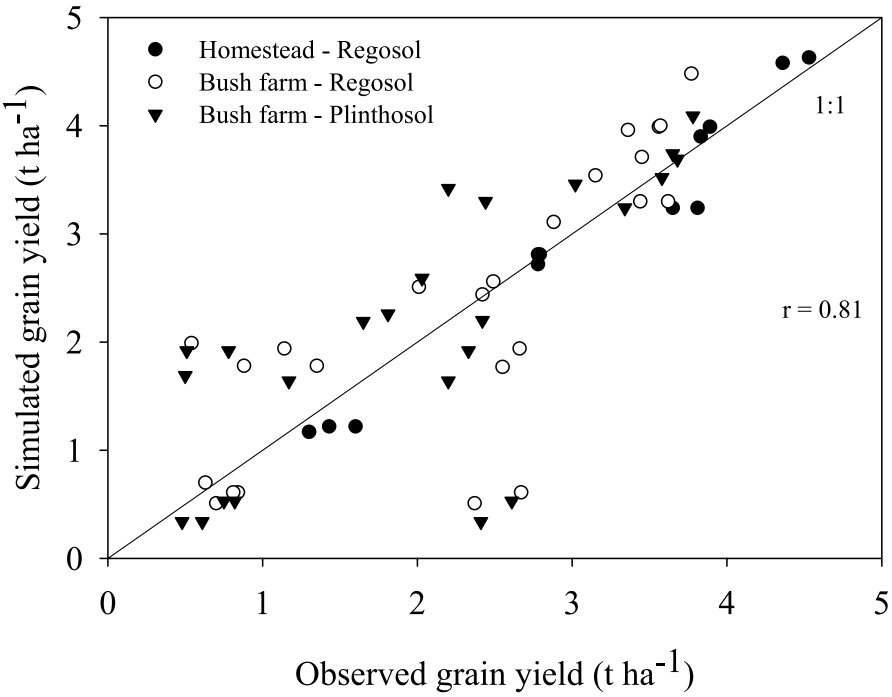


Figure 6.6: Comparison of mean measured and predicted sorghum grain yield grown in Navrongo, Ghana

Also, the trend of grain yield was successfully predicted for both soil types as well as the different management zones (Figure 6.6). There was, however, a small bias towards observed values of sorghum grain yield (RMSE of 0.50 t ha^{-1}). The performance of the model under the different soils and farming conditions is shown in Table 6.9.

Table 6.9: Performance of APSIM to predict sorghum grain yield response to inorganic fertilizer

Location	n	RMSE (t ha^{-1})	MdUAPE (%)	E_1	r
Homestead	84	0.35	28	0.73	0.96
Bush Regosols*	72	0.51	44	0.59	0.79
Bush Plinthosols*	96	0.60	45	0.56	0.73
Overall	252	0.50	39	0.64	0.81

** combined data from the two planting dates*

Grain yield predictions in response to the various levels of inorganic N and P fertilizer applications were well within standard deviations of the measured values (Figures 6.7 and 6.8). Grain yield were better simulated for the homestead farms than for the bush farms, recording MdUAPE values of 29 and 50 %, respectively. The RMSE of grain yield prediction in the homestead was lower than that in the bush farm on the Regosol (Table 6.9). The trend of sorghum grain yield response observed due to treatments (inorganic N and P) was reasonably predicted by the model in both farm types with MdUAPE of 39 %. The model simulated inorganic P application with zero N application on the homestead better than on the bush-farm. Grain yield however, was not within the standard deviation of observed yields in simulation of zero inorganic P applications at applications of 80 and 120 kg N ha^{-1} on the bush farms. This is an indication that organic P dynamics are better described by the model than inorganic P dynamics.

Grain yield was predicted on both the Regosol and Plinthosol soils (bush farms) within the standard deviations of measured grain yield data (Figure 6.7). The trend of grain yield response to inorganic N and P applications observed from measured data were also simulated by the model with a MdUAPE of 50 and 41 %. Overall, for the bush farms predictions for the Plinthosol soils were better than those for the Regosol, as evidenced by RMSE values of 0.41 and 0.63 t ha^{-1}, respectively.

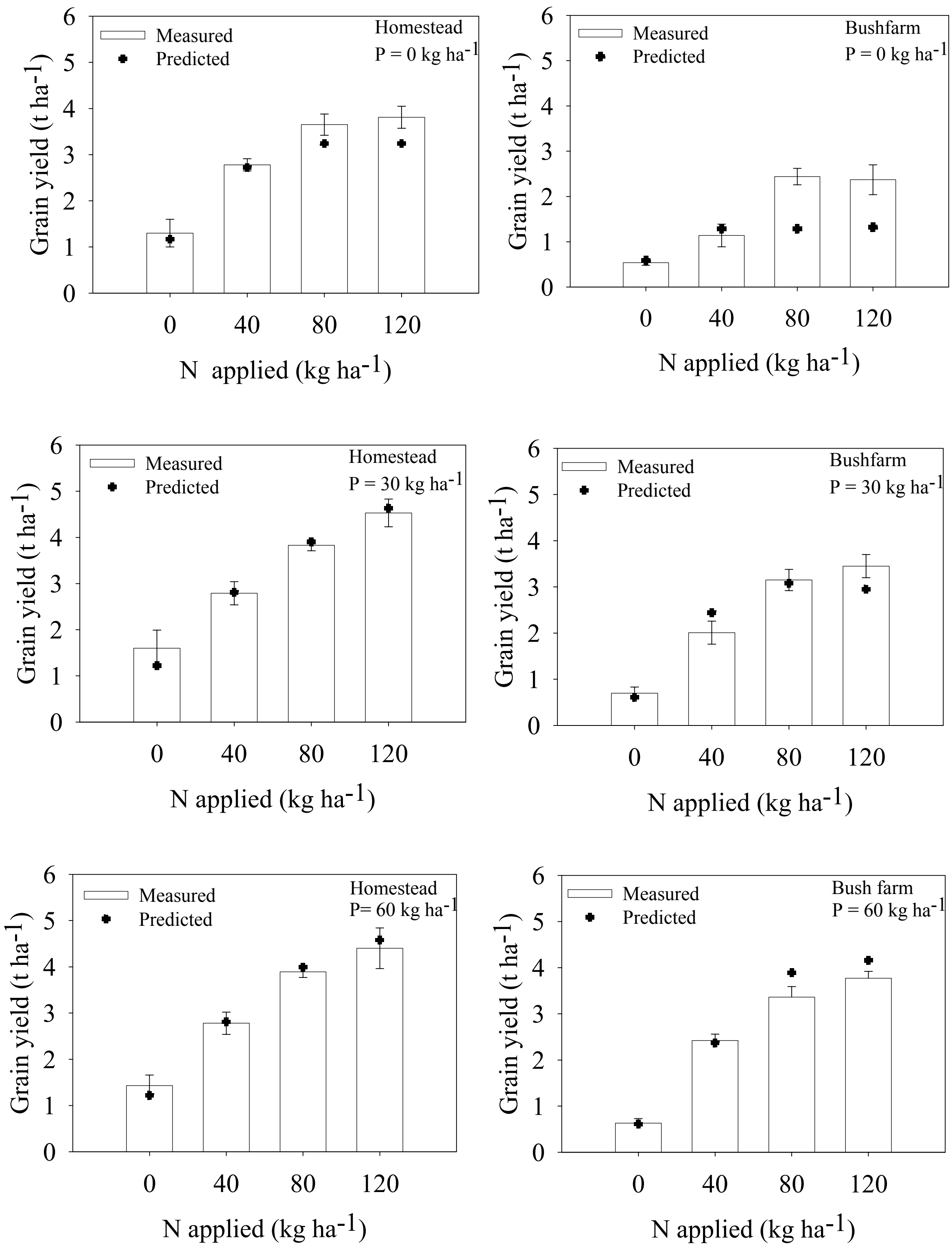


Figure 6.7: Comparison of measured (mean) grain yield of Sorghum and simulated yield values under different rates of inorganic N and P applications on the homestead and bush farms (Regosol)

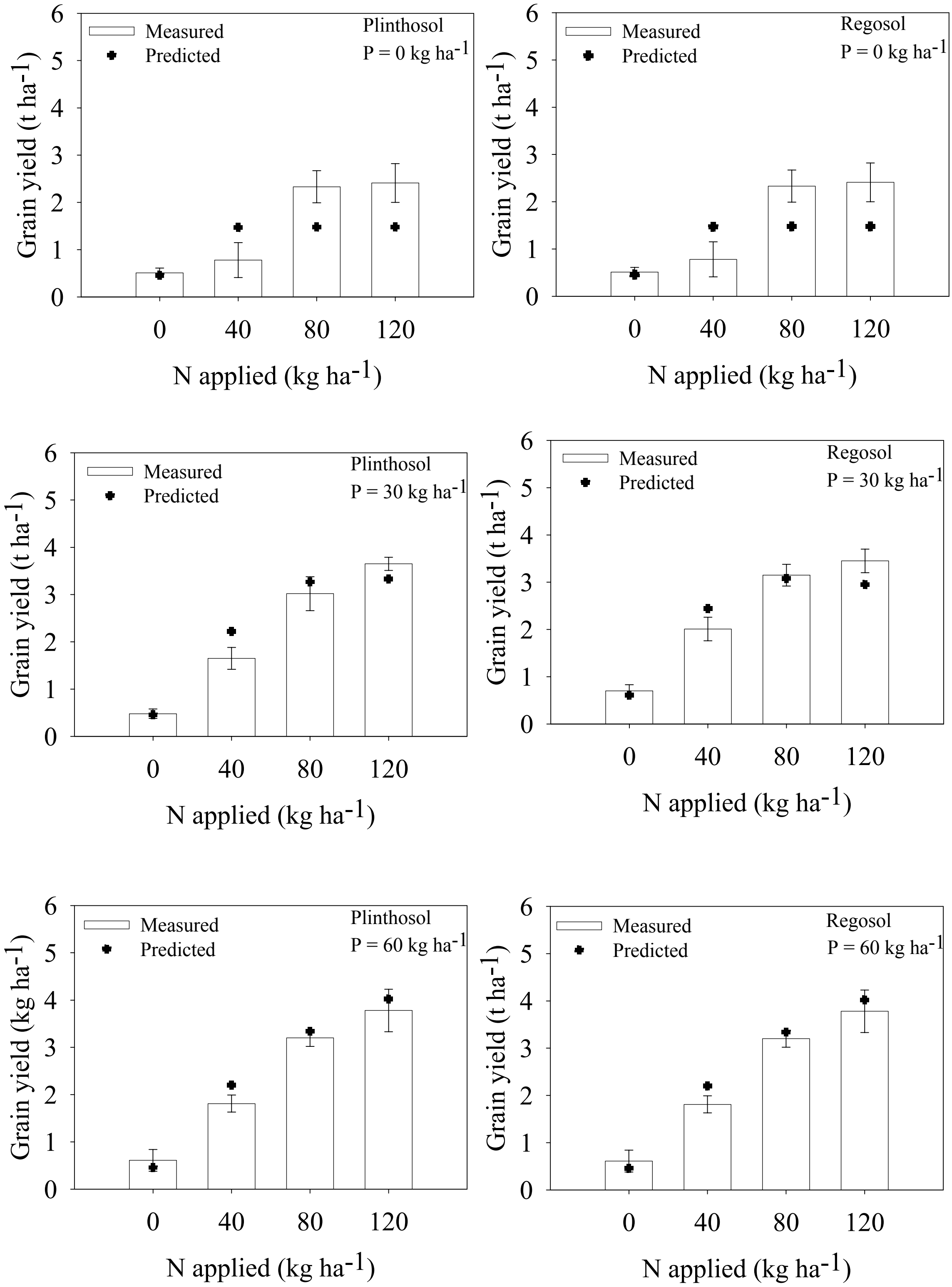


Figure 6.8: Comparison of mean measured and simulated grain yield of sorghum in response to inorganic P and N fertilizer in the bush farms (Regosol and Plinthosol). Error bars indicate the standard deviation of means

Inorganic P applications on both soils did not result in higher simulated grain yield in the bush farms at zero application of N due the low total N content of the soils which was well below the amount required for optimum crop production.

The coefficient of model efficiency was in decreasing order, homestead > bush farm Regosols > bush farm Plinthosols with the least value being 0.56. This implies the model is much better in predicting the response of sorghum grain yield to mineral N and P fertilizer applications as compared to using the mean of observed values. Considering the number of default sorghum model values used (Table 6.10), the internal predictive efficiency of the model could possibly be further improved by using calibrated values that are more specific to the sorghum cultivar.

Table 6.10: Model parameters of sorghum used in simulations

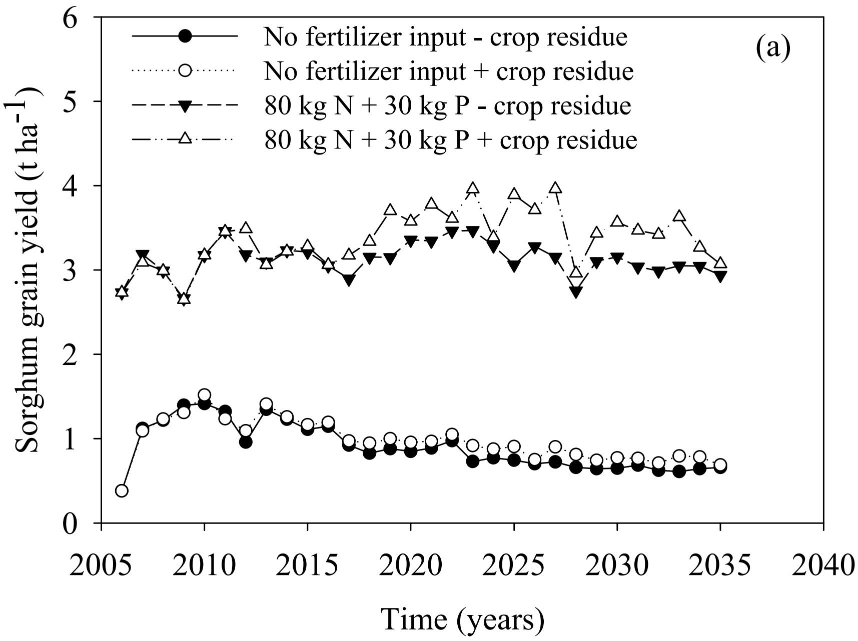
Parameter	Source	Value	Units
Thermal time accumulation			
Duration – end of juvenile to panicle initiation	C	280	^oC day
Duration – flag leaf to flowering stage	C	231	^oC day
Duration, flowering to start of grain filling	C	59	^oC day
Duration, flowering to maturity	C	650	^oC day
Duration - maturity to seed ripening	L	1	^oC day
Shoot lag (time lag before linear coleoptile growth starts)	D	15	^oC day
Photoperiod			
Day length photoperiod to inhibit flowering	D	12.3	H
Day length photoperiod for insensitivity	D	14.6	H
Photoperiod slope	L	0.01	^oC/h
N and P dependent growth			
N stress factor for photosynthesis	D	1.25	-
N stress factor for leaf expansion	D	1.0	-
N stress factor for phenology	D	1.25	-
P stress factor for photosynthesis	D	1.25	-
P stress factor for leaf expansion	D	1.0	-
P stress factor for phenology	D	1.25	-
Soil water stress factor	D	1.125	-
Plant height (max)	O	2100	mm
Grain water content	O	0.150	g/g
Base temperature	L	8	^oC day
Optimal temperature	D	30	^oC day

L: literature, D: default value, C: calibrated , O: observed.

6.3.5 Scenario analysis of farmers' practices

Impact of farmers' practices on temporal grain production

In both farm types – homestead and bush farm, grain yield fluctuated over the simulation period (29 years) with a trend of yield decline in simulations without application of mineral fertilizer (Figure 6.9). In contrast, sorghum yields remained relatively stable over the 29 year simulation period when mineral fertilizer was applied, but yields fluctuated stronger from season to season. In both farm types, incorporating crop residues resulted in significant yield increases, irrespectively of applying mineral fertilizer. This was supported by an increase in the soil organic carbon content over the simulation period in response to the retention of crop residues (Figure 6.10). The model also indicated that continuous removal of crop residue in the homestead, even with the application of 40 and 30 kg ha^{-1} mineral N and P (respectively) over the 29 years period would result in soil organic carbon of the soil declining to levels close to those in the bush farms (Figure 6.9). Similar trends of SOC decline were reported by Zingore et al (2006) using the FARMSIM model to simulate SOC content on virgin soils (sandy) with woodlands.



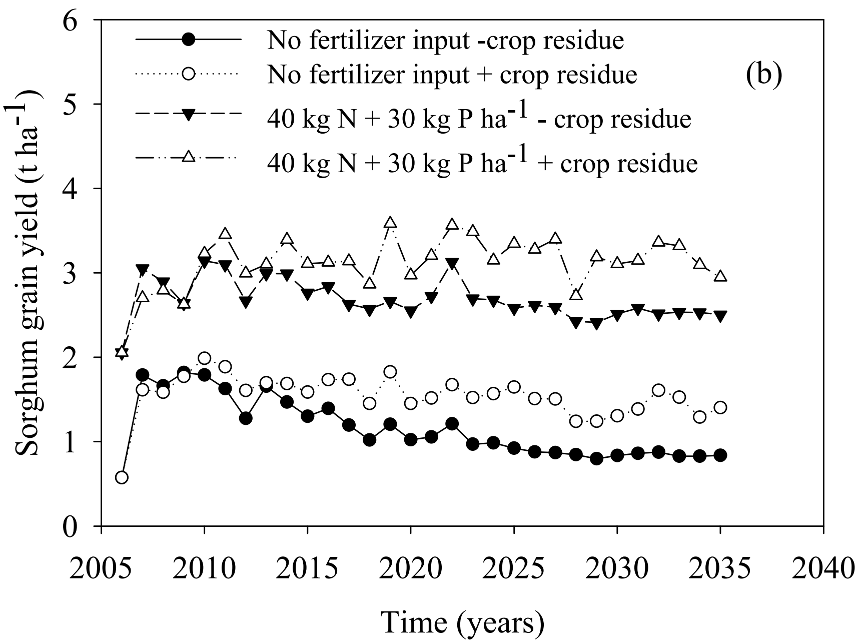


Figure 6.9: Effect of crop residue management practices on the long-term dynamics of sorghum grain production of bush farms (a) and homestead (b) in Navrongo, Ghana

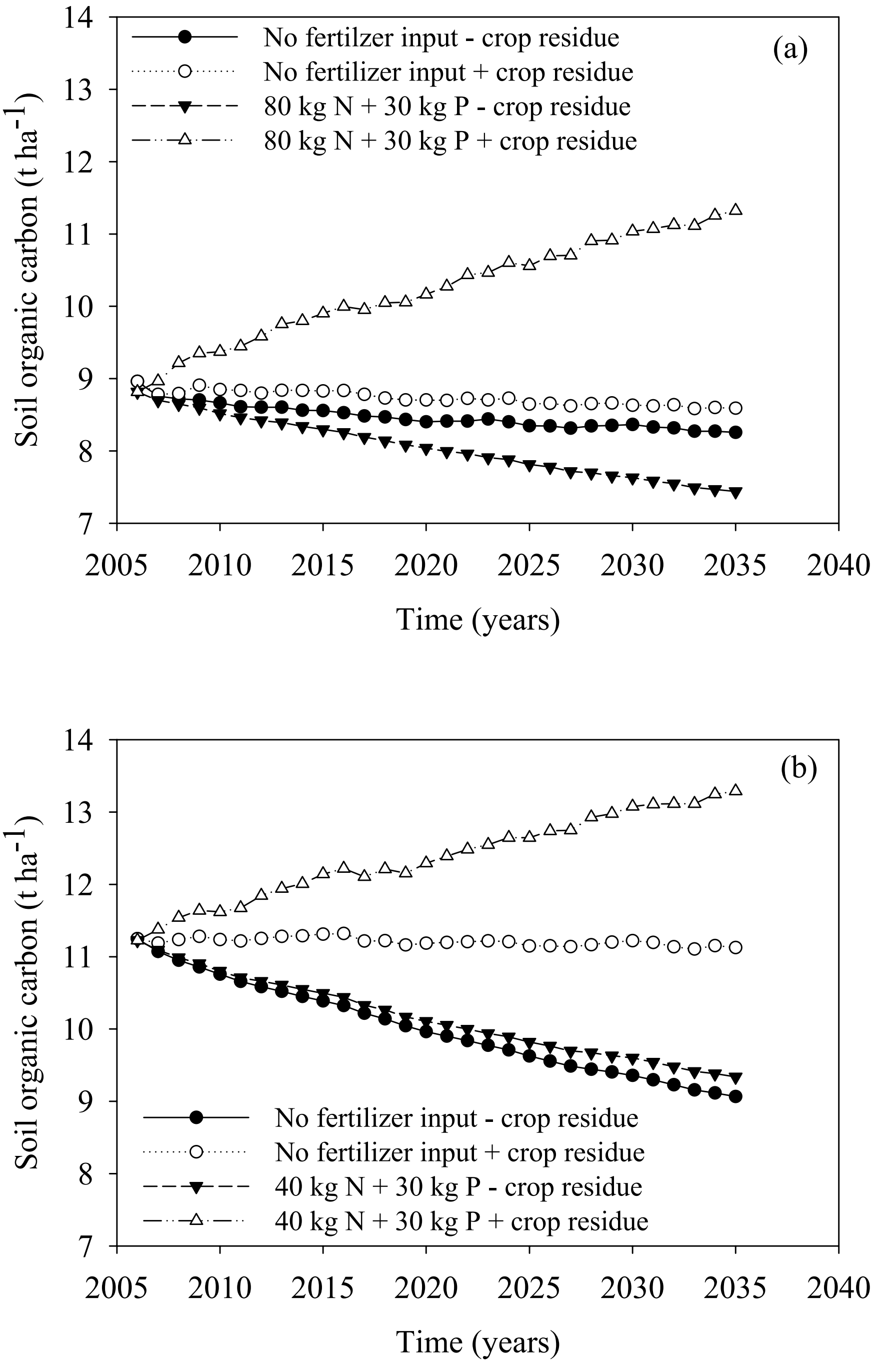


Figure 6.10: Effects of crop residue management practices on the long-term dynamics of soil organic carbon (0-15 cm) in the bush-farm (a) and homestead (b) in Navrongo, Ghana

Application of half the amount of mineral N applied on the bush farm with crop residue incorporation produced yields that were similar to those produced on the bush farm over the simulation period (Figure 6.11). Hence, when farmers are faced with limited amounts of fertilizer available to them, it will be more rational to invest it in the homestead fields rather than on fields in the bush farms. However, given the increasing demand for grains and the limited number of relatively fertile fields in the homesteads, mineral fertilizer will need to be used also in the bush fields as well.

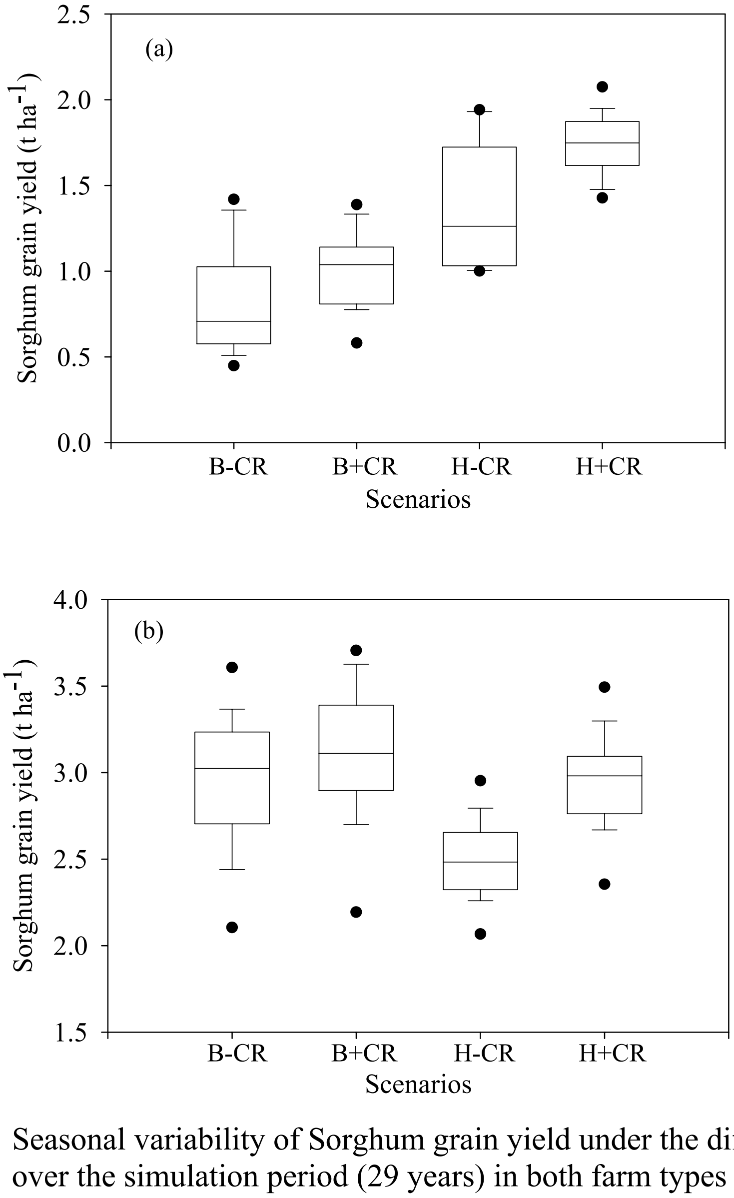


Figure 6.11: Seasonal variability of Sorghum grain yield under the different scenarios over the simulation period (29 years) in both farm types in Navrongo, Ghana. CR: Crop residue, B: Bush farms, H: Homestead fields, a: No fertilizer application, b: 80, 30 kg ha^{-1} N P for bush farm (B) and 40, 30 kg ha^{-1} N P for homestead fields (H)

The effect of crop residue incorporation on grain yield on the bush farm appeared only after approximately 6 years of continuous incorporation, whereas it showed up much earlier in the homestead. APSIM simulations do not reflect benefits of crop residue retention due to improved soil structure (porosity) and water retention capacity. Thus, figures show differences between adding and removing residues that are smaller than might be expected (particularly on the bush farms). Effects of crop residues were also higher with the application of mineral fertilizer on both types of farm. This may be explained by the high C:N ratio of sorghum residue, hence requiring external N input to overcome microbial immobilization of N. It may also account for the higher effect of crop residues in the homestead as compared to the bush farms. Inputs to SOC from root biomass contributed little to the SOC as carbon derived from root biomass are described as highly labile (Balesdent and Balabane,1992) and hence, having high turnover rate with most of it entering the active pool of SOC.

Although farmers are concerned about the deteriorating soil fertility of their fields, the driving force to adopting any soil fertility strategy is that of food security and income growth with increasing the fertility of their soils only as a by-product of these objectives. This was also reported by Snapp et al. (2002) in their study, ‘sustainable soil management options for Malawi: can smallholder farmers grow more legumes?’. This implies that the decreasing trend of soil organic matter as shown by the model per sé may not provide enough incentives for farmers to incorporate crop residues, but rather the evidence of grain yield decline with the continuous reduction of soil carbon content which is, in part, a result of the continuous removal of crop residues. Calculating the benefits of incorporating crop residue would also need to consider its labor requirements. Only farmers with sufficient labor stand to benefit from soil fertility improvements through incorporating crop residue (Defoer et al., 1998). Another draw back which makes incorporating crop residue a less likely practical option is their demand for the sorghum stover as fodder in the dry season and as fuel wood for domestic heating purposes (Mokwunye and Vlek, 1985).

Seasonal variability in grain yield was consistently higher with the removal of crop residues, for the bush and homestead fields, suggesting a more stable grain production with the incorporation of crop residues (Figure 6.11). Similarly, applying fertilizer also reduced temporal variability in grain yield, suggesting fertilizer and organic carbon (manure and crop residues) serve to increase the resilience of the resource base (soil) and temper grain yield variability. This is confirmed by Lithourgidis et al. (2006) in their study in Greece which reported stability in winter wheat yield over 25 years of continuous cultivation which they attributed to annual fertilizer application as well as incorporation of crop residue into the soil after each harvest.

Simulating 29 years of farmer's practice highlights the critical role of mineral fertilizer in maintaining and increasing soil organic carbon on these sandy soils. It offers estimates of the long-term effects of farmers' practices on the resource base (SOC) and its consequent effects on sorghum grain production and hence, on food security. Model outputs can also serve as inputs to long-term economic analysis of the management practices and thus, as a decision tool for and policy makers in the agricultural sector.

Spatial distribution of grain yield

Grain yield ranged from 402 to 1092 kg ha^{-1} with an average grain yield of 673 kg ha^{-1} within the landscape with no application of fertilizers. Variability in grain yield as measured by coefficient of variation was 15 %. Application of 40 and 30 kg ha-1 N and P fertilizers, respectively, yielded sorghum grain from 1314 to 3027 kg ha^{-1} with a mean of 2390 and a coefficient of variation of 14 %.

The pattern of grain yield distribution was similar to that of SOC (top and subsoil), with yield decreasing with increasing distance from the homestead fields located in the southeastern part of the region (Figure 6.12). The model was sensitive to all input parameters as indicated in their significant regression coefficients (Appendix 8.8) and also their correlation coefficients with grain yield with values ranging from 0.95 to 0.71 and SOC showing the strongest relationship. Not surprisingly, increasing sand negatively influenced grain yield and could be probably due to its negative impact on soil water holding capacity of soils. Point data extracted from the spatial maps of all input parameters and grain yield with no fertilizer application were analyzed using a linear regression with grain yield as the dependent variable. Input parameters accounted for 93 % of grain yield variability as indicated by the coefficient of determination. Not accounted for in the yield maps were the interactions between points in 3-dimensional way, which take into account, for instance, runoff.

(a)

(b)

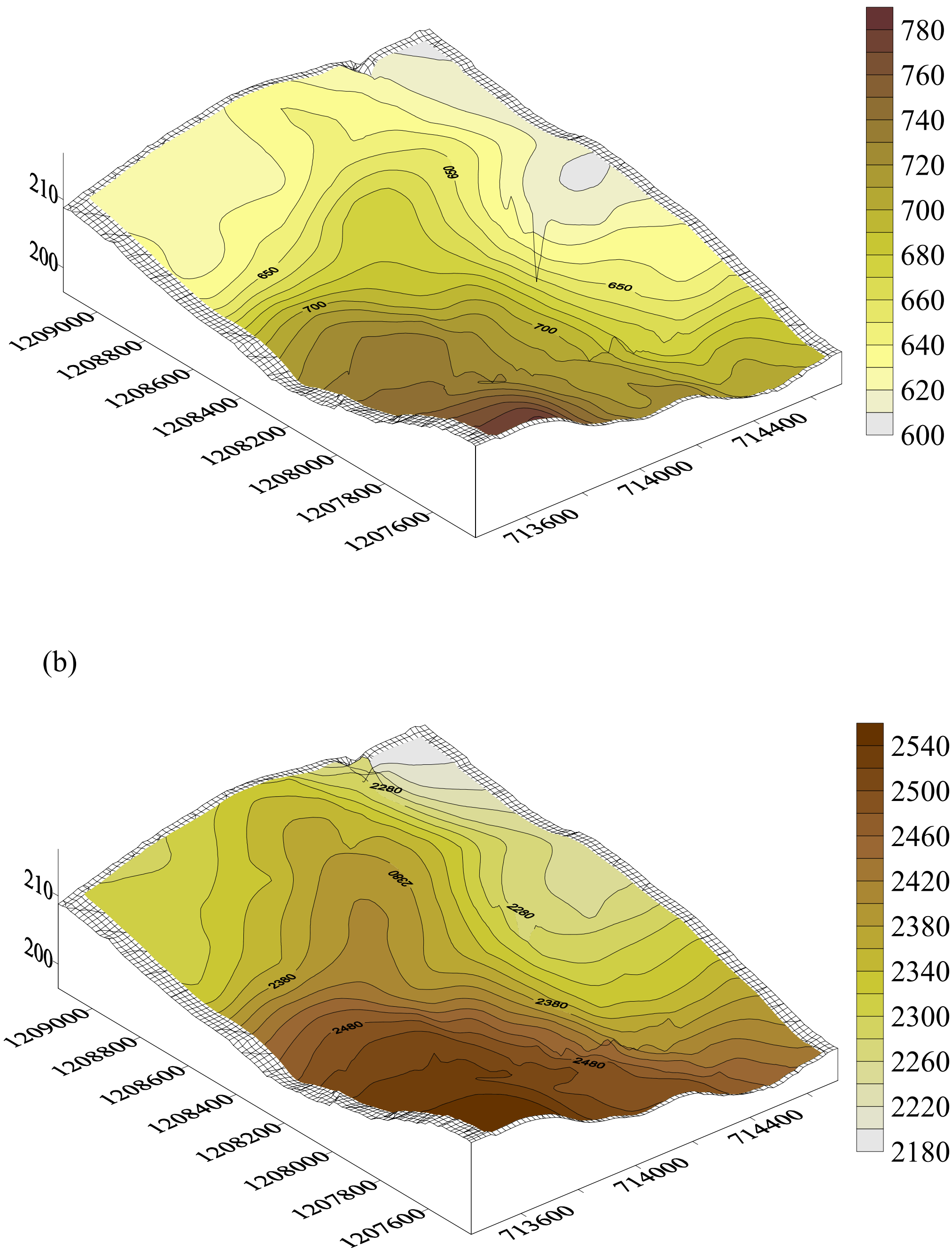


Figure 6.12: Spatial distribution of Sorghum grain yield in the selected landscape. Yield expressed in kg ha^{-1}; x-axis is easting, y-axis is northing and z-axis is height (m). a: simulations without fertilizer application, b: simulation with 40 and 30 kg ha^{-1} N and P (respectively) applied

The model nonetheless illustrates a grain yield pattern in smallholder farmers' fields with similar characteristics to those described by other authors (e.g. Wopereis et al., 2006; Defoer et al., 2000; Prudencio 1983). Not considered in this simulation is variability in soil labile P values, which were not measured for the point data set and were assumed to be the same over the landscape.

6.4 General discussion and conclusions

6.4.1 Fertilizer use efficiency

Agronomic efficiency as an index for fertilizer use efficiency is influenced by management practices and biotic/abiotic stress. In this study, the efficiency of N use generally increased with increasing application of mineral P fertilizer, with the impact higher on the bush farms than on the homestead fields, due to the lower available soil P content there. However, the use of this index for fertilizer use efficiency in contrastin farm types does not give good comparisons, as grain yields under control conditions from these systems differed significantly. In view of this, a partial factor productivity (PF) index should be preferred for comparing different farm types (Dobermann, 2005). The differences in AE in the two farm types argue against the commonly given "blanket" fertilizer recommendations, as responses to N and P differ between systems. Given the high cost of fertilizer and the fact that most farmers are cash-strapped at the beginning of planting season, it would be rational to apply it on the homestead fields, as benefits are higher here. Also Vlek (1990) Kaizzi et al. (2007) and Woperies et al. (2006) recommended the promotion of mineral fertilizer on relatively fertile soils (e.g. homestead fields) rather than on the poorer soils found in the bush farms, when decisions have to be made between the two farm types in environments where it is a scarce resource. However, to maintain or increase food security, cultivation has to be extended to, as well as additionally increased on bush farms by application of mineral fertilizer. Results show that this can also be done in an agronomically efficient way, though less efficient than on the homestead soils. As indicated by this study, the extension of (micro-) credit facilities to farmers for purchasing inputs (fertilizer) is recommended, as its (rational) use is highly profitable. Additionally, in the short term, restoration of some subsidies on inorganic fertilizer may need to be considered by policy and decision makers.

6.4.2 Modeling approach

The P modules of other models such as CENTURY (Metherell et al., 1993) were developed for soils with mainly N- limiting conditions where P dynamics have minor impact on crop growth (Gijsman, 1996). APSIM is suitable for this study area since it was developed with data mainly from the semi arid tropics where resource poor smallholders are faced with P limiting conditions in soils. This model therefore performs well in simulating crop growth and grain yield in this northern Ghana where P is deficient in soils and soil organic matter (organic P) is critical to P nutrition in plants (Abekoe and Tiessen, 1998).

The C:P ratio used to initialize the soil P module varies according to the P concentrations of sequential surface residue additions over the years. This ratio is critical as it determines the net mineralization or immobilization of organic P in these highly weathered tropical soils, particularly in multi-year simulations (Probert, 2004). Also, the accurate estimation of labile P and P sorption capacities play a vital role in simulating yield under P limiting conditions using the APSIM model.

6.4.3 Modeling sorghum growth and grain yield

The predictive performance of the model for grain yield was high with an internal model efficiency of 0.64. Phenology in general as well as delayed phenology that was observed in the bush farms as compared to the homestead farms due to the fertility gradient was well predicted under both farm types. An inaccurate phenology prediction predisposes essential physiological growth processes to be wrongly timed with the wrong dates possibly coinciding with adverse weather conditions. Delayed time to flowering observed under low input (inorganic N and P application) condition in both the homestead and bush farms were exaggerated by the model. This suggests the need for the N and P stress factors influencing phenology to be improved with considerations for highly weathered low input soils. Timsina and Humphreys (2006) reported poor performance of other models in simulating phenology under low N and water deficit conditions in Asia.

Low grain yield prediction by the model in the homestead at low rate of fertilizer use was also reported for maize by Zingore et al. (2006) in their study on evaluating resource management options for African smallholder farms using an integrated modeling approach in semiarid Zimbabwe. They attributed this to poor internal nutrient use efficiency of the maize module of APSIM at low soil N contents. However, the overall modified internal coefficient of efficiency of 0.64 provides sufficient precision for evaluating the long term impact of farmers' management practices on future grain yield production.

6.4.4 Implication of long-term grain yield on future food security in the study region

According to Nyanteng and Asuming-Brempong (2003), widespread food insecurity in the region has manifested itself in widespread high malnutrition and mortality rates. Given a population growth rate of 2.4 % per annum (GSS, 2000), and the fact that current levels of grain yield do not meet the current demand, any further reduction in yield, as indicated by the negative yield trend in the absence of fertilizer application and with crop residue removal poses a great threat to food sufficiency in the region. A negative trend in food production in the area between 1996 and 2000 was indeed reported by Braimoh (2003). Even under favorable climatic conditions adequate yields can not continued to be attained on poor soils (Ogunkunle, 1993) without investment in external inputs particularly inorganic fertilizer as indicated by this study. The model highlighted the critical influence of both inorganic fertilizer and crop residue on reducing the declining trend and temporal variability in sorghum grain production.

7 GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The use of expert knowledge of the farmers was an effective tool in classifying the areas into land-use history categories. The effectiveness, however, depends on the scale of the study. Restoring soil fertility through fallow systems goes beyond leaving land uncultivated to maintain it under continuous vegetation during the fallow period. This is supported by the nutrient stocks in soils under permanent vegetation, which was lower than would be expected. Except for fields located at the homestead that receive annual inputs of organic manure, the stock of nutrients and soil organic carbon decreased with increasing number of years they were under cultivation. Though farmers' management practices resulted in the concentration of nutrients and soil carbon content in the homestead fields, the magnitude of the differences were influenced by availability of organic manure, which in turn is determined by livestock population. The importance of soil organic carbon in managing soil nutrients is underscored by the significant correlations observed between this parameter and soil nutrients. Correlations became weaker under conditions of lower soil nutrient status (bush farms).

The considerable variations observed within the various soils in this study put into question the use of soil mapping units as homogeneous zones for crop management, especially in precision farming. Three factors were identified to have influenced the spatial variations/distribution of soil parameters at the landscape scale, namely; influence of farmers' management activities, farm location within the landscape, and the underlying soil. Soil parameters were characterized by a wide range of spatial distribution models and level of dependencies within the landscape, a phenomenon that complicates the collective precise management of these parameters for agricultural purposes.

The use of inorganic fertilizer on the bush farms was agronomically efficient, though less efficient than that on the homestead farms, though the use of inorganic fertilizer on the bush farms is economically feasible. Applying inorganic P fertilizer increased the efficiency of inorganic N fertilizer in grain yield production, hence P nutrition of soils is critical for the efficient use of inorganic N fertilizer in the study area. Though plants were more responsive to N fertilizer applications, efficiency of inorganic N applied was limited by P deficiency. Inorganic fertilizer use was generally more efficient on the homestead fields than on the bush farms. With the high spatial variability in soil nutrients stocks, the current practice of uniform recommendation of fertilizer application rates needs to be reconsidered. Agronomists and extension officers that deal with farmers also need to take into account the variable nutrient stock in space in recommending rates of inorganic fertilizer.

The APSIM provided a flexible working environment to configure a user-specific model by selecting a set of modules from a collection of crops, soils and utility modules. It successfully captured the effects of inorganic nitrogen and phosphorous fertilizer applications on grain and biomass yield of sorghum for both farm types in the study area. The model demonstrated a gradual decline over the 29-year simulation period on the bush farms, a phenomenon that is counter productive to attaining food sufficiency when population continues to increase (2.4 % per annum). It also illustrated that attaining food sufficiency is not possible with the current practice of removing crop residues from the fields at the end of each cropping season, even with the application of inorganic fertilizer. More so, SOC content in the topsoil (0-15 cm) of the homestead fields, which is an important resource base for crop production particularly on sandy soils (characterized by low external input), declined over the simulation period to levels close to the current levels on the bush farms with the current level of manure application. Thus, land-use activities that contribute to SOC are very critical to the future of crop production, even with fertilizer applications. The model thus provides a sound scientific projection of sorghum grain yield in response to inorganic fertilizer use and SOC dynamics under farmers' management practices.

The APSIM also demonstrated that farmers can reduce temporal variability in grain yield by applying mineral fertilizers. Similarly, incorporating crop residues reduced variation in temporal grain yield on both the homestead fields and the bush farms. Thus factors that limit or reduce stress during crop growth in turn reduce temporal variability in crop yield.

The current management practices of farmers in the study area can not ensure sustainable sorghum grain, and for that matter, food production. Thus, future food security is threatened unless measures are taken to address organic matter content of the soils and the adoption of inorganic fertilizer.

7.2 Recommendations, future outlook

This study indicates that it is economically and agronomically feasible to use inorganic fertilizers for sorghum production in both farm types (homestead fields and bush farms) in the study region. Farmers, however, are often too cash-strapped to purchase inorganic fertilizers. There is therefore the need for policies in the agricultural sector that favor some forms of access to credit facilities to enable farmers to purchase fertilizers. A further study on the interactions between water availability and the efficiency (economic) of inorganic fertilizer on sorghum yield in both farm types could compliment this study.

The higher use efficiency of inorganic fertilizers in the homestead fields as compared to the bush farms emphasizes the importance of organic carbon in improving the efficiency of inorganic fertilizers, thus, the need to promote strategies that improve soil organic carbon. Although the benefits of cover crops have been documented for this region, farmers are reluctant to adopt these systems, because of their intensive nature among other reasons. It is also evident from model simulations that crop production cannot be sustained in the long-term with the continuous removal of crop residues at the end of each season, even with the application of inorganic fertilizers. This calls for research into alternative sources of fuel that can be acceptable to farmers so as to reduce their dependence on crop residues as fuel for domestic purposes.

Since future generations are more at risk of the consequences of the current practice of farmers, there is a need for Government policy interventions in the form of appropriate incentives for farmers to motivate them to use resource conserving technologies (such as cover crops, production of farm yard manure and return of straw to the field). Posterity should not pay the price for current farmers' practices.

Evaluation of the APSIM model revealed its credible performance in predicting both grain and biomass yield of sorghum in response to inorganic fertilizer inputs and in establishing a logical trend in soil organic carbon dynamics. A follow up study, incorporating the collection of time-series biomass accumulation, N and P uptake, soil water dynamics as well as leaf development could further enhance the robustness of its capability to predict plant physiological processes. Given the current robustness, the model can be used to study the impact of various climate change scenarios on future crop production and soil degradation processes. It is recommended to scale-up this study over the sorghum growing area of the whole Volta basin so it can serve as a tool for policy recommendations. It can also serve as input to the decision support systems (DSS) being developed by the GLOWA-Volta project in order to assess the impact of climate change. The incorporation of additional soil degradation processes such as a soil erosion subroutine in future models would further enhance its usefulness as a tool to assess long-term crop production trends in this study region.

8 REFERENCES

Abatania L. and Albert H. 1993. Potentials and constraints in legumes production in the farming systems of Northern Ghana. In: Proceedings of the third workshop on improving farming systems in the interior Savannah Zone of Ghana, Nyankpala Agricultural Experimental Station, NAES, Tamale. 27th-29th April, Nyankpala, Ghana, pp. 170-181.

Abekoe M.K. 1996. Phosphorous fractions and rock phosphate transformations in soils from different landscape positions from northern Ghana. PhD Thesis, University of Saskatoon, Canada.

Abekoe M.K. and Tiessen H. 1998. Fertilizer P transformations and P availability in hillslope soils of Northern Ghana. Nutr. Cycl. Agroecosys. 52: 45-54.

Abekoe M.K. and Tiessen H. 1998. Phosphorous forms, lateritic nodules and soil properties along a hillslope in Northern Ghana. Catena. 33: 1-15.

Adu S.V. 1969. Soils of the Navrongo-Bawku area, Upper Regions of Ghana. Memoir No. 5. Soil Research Institute, Kumasi, Ghana.

African Fertilizer Summit 2006. Achieving an African Green Revolution: A vision of sustainable africultural growth in Africa. Background Papers. 9-13th June Abuja, Nigeria.

Agyare W.A. 2004. Soil characterization and modeling of spatial distribution of saturated hydraulic conductivity at two sites in the Volta Basin of Ghana. PhD Dissertation University of Bonn, Bonn, Germany.

Amissah-Arthur A., Mougenot B. and Loireau M. 2000. Assessing farmland dynamics and land degradation on sahelian landscape using remotely sensed and socio-economic data. Int. J. Geogr. Inf. Sci. 14:6, 583 – 599.

Annan-Afful E. and Wakatsuki T. 2002. Toposequence as influenced by land use in the inland valley watershed of Ashanti region, Ghana. Paper presented at 17th WCSS, Symposium no. 19, paper no. 1146, 14-21 August, Thailand.

Appiah M.A. 1996. Solutions from Sandema? A research report presented to Larentein International Agricultural College in Partial fulfillment of B.Sc. Degree. Deventer.

Armstrong J.S. and Collopy F. 1992. Error measures for generalizing about forecasting methods: Emperical comparisons. Int. J. Forecasting. 8: 69-80.

Arshad M.A. and Coen G.M. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Alternative Agr. 7: 25 - 31.

Asiamah R.D., Senayah J.K. and Adjei-Gyapong T. 1996. Ethno-Pedology surveys in the semi-arid savanna zone of Ghana. Tech. Report No. 185. SRI, Kumasi, Ghana.

Atsivor L., Dowuona G.N. and Adiku S.G.K. 2001. Farming system-induced variability of some soil properties in a sub-humid zone of Ghana. Plant Soil. 236 (1): 83-90.

Bagamsah T.T. 2005. The impact of bushfire on carbon and nutrient stocks as well as albedo in the savanna of northern Ghana. PhD Dissertation. University of Bonn. Bonn, Germany.

Balesdent J. and Balaane M. 1992. Maize root-derived soil organic estimated by 13C natural abundance. Soil Biol. Biochem. 24: 97-101.

Bationo A. and Mokwunye A.U. 1991. Role of manure and crop residues in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. Fert. Res. 29:117-125.

Bationo A., Hartemink A., Lungu O., Naimi M., Okoth P., Smaling E. and Thiombiano L. 2006. African soils: Their productivity and profitability of fertilizer use. Background paper presented at African Fertilizer Summit. Abuja, Nigeria, 6th June.

Bationo A., Mokwunye U., Vlek P.L.G., Koala S. and Shapiro B.I. 2003. Soil fertility management for sustainable land use in the West African Sudano-Sahelian Zone. In: Soil fertility management in Africa: A regional perspective. Academic Science Publishers. African Academy of Sciences, Nairobi, Kenya.

Belanger G., Walsh J.R., Richard J.E., Milburn P.H. and Ziadi N. 2000. Comparison of three statistical models describing potato yield response to nitrogen fertilizer. Agron. J. 92: 902-908.

Bindraban P.S., Stoorvogel J.J., Jansen D.M., Vlaming J. and Groot J.J.R. 2000. Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. Agr. Ecosyst. Environ. 81: 103-112.

Blackmore S., Godwin R.J. and Fountas S. 2003. The analysis of spatial and temporal trends in yield map data over six years. Biosyst. Eng. 84 (4) 455-466.

Boote K.J., Jones J.W. and Hoogenboom G. 1998. Simulation of crop growth: CROPGRO Model. In: Peart R.M. and Curry R.B. (ed.) Agricultural systems and Simulation. Marcel Dekker. Inc., New York, pp. 651-692.

Bowen W.T. and Baethgen W.E. 1998. Simulation as a tool for improving nitrogen management. In: Understanding Options for Agricultural Production. Tsuji G.Y., Hoogenboom G. and Thornton P.K. (Eds.) Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 189-204.

Braimoh A.K. 2003. Modeling land-use change in the Volta Basin of Ghana. PhD Dissertation University of Bonn, Bonn, Germany.

Braimoh A.K. 2004. Seasonal migration and land-use change in Ghana. Land Degrad. Dev. 15 (1): 37-47.

Braimoh A.K. and Vlek P.L.G. 2004. The impact of land-cover change on soil properties in Northern Ghana. Land Degrad. Dev. 15: 65 – 74.

Braimoh A.K. and Vlek P.L.G. 2005. Land cover change trajectories in Northern Ghana. Environ. Manage. 36 (3): 356-373.

Bray I.L. and Kurtz L.T. 1945. Determination of Total Organic and available forms of phosphorous in soils. Soil Science 59: 39-45.

Breman H. and Debrah S.K. 2003. Improving African food security. SAIS Review vol XXIII (Winter-Spring) no. 1, pp.153-170.

Breman H., Fofana B. and Mando A. 2005. The lessons of Drente's 'ESSEN': Soil nutrient depletion in sub-saharan Africa and the management strategies for soil replenishment. Paper presented at IHDP Open meeting session "Impact of land use change on soil resources" Bonn Germany, 11th October.

Bremner J.M. 1996. Nitrogen –Total. In: Sparks D.L. et al. (Ed.) Methods of Soil Analysis. Part. 3. Chemical Methods. SSSA Book Set. 5. SSSA, Madison, WI, pp. 1085-1121.

Brouwer J., Fussell L.K. and Herrmann L. 1993. Soil and crop growth micro variability in the West African semi-arid tropics: a possible risk-reducing factor for subsistence farmers. Agr. Ecosyst. Environ. 45: 229-238.

Bumb B., Teboh J.F., Atta J.K., and Asenso-Okyere W.K. 1994. Ghana: Policy Environment and Fertilizer Sector Development. Technical Bulletin T-41. International Fertilizer Development Center, Muscle Shoals, Alabama.

Caiado M.A.C. 2005. Modeling Fate and Transport of Nitrogen and Phosphorous in crop fields under tropical conditions. PhD Thesis. Virginia Polytechnic and State University.

Cambardella C.A. and Karlen D.K. 1999. Spatial analysis of soil fertility parameters. Precis. Agric. 1: 5-14.

Carberry P.S., Hochman Z., McCown R.L., Dalghliesh N.P., Foale M.A., Poulton P.L., Hargreaves J.N.G., Hargreaves D.M.G., Cawthray S., Hilcoat N., Robertson M.J. 2002. The FARMSCAPE approach to decision support: farmers' advisers', researchers' monitoring, simulation, communication and performance evaluation. Agr. Syst. 74 (1): 141-177.

Carberry P.S., Probert M.E., Dimes J.P., Keating B.A. and McCoown R.L. 2002. Role of modeling in improving nutrient efficiency in cropping systems. Plant Soil. 245: 193-203.

Crawford E.W., Jayne T.S., Kelley A., 2006. Alternative approaches for promoting fertilizer use in Africa. Agriculture and Rural Development. Discussion Paper 22. World Bank, Washington DC.

Dass S., Dang A.K., Singh N.N. and Kumar S. 1997. Morpho-physio-logical basis of breeding drought and low-N tolerant maize genotypes in India. Combining ability for nitrogen use in maize. In Edmeades: G.O., Banziger M., Mickelson H.R. and Pena-Valdivia C.B. (Eds.) Developing drought- and low N-tolerantmaize. Proc. Symp., El Batan, Mexico. 25–29 Mar. 1996. CIMMYT, El Batan, Mexico, pp. 107–111.

Dawidson E. and Nilsson C. 2000. Soil organic carbon in Ghana – Measurements and Modeling. Physical geography department, Seminar Paper no. 77, Lunds Unviversity, Sweden.

De Jager A., Onduru D. and Walaga C. 2003. Using NUTMON to evaluate conventional and low external input farming practices in Kenya and Uganda. In: Struif Boutkes T.E. and Wopereis M.C.S. (Eds.), Decision support tools for smallholder agriculture in Sub-Saharan Africa: A practical guide. IFDC, Muscle Shoals, USA and ACP-EU Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, The Netherlands. pp. 44-53.

Decker W. 1996. Landforms of Muteesa and Zuedema. A qualitative and quantitative analysis.

Deckers J. 2002. A system approach to target balanced nutrient management in soilscapes of Sub-Saharan Africa. In: Vanlauwe B., Diels J., Sanginga N. and Merckx R. (Eds.), Integrated Plant Nutrient Management in Sub-Saharan Africa. From Concepts to Practice. CAB International, Wallingford, Oxon, UK, pp. 47-61.

Defoer T., Budelman A., Toulmin C. and Carter S.E. 2000. Managing soil fertility in the tropics. Building common knowledge: participatory learning and action research (part 1). In: Defoer T. and Budelman A. (Eds.), Managing Soil Fertility in the Tropics. A Resource Guide for Participatory Learning and Action Research. Royal Tropical Institute, Amsterdam, The Netherlands.

Dobermann A. 2005. Nitrogen use efficiency- State of the art. IFA International workshop on enhanced-efficiency fertilizers. Frankfurt, Germany, June 28-30.

Dowuona G.N., Mermut A.R., Adiku S.G.K., Nartey E. and Tete-Mensah I. 1998. Improvements in the quality of soils under agro-forestry practices in Ghana. In: Renard G, Neef A, Baker K and van Oppen M. (Eds.). Soil fertility management in West African land use systems. Margraf Verlag, Filderstadt, Germany, pp 251-258.

Eilitta M. 2006. Achieving an African green revolution: A vision for sustainable agricultural growth in Africa. Background paper presented at African Fertilizer Summit. Abuja, Nigeria, 6th June.

Evans J.P., Smith R.B. and Oglesby R.J. 2004. Middle East climate simulations and dominant precipitation processes. Int. J. Climatol. 24: 1671–1694. DOI: 10.1002/joc.1084.

Fairhust T., Lefroy R., Mutert E. and Batjes N. 1999. The importance, distribution and causes of phosphorus deficiency as a constraint to crop production in the tropics. Agroforestry Forum 9: 2-8.

FAO Statistical Data Base 1998. FAO, Rome. http://apps.fao.org/default.htm. Cited 24 Feb 2004.

FAO 2002. Land degradation assessment in drylands, Rome, Italy.

FAO 2004. FAOSTAT Database--Agricultural Production. http://apps.fao.org. Food and Agriculture Organization of the United Nations, Rome.

Fening J.O., Adjei-Gyapong, T., Yeboah E., Ampontuah E.O., Quansah G. and Danso S.K.A. 2005. Soil fertility status and potential organic inputs for improving smallholder crop production in the interior savanna zone of Ghana. J. Sustain. Agr. 25 (4): 69-92.

Folliard A., Traore P.C.S., Vaksmann M. and Kouressy M. 2004. Modeling Sorghum response to photoperiod: a threshold-hyperbolic approach. Field Crop Res. 89: 59-70.

Forestry Department of Ghana 1998. Annual report of Forestry department of Ghana.

Fortin M.-J. and Dale M.R.T. 2005. Spatial Analysis: A Guide for Ecologists. Cambridge University Press, Cambridge, pp 32-110.

Franzen D.W., Hopkins D.H., Sweeney M.D., Ulmer M.K., and Halvorson A.D. 2002. Evaluation of Soil Survey Scale for Zone Development of Site-Specific Nitrogen Management. Agron. J. 94: 381–389.

Gerikis A. and Baer B. 1999. A computer program for soil textural classification. Soil Sci. Soc. Am. J. 63: 807-808.

Gerner H. and Harris G. 1994. The use and supply of fertilizers in sub-Saharan Africa. In: Van Reuler H., Prins W.H. (Eds.) The role of plant nutrients for sustainable food crop production in sub-Saharan Africa. VKP, Leidschendam, Netherlands.

Geypens M., Vanongeval L., Vogels N. and Meykens J. 1999. Spatial variability of agricultural soil fertility parameters in a Gleyic Podzol of Belgium. Precis. Agric. 1: 319-326.

Ghana Statisistical Services. 2002. 2000 Population and Housing Census. Special Report on 20 largest localities by local authorities. Ghana Statistical Service, Accra, Ghana.

Gijsman A.J., Oberson A., Tiessen H. and Friesen D.K. 1996. Limited applicability of the CENTURY Model to highly weathered Tropical Soils. Agron. J. 88: 894-903.

Godwin D.C. and Singh U. 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping system. In: Tsuji G.Y., Hoogenboom G. and Thornton P.K. (Eds.) Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 55-78.

Gungula D.T., Kling J.G. and Togun A.O. 2003. CERES-Maize Predictions of Maize Phenology under Nitrogen-Stressed Conditions in Nigeria. Agron. J. 95:892–899.

Haefele S.M. and Wopereis M.C.S. 2005. Spatial variability of indigenous supplies for N, P and K and its impact on fertilizer strategies for irrigated rice in West Africa. Plant Soil 270 (1): 57 -90.

Haileslassie A., Priess A.J., Veldkamp E., Teketay D. and Lesschen J.P. 2005. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. Agr. Ecosyst. Environ. 108 (1): 1-16.

Halm A.T. and Dartey K. 1991. Efficient fertilizer use for increased crop production: The Ghana experience. In: Mokwunye A.U. (Ed.) Alleviating soil fertility constraints to increased crop production in West Africa. Kluwer Academic Publishers, pp. 139-148.

Hamilton L.C. 1990. Modern data analysis: a first course in applied statistics. Pacific Groove, Brooks/Cole Pub. Co., California.

Hedley M.J., Stewart J.W.B. and B.S. Chauhan 1982. Changes inorganic and organic fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46:970-976.

Helmke P.A. and Sparks D.L. 1996. Methods of soil analysis. Part 3. Chemical methods - Soil science society of America. Book series no. 5. Madison, Wisconsin, USA.

Henao J. and Baanante C.A. 1999. Estimating rates of nutrient depletion in soils of Africa. International Food Policy Research Institute, USA.

Heng L.K., Asseng S., Mejahed K.E.L., Rusan M.M. and Keerthisinghe G. 2004. Optimizing wheat productivity under extreme dry rainfed environments of West-Asia-North Africa (WANA) using APSIM. Technical Document for International Atomic Energy Agency, Vienna, Austria. In: 8th European Society for Agronomy Congress. Copenhagen, Denmark. July 2004.

Hengsdijk H. and van Keulen H. 2002. The effect of temporal variation on inputs and outputs of future-oriented land use systems in West Africa. Agr. Ecosyst. Environ. 91 (1-3): 245 – 259.

Hilhorst T. and Muchena F. (Eds.) 2000. Nutrients on the move. Soil fertility dynamics in African farming systems. IIED, London.

Hillel D. 1998. Environmental soil physics. Academy Press, New York.

Hoffmann I., Gerling D., Kyiogwom U.B. and Mané-Bielfeldt A. 2001. Farmers' management strategies to maintain soil fertility in a remote area in northwest Nigeria. Agr. Ecosyst. Environ. 86 (3): 263 – 275.

Hoogenboom G., Wilkens P.W. and Tsuji G.Y. (Eds.) 1999. DSSAT version 3 (4). International Consortium for Agricultural Systems application. University of Hawaii.

Isaaks E.H. and Srivastava R.M. 1989. An introduction to applied geostatistics. Oxford University Press, New York.

Jame Y.W. and Cutforth H.W. 1996. Crop growth models for decision support systems. Can. J. Plant Sci. 76: 9–19.

Jones C.A., and Kiniry J.R. 1986. CERES-Maize. A simulation model of maize growth and development. Texas A&M Univ. Press, College Station, TX.

Jones J.W., Hoogenboom G., Porter C.H., Boote K.J., Batchelor W.D., Hunt L.A., Wilkens P.W., Singh U., Gijsman A. and Ritche J.T. 2003. The DSSAT cropping system model. Eur. J. Agron. 18: 235-265.

Jones J.W., Keating B.A. and Porter C.H. 2001. Approaches to modular model development. Agr. Syst. 70: 421-443.

Journel A.G. and Huijbregts C.J. 1978. Mining geostatistics. Academic Press. London.

Kaizzi K.C. 2002. The potential benefit of green manures and inorganic fertilizers in cereal production on contrasting soils in eastern Uganda. PhD Dissertation University of Bonn, Bonn, Germany.

Kaizzi K.C., Byalebeka J., Wortmann C.S., Mamo M. 2007. Low Input Approaches for Soil Fertility Management in Semiarid Eastern Uganda. Agron. J. 99: 847-853.

Kanabo I.A.K., Halm A.T. and Obeng H.B. 1978. Phosphorus adsorption by surface samples of five iron pan soils of Ghana. Geoderma 20: 299–306.

Kasei C.N. 1990. A synopsis on the North of Ghana. Presented at the 2nd Workshop on improving farming systems in the savannah zone of Ghana. April 24-26, 1990. Nyankpala Agricultural College. Nyankpala – Tamale, Ghana.

Keating B.A. and McCown R.L. 2001. Advances in farming systems analysis and intervention. Agr. Syst. 70 (2-3): 555-579.

Keating B.A., Carberry P.S., Hammer G.L., Probert M.E., Robertson M.J., Holzworth D., Huth N.I., Hargreaves J.N.G., Meinke H., Hochman Z., Mclean G., Verburg K., Snow V., Dimes J.P., Silburn M., Wang .E, Brown S., Bristow K.L., Asseng S., Chapman S., Mccown R.L., Freebairn D.M. and Smith C.J. 2003. An Overview of Apsim, a Model Designed for Farming Systems Simulation. Eur. J. Agron. 18: 267-288.

Lagacherie P., Cazemier D.R., Martin-Clouaire R. and Wassenaar T. 2000. A spatial approach using imprecise soil data for modeling crop yield over vast areas. Agr. Ecosyst. Environ. 81: 5-16.

Landon J.R. 1991. Booker Tropical soil manual. A handbook for soil survey and Agricultural land evaluation in the tropics and subtropics. Longman, London, UK.

Le Mare P.H., Pereira J. and Goedert W.J. 1987. Effects of green manure on isotopically exchangeable phosphate in a dark-red Latosol in Brazil. J. Soil Sci. 38: 199 – 209.

Legates D.R. and McCabe G.J. 1999. Evaluating the use of 'goodness-of-fit' measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35: 233-241.

Legendre P., Dale M.R.T., Fortin M.J., Gurevitch J., Hohn M., and Myers D. 2002. The consequences of spatial structure for the design and analysis of ecological field surveys. Ecography 25: 601–615.

Lithourgidis A.S., Damalas C.A. and Gagianas A.A. 2006. Long-term yield patterns for continous winter wheat cropping in northern Greece. Eur. J. Agron. 25: 208-214.

Littleboy M., Silburn D.M., Freebairn D.M., Woodruff D.R. and Hammer G.L. 1989. PERFECT-A computer simulation model of productivity erosion runoff functions to evaluate conservation techniques Queensland department of primary industries Bullentin, QB89005.

Littleboy M., Freebairn D.M., Hammer G.L. and Silburn D.M.1992. Impact of soil erosion on production in cropping systems. I: Development and validation of a simulation model. Aust. J. Soil Res. 30:757-774.

López-Granados F., Jurado-Expósito M., Atenciano S., García-Ferrer A., Sánchez de la Orden M. and García-Torres L. 2002. Spatial variability of agricultural soil parameters in southern Spain. Plant Soil 246 (1): 97 - 105.

Ludwig F. and Asseng S. 2006. Climate change impacts on Wheat production in a Mediterranean environment in West Australia. Agr. Syst. 90(1-3): 159-179.

Makridakis S. 1993. Accuracy measures: Theoretical and practical concerns. Int. J. Forecasting 9: 527-529.

Mallarino A.P., Oyarzabal E.S. and Hinz P.N. 1999. Interpreting within-field relationships between crop yields and soil and plant variables using factor analysis. Precis. Agric. 1: 15-26.

Manu A., Bationo A. and Geiger S.C. 1991. Fertility status of selected millet producing soils of West Africa with emphasis on phosphorous. Soil Sci. 152: 315-320

Mapfumo P., Giller K.E. and Mimeo A.P. 2001. Soil fertility management and practices by smallholder farmers in semi-arid areas of Zimbabwe. ICRISAT/FAO, Patancheru, AP. Mimeo.

Mavromatis T., Boote K.J., Jones J.W., Irmak A. Shinde D and Hoogenboom G. 2001. Developing Genetic Coefficients for crop simulation Models with Data from Crop performance trials. Crop Sci. 41: 40-51.

Meinke H., Stone R.C. and Hammer G.L. 1996. Using SOI phases to forecast climatic risk to peanut production: a case study for the northern Australia. Int. J. Climatol. 16: 783-789.

Mengel K., Hutsch B. and Kane Y. 2006. Nitrogen fertilizer application rates on cereal crop according to available mineral and organic soil nitrogen. Eur. J. Agron. 24 (4): 343-348.

Menz G. and Bethke M. 2000. Vegetation map of Ghana. Regionalization of the IGBP Global Land Cover Map for Western Africa (Ghana, Togo and Benin). In: Proceedings of the 20th EARSeL-Symposium, June, 200, Dresden. Remote Sensing Research Group. Institute of Geograghy. University of Bonn, Germany, 6.

Metherell A.K., Harding L.A., Cole C.V. and Parton W.J. 1993. CENTURY soil organic model environment. Technical documentation agroecosystem version 4.0. Great Plains System Res. Unit, Tech Rep. 4. USDA-ARS, Fort Collins, CO.

Mokwunye A.U. and Vlek, P.L.G. 1985. Developments in plant and soil sciences: Management of Nitrogen and Phosphorous fertilizers in Sub-Saharan Africa. Proceedings of a symposium, held in Lome, Togo, March 25-28, 1985. IFDC, Togo.

Monreal C.M., Dinel H., Schnitzer M., Gamble D.S. and Biederbeck V.O. 1998. Impacts of carbon sequestration on functional indicators of soil quality as influenced by management in sustainable agriculture. In: Lal R. and Stewart B.A. (Eds.) Soil processes and the carbon cycle. Lewis Pub, CRC Press, Roca Baton, Florida.

Moore D.S. and McCabe G.P. 1993. Introduction to the practice of Statistics, Second edn. Freeman, New York, pp. 854.

Mulla D.J. and McBratney A.B. 2000. Soil spatial variability. In: Sumner M.E. (Ed) Handbook of soil science. CRC Press LLC, Boca Raton.

Murty D.S., Nwasike C.C. and Atokple I.D.K. 1998. Registration of 'ICSV III' Sorghum Cultivar. Crop Sci. 38: 1716-1717.

Mushayi P., Waddington S.R. and Chiduza C. 1999. Low efficiency of Nitrogen use by maize on smallholder farms in sub-humid Zimbabwe, Maize Production Technology for the future: Challenges and Opportunities. Proceedings of the sixth Eastern and Southern African Regional maize conference, 21-25 September 1998. CIMMYT and EARO, Addis Ababa, pp. 278-281.

Mwangi W.M. 1997. Low use of fertilizers and low productivity in Sub-Saharan Africa. Nutr. Cycl. Agroecosyst. 47: 135-147.

Nandwa S.M. and Bekunda M.A. 1998. Research on nutrient flows and balances in East and Southern Africa: state-of-the-art. Agr. Ecosyst. Environ. 71: 5-18.

Nash J.E. and Sutcliffe J.V. 1970. River flow forecasting through conceptual models part I – discussionn of principles. J. Hydrol. 10 (3): 282–290.

Nelson R.A., Dimes J.P., Silburn D.M., Paningbatan E.P., and Cramb R.A. 1998. Erosion/productivity modeling of maize farming in the Philippine uplands Part II: Simulation of alternative farming methods. Agr. Syst. 58 (2):147-163.

Nicholson S.E., Ba M.B. and Kim J.Y., 1996. Rainfall in the Sahel during 1994. J. Climate. 9(7):1673-1676.

Nicholson S.E., Some B. and Kone B. 2000. Analysis of recent rainfall conditions in West Africa, including the raining seasons of the 1997 El Nino and the La Nina years. J. Climate. 13: 2628 – 2640.

Nwoke O.C., Vanlauwe B., Diels J., Sangginga N. and Osonubi O. 2004. The distribution of phosphorous fractions and desorption characteristics of some soils in the moist savanna zone of West Africa., Nutr. Cycl. Agroecosyst. 69: 127-141.

Nyanteng V.K. and Asuming-Brempong S. 2003. The role of Agriculture in Food security in Ghana. Roles of Agriculture Project International Conference. 20-22 October, 2003 Rome, Italy.

Nye P.H. and Bertheux M.H. 1957. The distribution of phosphorous in forest and savannh soils of the Gold Coast and its significance. J. Agric. Sci. Camb. 49: 141-150.

Nye P.H. and Stephens D. 1962. Soil fertility. In: Wills J.G. (Ed.) Agriculture and land use in Ghana. Oxford University Press, London, pp 127-143.

Nziguheba G., Merckx R., Palm C.A. and Rao M.R. 2000. Organic residues affect phosphorous availability and maize yields in Nitisol of Western Kenya. Biol. Fert. Soils 32: 328 – 339.

Nziguheba G., Palm C.A., Buresh R.J. and Smithson P.C. 1998. Soil phosphorous fractions and adsorption as affected by organic and inorganic sources. Plant Soil 198: 159 – 168.

Odeh I.O.A., McBratney A.B. and Chittleborough D.J. 1994. Spatial prediction of soil properties from landform attributes derived from a digital elevation model. Geoderma 63: 197-214.

Ogunkunle A.O. 1993. Soil in land suitability evaluation: an example with oil palm in Nigeria. Soil Use Manage. 9: 37-42.

Okalebo, J.R., Simpson, J.R. and Probert M.E. 1992. Phosphorous status of cropland soils in the semi-arid areas of Machakos and Kitui Districts of Kenya. In: Probert, M.E. (Ed.). A search for strategies for sustainable dryland cropping in semi-arid eastern Kenya. Proceedings of a Symposium held in Nairobi , kenya , 10-11 December 1990. ACIAR Proceedings No. 41, 138 pp.

Oldeman L.R., Hakkeling R.T.A. and Sombroek W.G. 1991. World Map of the Status of Human-Induced Soil Degradation. An Explanatory Note, second revised version. Global Assessment of Soil Degradation. ISRIC, Wageningen, The Netherlands.

Oldeman L.R., Hakkeling R.T.A. and Sombroek W.G. 1992. World Map of the status of Human-Induced soil degradation: An explanatory Note, ISRIC, Wageningen, The Netherlands.

Onofiok O.E. 1993. Determination of spatial and temporal variations in soil organic matter in tropical soil using different sampling schemes. In: Mulongoy K. and Merckx R. (Eds.) Soil organic matter dynamics and sustainability of tropical agriculture. John Wiley and Sons, New York, pp. 65-74.

Overseas Development Institute. 1999. Rethinking Natural Resources Degradation in semi-arid Sub-Saharan Africa: The case of semi-arid Ghana. ODI Rural Policy and Environment Group, London.

Owusu-Bennoah E. Acquaye D.K. and Abekoe M. 1991. Efficient fertilizer use for increased crop production: Use of phosphorous fertilizers in concretional soils of Northern Ghana. In: Mokwunye A.U. (Ed.) Alleviating soil fertility constraints to increased crop production in West Africa. Kluwer Academic Publishers, pp. 149-154.

Owusu-Bennoah E. and Acquaye D.K. 1989. Phosphate sorption characteristics of selected major Ghanaian soils. Soil Sci. 148: 114-123.

Page A.L., Miller R.H. and Keeney D.R. 1982. Nitrogen-inorganic forms. Methods of soil analysis. No. 9, part 2. American Society of Agronomy Inc., and Soil Science Society of America Inc., Madison, Winconsin, pp. 643 – 698.

Park S.J. and Vlek P.L.G. 2002. Environmental correlation of three dimensional spatial soil variability: A comparison of three adaptive techniques. Geoderma 109: 117 – 140.

Park S.J., Hwang C.S. and Vlek P.L.G. 2005. Comparison of adaptive techniques to predict crop yield response under varying soil and land management conditions. Agr. Syst. 85(1): 59-81.

Parton W.J., Schimel D.S., Cole C.V. and Ojima D.S. 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Sci. Soc. Am. J. 51: 1173-1179.

Pierce F.J. and Nowak P. 1999. Aspects of precision agriculture. Adv. Agron. 67:1-85.

Piha M.I. 1993. Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp. Agr. 29: 405-415.

Pingali P.L. and Heisey P.W. 1999. Cereal crop productivity in developing countries: Past and future prospects. Economics: Working paper 99-03, CIMMYT, Mexico D.F.

Prendergast J.B. 1992. A model of crop yield response to irrigation water salinity: theory, testing and application. Irrigation Sci. 13: 157-164.

Probert M.E. 2004. A capability to model P response in crops. In: Delve R.J. and Probert M.E. (Eds.) Modeling nutrient management in tropical cropping systems. ACIAR Proceedings No. 114, pp. 92-100.

Probert M.E., Dimes J.P., Keating B.A., Dalal R.C. and Strong W.M. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water in fallow systems. Agr. Syst. 56 (1): 1-28.

Prudencio C.Y. 1983. A village study of soil fertility management and food production in Upper-Volta. Technical and Economic analysis. PhD. Thesis, University of Arizona, USA.

Prudencio C.Y. 1993.Ring management of soils and crops in the West African semi-arid tropics: The case of the Mossi farming system in Burkina Faso. Agr. Ecosyst. Environ. 47: 237–264.

Ramisch J.J. 2005. Inequality, agro-pastoral exchanges, and soil fertility gradients in Southern Mali. Agr. Ecosyst. Environ. 105: 353-372.

Rhodes E.R. 1995. Nutrient Depletion by Food Crops in Ghana and Soil organic nitrogen management. Agr. Syst. 48:101-118.

Ritchie J.T. 1998. Soil water balance and plant water stress. In: Tsuji G.Y., Hoogenboom G. and Thornton P.K. (Eds.) Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41-54.

Ritchie J.T., Singh U., Godwin D.C. and Bowen W.T. 1998. Cereal growth, development and yield. In: Tsuji G.Y., Hoogenboom G. and Thornton P.K. (Eds.) Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 79-98.

Rowe E.C., van Wijk M.T., de Ridder N. and Giller K.E. 2006. Nutrient allocation strategies across a simplified heterogeneous African smallholder farm. Agr. Ecosyst.Environ. 116: 60–71.

Ruecker G.R. 2005. Spatial variability of soils on national and hillslope scale in Uganda. PhD Dissertation University of Bonn, Bonn, Germany.

Ruecker G.R., Park S.J., Ssali H. and Pender J. 2003. Strategic targeting of development plicies to a complex region: A GIS-based stratification applied to Uganda. ZEF- Discussion Papers on Development Policy, Center for Development Research, Bonn, Germany, No. 69.

Sadler E.J., Bauer P.J. and Busscher W.J. 2000. Site-Specific Analysis of a Droughted Corn Crop: I. Growth and Grain Yield. Agron. J. 92: 395-402.

Sanchez P.A. 2002. Soil fertility and hanger in Africa. Science 295: 2019–2020.

Sanchez P.A., Shepherd K.D., Soule M.J., Place F.M., Buresh R.J., Izac A-M.N., Mokwunye A.U., Kwesiga F.R., Ndiritu C.G. and Woomer P.L. 1997. Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh R.J., Sanchez P.A., and Calhoun F. (Eds.) Replenishing soil fertility in Africa. SSSA and ASA, Madison, WI, USA, pp 1–46

Saxton K.E., Rawls W.J., Romberger J.S. and Papendick R.I. 1986. Estimating generalised soil water characteristics from texture. Soil Sci. Soc. Am. J. 50: 1031-1035.

Scherr S.J. 1999. "Past and present effects of soil degradation" In: Scherr S.J. (Eds.) Soil degradation- A threat to developing country food security by 2020. International Food Policy Research Institute 2020 Discussion Paper 27, Washington DC., pp. 13-30.

Schippack W. and Abdulai M.S. 1992. Sorghum and Millet improvement in Ghana. In: Acquaye, D.K. (Ed.) Improving farming systems in the interior Savannah zone of Ghana. Nyankpala Agricultural Research Report (8). Annual Report. Nyankpala, Ghana, pp. 1-2.

Scoones I. and Toulmin C. 1999. Policies for soil fertility management in Africa. Report prepared for the department for international development. IDS, IIED, Brighton.

Seeling B. and Zasoski R.J. 1993. Microbial effects in maintaining organic and inorganic solution phosphorous concentrations in a grassland topsoil. Plant Soil 148: 277–284.

Semenov M.A. and Brooks R.J. 1999. Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain. Climate Res. 11: 137-148.

Shaffer M.J., Gupta S.C., Linden D.R., Molina J.A.E., Clapp L.E. and Larson W.E. 1983. Simulation of nitrogen, tillage, and residue management effects on soil fertility. In: Lauenroth W.K., Skogerboe G.V., Flug M. (Eds.) Analysis of ecological systems: State-of-the-art in Ecological Modeling. Elsevier, New York.

Sinja S., Buerkert A., El-Hajj G., Bationo A., Traore H. and Frossard E. 2001. Effects of fertility management strategies on phosphorous bioavailability in four West African soils. Plant Soil 233: 71-83.

Six Y., Conant R.T., Paul E.A. and Paustian K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241: 115-176.

Smalberger S.A., Singh U., Chien S.H., Henao J. and Wilkens P.W. 2006. Development and validation of a phosphate rock decision support system. Agron. J. 98: 471-483.

Smeck N.E. 1985. Phosphorous dynamics in soils and landscapes. Geoderma 58: 185-189.

Snapp S.S., Rohrbach D.D., Simtowe F. and Freeman H.A. 2002. Sustainable soil management options for Malawi: can smallholder farmers grow more legumes? Agr. Ecosyst. Environ. 91: 159-174.

Sokal R.R. and Rohlf F.J. 1995. Biometry, 3rd ed. Freeman W.H. and Company, New York.

Steiner J.L., Williams J.R. and Jones O.R. 1987. Evaluation of EPIC simulation model using dryland wheat-sorghum-fallow crop rotation. Agron. J. 79: 732-738.

Stephens W. and Middleton T. 2002. Why has the uptake of decision support systems been so poor? In: Matthews, R. and Stephens W. (Ed.) Crop-soil simulation models. 129-147. CAB International, Wallingford, UK, pp. 129-147.

Stoorvogel J.J. and Smaling E.M.A. 1990. Assessment of Soil Nutrient Depletion in sub-Saharan Africa. Winand Staring Centre, Wageningen, the Netherlands.

Stoorvogel J.J., Smailing E.M.A., Janssen B.H. 1993. Calculating soil nutrient balances in Africa at different scales. II Supra-national scale. Fert. Res. 35: 227-235.

Taylor C.J. 1952. The vegetation zones of the Gold Coast. Accra. Forestry Department Bulletin No 4.

Tiessen H. and Moir J.O. 1993. Characterization of available P by sequential extraction. In: Carter M.R. (Ed.) Soil sampling and methods and analysis. Canadian Society of soil science (Lewis Publishers), Boca Raton, Florida, pp. 75-86.

Tiessen H., Salcedo I.H. and Sampaio E.V.S.B. 1992. Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. Agr. Ecosyst. Environ. 38: 139-151.

Tiessen H., Stewart J.W.B. and Cole C.V. 1984. Pathways of phosphorous transformation in soils of differing pedogenesis. Soil Sci Soc. Am. J. 48: 853-858.

Timsina J. and Humphreys E. 2006. Performance of CERES-Rice and CERES-Wheat models in rice-wheat systems: A review. Agr. Syst. 90: 5-31.

Tirol-Padre A. and Ladha J.K. 2004. Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Sci. Soc. Am. J. 68:969-978.

Tittonell P.B., Vanlauwe B., Leffelaar P.A., Rowe and E.C. and Giller K.E. 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agr. Ecosyst. Environ. 110:149 – 165.

Tittonell P.B., Vanlauwe B., Leffelaar P.A., Shepherd K.D. and Giller K.E. 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within farm variability in resource allocation, nutrient flows and soil fertility status. Agr. Ecosyst. Environ. 110:166 – 184.

Triantafilis J., Odeh I.O.A. and McBratney A.B. 2001. Five geostatistical models to predict soil salinity from electromagnetic induction data across irrigated cotton. Soil Sci. Soc. Am. J. 65: 869-878.

Van Ittersum M.K., Howden S.M. and Asseng S. 2003. Sensitivity of productions and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO2, temperature and precipitation. Agr. Ecosyst. Environ. 97 (1-3): 255-273.

van Lynden G.W.J. (Ed.) 1995. Guidelines for the Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD). ISRIC, Wageningen, The Netherlands.

Vanlauwe B. and Giller K.E. 2006. Popular myths around soil fertility management in sub-Saharan Africa. Agr. Ecosyst. Environ. 116: 34–46.

Vitousek P.M., Mooney H.A., Lubchenco J. and Melillo J.M. 1997. Human Domination of Earth's Ecosystems. Science 277: 494-499.

Vlek P.L.G. 1990. The role of fertilizers in sustaining agriculture in Sub-Saharan Africa. Fert. Res. 26:327-339.

Vlek P.L.G. 1993. Strategies for sustaining agriculture in sub-Saharan Africa: The fertilizer technology issue. In: Technologies for sustainable agriculture in the tropics. , pp. 265-277. ASA, Special publication, 58, Madison, WI, USA.

Vlek P.L.G., Kühne R.F. and Denich M. 1997. Nutrient resources for crop production in the tropics. Phil. Trans. R. Soc. Lond. B. 352: 975-985.

Walker T.S. and Ryan J.G. 1990. Village and household economies in India's Semi arid Tropics. John Hopkins University Press, Baltimore, Maryland, USA.

Webster R. and Oliver M.A. 1990. Statistical Methods in Soil and Land Resource Survey. Oxford University Press.

Williams J.R. 1983 EPIC: The Erosion-productivity Impact Calculator, Vol 1. Model Documentation. Agricultural Research Service, United States Department of Agriculture.

Willmott C.J. 1996. Smart interpolation of climate variables. Third International Conference/Workshop on Integrating GIS and Environmental Modeling. http://www.sbg.ac.at/geo/idrisi/gis_environmental_modeling/sf_papers/willmott_cort/willmott_mon1.htm. Cited 15 Dec 1999.

Willmott C.J., Rowe C.M. and Mintz Y. 1985. Climatology of the terrestrial seasonal water cycle. J. Climatol. 5: 589- 606.

Wolf J. and van Keulen H. 1989. Modeling long-term crop response to fertilizer and soil Nitrogen. II. Comparison with field results. Plant Soil 120: 23-38.

Wong A.T.F. and Asseng S. 2006. Determining the Causes of Spatial and Temporal Variability of Wheat Yields at Sub-field Scale Using a New Method of Upscaling a Crop Model. Plant Soil 283(1-2): 203–215.

Wopereis M.C.S., Tamelokpo A., Ezui K., Gnakpenou D., Fofana B. and Breman H. 2006. Mineral fertilizer management of maize on farmer fields in differing in organic inputs in the West African Savanna. Field Crop Res. 96 (2-3): 355-362.

Zhang X. and Evans P.E. 2003. Crop yield response to pasture and legumes in a pasture – crop rotation. Proceedings of 11th Australian Agronomy Conference: 'solutions for a new environment'. Geelong, Australia.

Zingore S. 2006. Exploring diversity within smallholder farming systems in Zimbabwe: Nutrient use efficiencies and resource management strategies for crop production. PhD Thesis. Wageningen University. Wageningen, The Netherlands.

Zingore S., Murwira H.K., Delve R.J. and Giller K.E. 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agr. Ecosyst Environ. 119 (1-2): 112-126.

Zougmore R.B. 2003. Integrated water and nutrient management for sorghum production in semi-arid Burkina Faso. Phd Thesis, Wageningen University, The Netherlands.

9 APPENDICES

Appendix 9.1: Calculation procedure for fertilizer rates per plot

Calculation of Fertilizer rates per plot

To determine the amount of each of the straight fertilizers to apply to each plot, the formula below in Equation 1, was used:

$$\text{Amount of fertilizer per plot} = \frac{\text{Nutrient rate (kg ha}^{-1}\text{) x plot area in m}^2}{\text{Percentage nutrient in fertilizer x 100}}$$

Taking treatment 3 for example, N, P and K were required in the quantities of 40, 30, 60 kg ha^{-1}.

With a nutrient rate of 40 kg/ha N, a plot area of 30 square meters and AS with 21% N as nitrogen fertilizer the calculation,

Amount of AS needed per plot: $\frac{40 \times 30}{21 \times 100}$

= 0.57 kg of ammonia sulphate needed per plot

With a nutrient rate of 30 kg/ha P, a plot area of 30 square meters and TSP with 20.07% P as phosphorous fertilizer the calculation,

Amount of TSP needed per plot: $\frac{30 \times 30}{20.07 \times 100}$

= 0.45 kg of TSP needed per plot

With a nutrient rate of 60 kg/ha K, a plot area of 30 square meters and KCl with 49.8% K as potassium fertilizer the calculation,

Amount of KCl needed per plot: $\frac{60 \times 30}{49.8 \times 100}$

= 0.36 kg of ammonia sulphate needed per plot

Appendix 9.2: Brief description of laboratory analysis

Soil pH

The pH of the soil was determined by using 0.0IM $CaCl_2$ solution with a ratio of 1:2.5 following the method of Thomas (1996).

Nitrogen

Total nitrogen content of soil samples was determined using the Kjeldahl method (Bremner, 1996).

Available phosphorus

The Bray 1 extraction solution (0.025M HCl and 0.03M NH_4Fl) and procedure was used. The measurement of P was done by the phospho-molybdate blue complex, which is ammonium molybdate and Potassium antimonate tartrate with ascorbic acid as the reducing agent to the blue complex (Bray and Kurtz, 1945).

Cation exchangeable capacity (CEC)

Soil CEC gives an indication of the soil's nutrient retention capacity. It is influenced by clay mineralogy, organic matter and pH. Silver –thiourea (AgTu) acts as a large cation with single positive charge and thus can be used to displace the adsorbed cations (Equation below). Therefore, 25 ml of 0.01M AgTu solution was added to 10g of soil and shaken for 30 minutes and filtered with Whatman 42 filter paper. The cations Ca^{2+}, Mg^{2+}, K^+, H^+, Al^{3+} in the filtrate were measured by AAS, flame photometer, and by titration (Helmke and Sparks 1996).

$$\text{Soil (Ca,Mg,K,Na,Al)} + \text{AgTu}^{(+)} \rightarrow \text{AgTu-Soil} + Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}$$

The equivalent charges of the individual cations were summed up to obtain the CEC:

$$\text{CEC} = \frac{mgCa/kgsoil}{200.4} + \frac{mgMg/kgsoil}{121.6} + \frac{mgK/kgsoil}{391.0} + Al^{3+}\text{ cmol} + H^{+}\text{ cmol}$$

Organic Carbon

In highly weathered soils of the tropics, the soil organic carbon (SOC) stock is an indication of the soils capacity to support crop production. It also influences other soil properties such as CEC, water holding capacity and erodibility. To determine SOC, a known concentration of potassium dichromate was added in excess. The excess un-reacted dichromate was determined by titrating it with ammonium iron (II) sulphate in a redox reaction using diphenylamine indicator. The amount of reduced $Cr_2O_7^{2-}$ is quantitatively related to organic C present in soil sample (Nelson and Sommers, 1996).

$$2Cr_2O_7^{-} + 3C + 16H^{+} \text{----------} 4Cr^{3+} + 3CO_2 + 8H_20$$

$$Cr_2O_7^{-} + 6Fe^{2+} + 14H^{+} \text{----------} 2Cr^{3+} + 6Fe^{3+} + 7H_20$$

$$\text{\% organic carbon} = \frac{M(V_1 - V_2) \times 0.39}{S}$$

where M is molarity of potassium dichromate, V_1 is blank titration, V_2 is sample titration and S is weight of soil sample. The factor 0.39 is a constant and takes into account the incomplete combustion of organic. The organic carbon content is multiplied by a factor of 1.724 to obtain the soil organic matter (SOM) content, assuming that SOM contains 0.58 % SOC.

Appendix 9.3a: Kolmogorov-Simirnov normality test statistics and probability values of soil parameters, from the 1 x 1.5km landscape

Soil parameter	Soils	N	Top soil (K-S normality)		Sub soil (K-S normality)	
			Statistics	P	Statistics	P
pH	EGR	106	0.077	0.118	0.145	0.001
	ESP	32	0.104	0.200	0.116	0.200
	EG	21	0.194	0.039	0.243	0.003
	GA	8	0.198	0.200	0.241	0.183
	EP	9	0.318	0.009	0.192	0.200
SOC	EGR	106	0.113	0.002	0.172	0.001
	ESP	32	0.150	0.067	0.208	0.001
	EG	21	0.127	0.200	0.156	0.200
	GA	8	0.248	0.158	0.249	0.153
	EP	9	0.218	0.200	0.330	0.005
Total N	EGR	106	0.424	0.001	0.239	0.001
	ESP	32	0.264	0.001	0.232	0.001
	EG	21	0.129	0.200	0.214	0.013
	GA	8	0.194	0.200	0.280	0.065
	EP	9	0.195	0.200	0.348	0.002
$P_{available}$	EGR	106	0.208	0.001	0.121	0.001
	ESP	32	0.173	0.015	0.341	0.001
	EG	21	0.209	0.200	0.140	0.200
	GA	8	0.264	0.104	0.430	0.001
	EP	9	0.417	0.001	0.468	0.001
$K_{available}$	EGR	106	0.143	0.001	0.149	0.001
	ESP	32	0.160	0.037	0.283	0.001
	EG	21	0.149	0.200	0.159	0.176
	GA	8	0.161	0.200	0.200	0.200
	EP	9	0.233	0.168	0.196	0.200
CEC	EGR	106	0.185	0.001	0.185	0.001
	ESP	32	0.128	0.196	0.214	0.001
	EG	21	0.146	0.200	0.116	0.200
	GA	8	0.185	0.200	0.220	0.200
	EP	9	0.254	0.097	0.243	0.131

EGR: Eutric Gleyic Regosol, ESP: Endo-stagnic Plinthosol, EG: Eutric Gleysol, GA: Gleyic Arenosol, EP: Eutric Plinthosol. KS normality test- when $p < 0.05$, then data fails normality test.

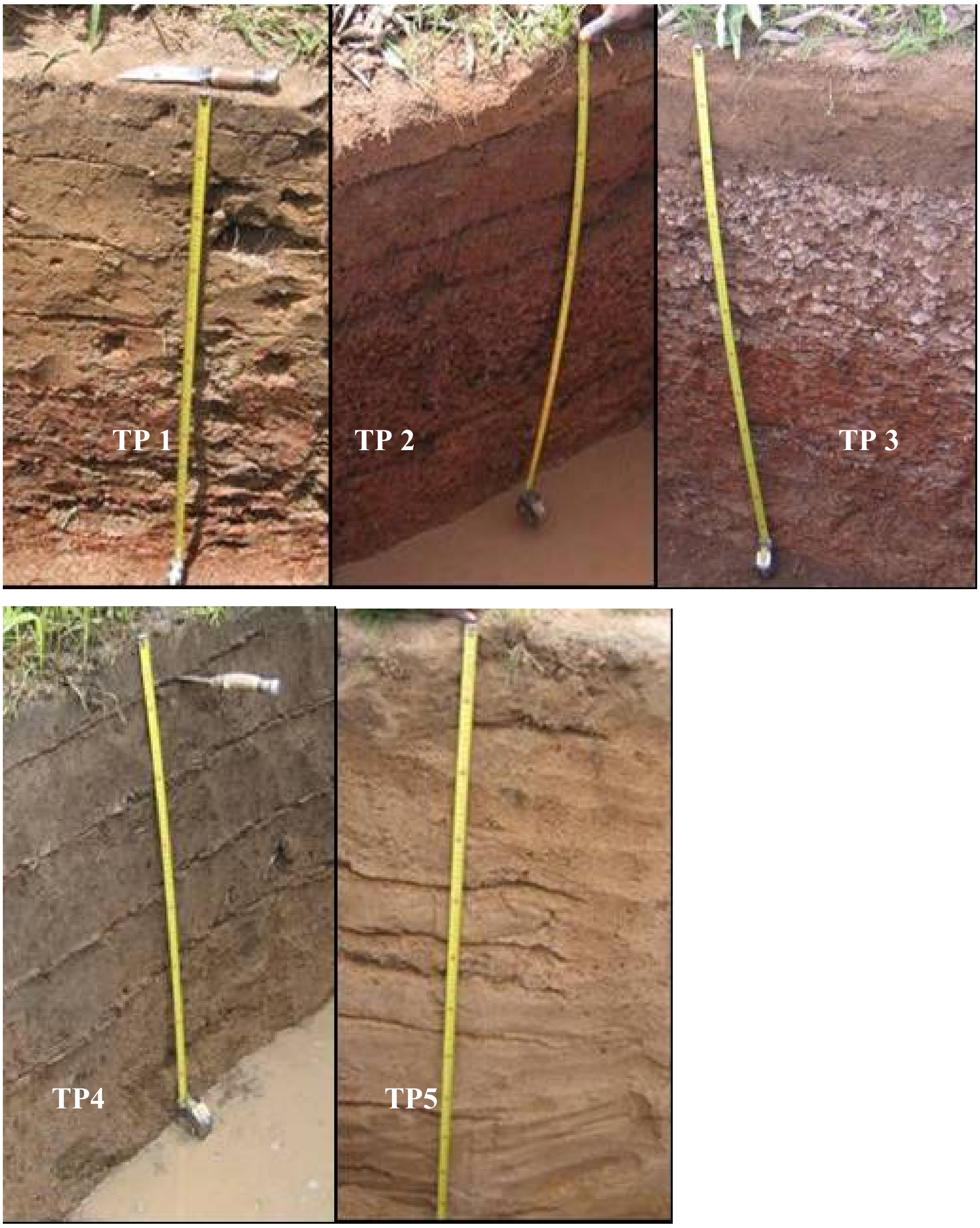
Appendix 9.3b: Kolmogorov-Simirnov normality test statistics and probability values of soil parameters (physical), from the 1 x 1.5km landscape

Soil parameters	Soils	N	Top soil (K-S normality)		Sub soil (K-S normality)	
			Statistics	P	Statistics	P
Sand	EGR	106	0.103	0.008	0.097	0.016
	ESP	32	0.108	0.200	0.132	0.162
	EG	21	0.163	0.148	0.143	0.200
	GA	8	0.287	0.051	0.211	0.200
	EP	9	0.293	0.025	0.183	0.200
Silt	EGR	106	0.093	0.026	0.075	0.148
	ESP	32	0.090	0.200	0.117	0.200
	EG	21	0.187	0.052	0.117	0.200
	GA	8	0.239	0.195	0.209	0.200
	EP	9	0.262	0.074	0.263	0.074
Clay	EGR	106	0.144	0.001	0.106	0.005
	ESP	32	0.202	0.002	0.223	0.001
	EG	21	0.214	0.013	0.193	0.040
	GA	8	0.396	0.001	0.239	0.193
	EP	9	0.386	0.001	0.185	0.200
Bulk Density	EGR	106	0.085	0.054	0.094	0.023
	ESP	32	0.115	0.200	0.107	0.200
	EG	21	0.104	0.200	0.138	0.200
	GA	8	0.133	0.200	0.193	0.200
	EP	9	0.161	0.200	0.147	0.200
Ks	EGR	106	0.325	0.001	0.379	0.001
	ESP	32	0.254	0.005	0.252	0.005
	EG	21	0.264	0.009	0.490	0.001
	GA	8	0.260	0.200	0.260	0.200
	EP	9	0.466	0.001	0.219	0.200

EGR: Eutric Gleyic Regosol, ESP: Endo-stagnic Plinthosol, EG: Eutric Gleysol, GA: Gleyic Arenosol, EP: Eutric Plinthosol. KS normality test- when $p < 0.05$, then data fails normality test.

Appendix 9.4: Profile pits of soil series within the landscape

Profile Code	FAO Classification	Local Names	Altitude (m)	Relief position	Coverage Area (%)
TP1	Eutric Gleyic Regosol	Pu	210	Middle slope	60.2
TP2	Endoeutric-stagnic Plintosol	Tanchera	208	Up slope	18.3
TP3	Eutric Plintosol	Puga	207	Up slope	11.9
TP4	Eutric Gleysol	Kupela	202	Lowland	4.5
TP5	Gleyic Arenosol	Brenyasi	201	Lowland	5.1



Appendix 9.4 continued: Profile pits of soils in the landscape

Appendix 9.5a: Profile description for Eutric Gleysol

0 – 22 cm (Ap) Dark grayish brown (10YR 4/2) moist, clay loam, moderate medium and coarse blocky, sticky, firm common tabular pores, many fine roots, clear and smooth boundary

22 – 50cm (BWg1) Dark gray (10YR 4/1) moist, gritty clay, moderate medium and coarse sub-angular blocky, sticky, tubular pores, abundant fine and medium roots, clear and smooth boundary, common strong brown (7.5YR 5/6) mottles

50 – 95 cm (BWg2) Yellowish brown (10YR 5/4) moist, sandy loam, structure-less, common brown (7.5YR 5/4) mottles, common medium roots, clear smooth boundary

95 – 115 cm (BWg3) Yellow brown (10YR 5/4) moist, sandy loam, structure-less, common brown (7.5YR 5/4) mottles, few medium roots, presence of white mica flakes abrupt boundary

115 – 150 cm (BWg4) Light olive brown (2.5YR 5/3) moist, clay, brownish yellow (10YR 6/6), moderate medium sub angular blocky, common medium and coarse roots

Appendix 9.5b: Profile description for Eutric-Gleyic Regosol

0 -15 cm (Ap) Dark brown (10YR 3/3) moist, Coarse sandy loam, weak fine granular, non sticky, abundant and coarse tubular pores, abundant fine and medium roots, smooth boundary

15 – 35 cm (BAq) Dark yellowish brown (10YR 4/4) moist, sandy loam, few brown (7.5YR 4/6) mottle, weak medium granular, non sticky, many fine and common coarse pores, abundant medium and fine roots, abrupt boundary

35 – 55 cm (B) Grayish yellow brown (10YR 4/2) moist, sandy loam, weak medium sub-angular blocky, few quartz stones, few fine and abundant coarse roots, smooth boundary

55 – 105 cm (Btg)Pale brown (2.5YR 6/3) moist, gritty clay loam strong brown (7.5YR 4/6), weak fine and medium sub angular blocky, few coarse roots, clear boundary

105 – 150 cm (BCg) Light yellowish brown (2.5YR 6/3) moist, gritty clay loam, few strong brown (2.5YR 6/3), decomposed biotite granite, very few coarse roots

Appendix 9.5c: Profile description for Gleyic Arenosol

0 – 14 cm (Ap) Dark olive brown (2.5YR 3/3) moist, sandy loam, weak fine granular, fine quartz, common fine and very fine roots, clear boundary

14 – 30 cm (AB) Dark brown (10YR 4/4) moist, sandy clay loam, weak fine and medium granular, many quartz, common fine roots and medium coarse roots, clear boundary

30 – 63 cm (BWg1) Yellowish brown (10YR 5/4) moist, sandy clay loam, weak fine sub angular blocky, distinct yellowish red (5YR 4/6) mottle, common fine and medium roots, clear and diffused boundary

63 – 95 cm (BWg2) Yellowish brown (10YR 5/4) moist, sandy clay loam, distinct yellowish red (5YR 4/6) mottle, weak fine sub-angular blocky, few medium and few fine roots clear and diffused boundary

95 – 150 cm (BWg3) Light yellowish brown (2.5YR 6/3) moist, gritty clay, moderate medium sub-angular blocky, distinct brown (7.5YR 4/4) mottle, very few fine roots

Appendix 9.5d: Profile description for Endoentri-Stagnic Plinthosol

0 – 18 cm (Ap) Brown (7.5YR 4/3) moist, coarse sand, weak fine granular structure, abundant quartz, non-sticky, many fine and very fine roots, clear boundary

18 – 45 cm (ABg) Brown (7.5YR 4/4) moist, coarse sandy loam, prominent red (2.5YR 4/6) mottle, weak fine and medium granular structure, non sticky, common fine pores, very few coarse roots, diffused smooth boundary.

45 – 74 cm (Btcsv1) Reddish brown (5YR 4/4) moist, sandy clay loam, massive sticky, hard common medium irregular structure, soft and hard red and black iron manganese dioxide concretions, common fine and medium pores, very few coarse roots, diffuse smooth boundary

74 – 105 (Btcsv2)Brown (7.5YR 5/4) moist, sandy clay loam, massive, abundant medium irregular structure, soft and hard, red and black iron manganese dioxide concretions, common fine medium pores, few fine roots, clear smooth boundary

105 – 120 cm (BCv) Pale yellow (2.5YR 7/3) moist, gritty clay loam, strong medium coarse sub angular blocky, pale red (10YR 6/4) mottle, common medium pores, few roots, presence of weathered decomposed granite

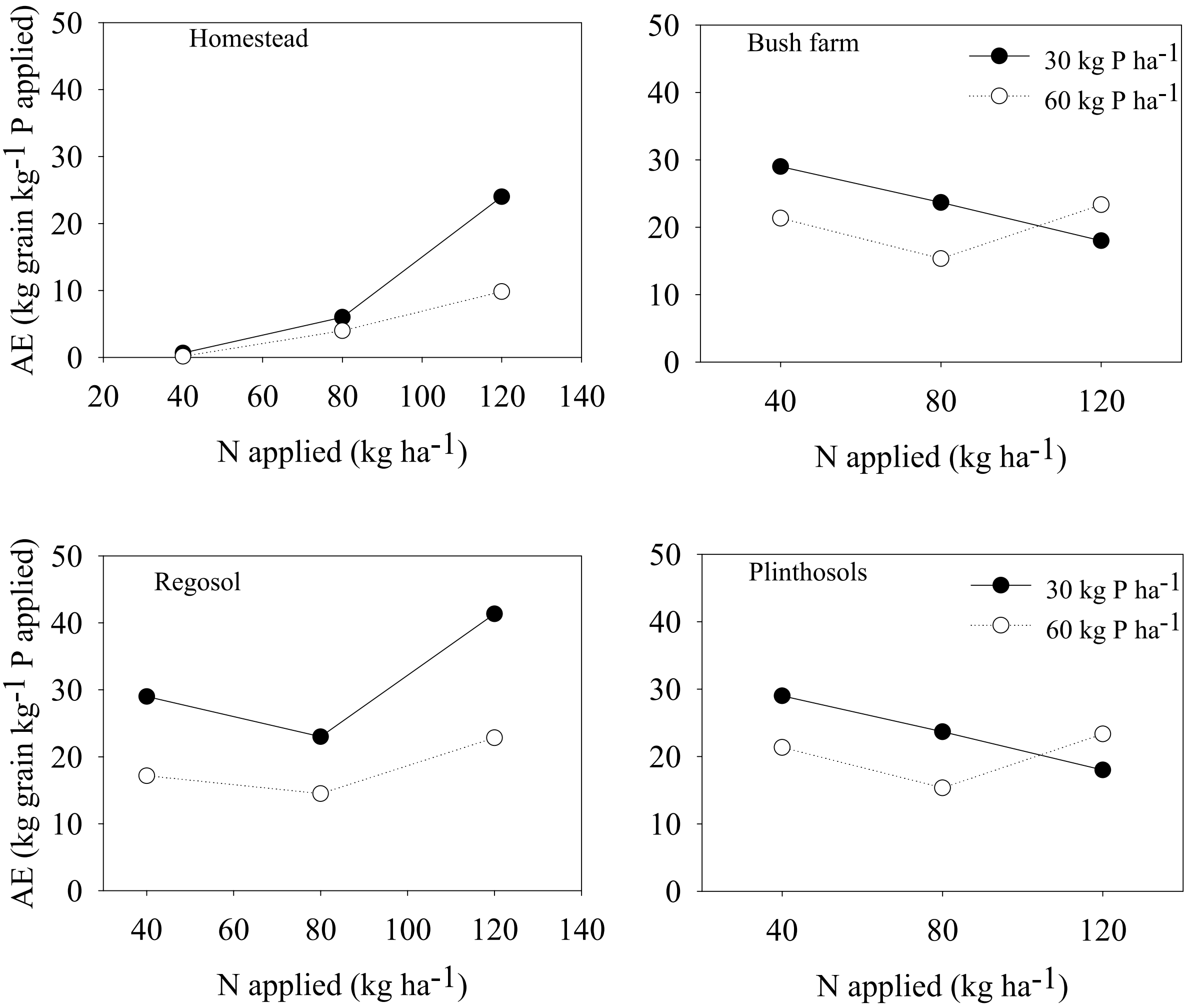
Appendix 9.5e: Profile description for Eutric Plinthosol

0 – 12 cm (Ap) Brown (7.5YR 5/3) moist, loamy sand, weak fine granular, non sticky, non plastic, few tabular pores, many fine roots, clear smooth boundary

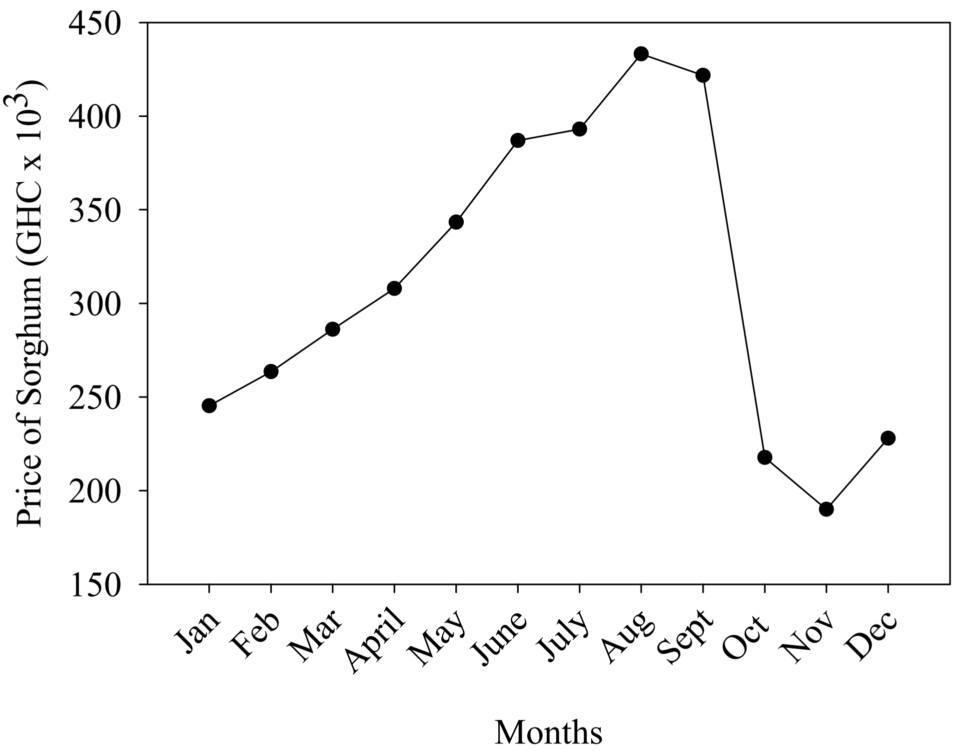
12 – 33 cm (ABcs) Brown (7.5YR 5/3) moist, sandy loam, moderate medium granular, non-sticky, common fine tubular pores, many medium irregular, hard red and black iron and magnesium dioxide concretions, few medium and coarse roots, abrupt boundary

33 – 95 cm (Btcsv) Brown (7.5YR 5/3) moist, sandy loam, moderate medium granular, non-sticky, common fine tubular pores, many medium irregular, hard red and black iron and magnesium dioxide concretions, few medium and coarse roots, abrupt boundary

95 – 145 cm (BCcsv) Reddish brown (5YR 5/4) moist, clay loam, moderate medium sub angular blocky structure, sticky, common medium tubular pores, many medium iron, manganese dioxide concretions, common quartz stones and gravels, very few fine and medium roots



Appendix 9.6: Average agronomic P use efficiencies of Sorghum yield as influenced by different rates of mineral N applications in two farm types and soils (Plinthosols and Regosols; data from 1st planting date) in the bush farm fields



Appendix 9.7: Fluctuation in price of grain Sorghum for the year 2005 in Navrongo (Upper East region) Ghana. Data source: MoFA market survey. 1 GHC = $ 9,632.70 (US). GHC – Ghanaian cedis

Appendix 9.8: Relative importance of input parameter to yield prediction

Source	Coefficients	Standard errors	t	Probability
Intercept	326.84	15.85	20.63	0.00
SOC	333.37	3.58	93.04	0.00
Clay	6.82	0.31	21.82	0.00
pH	80.84	2.79	28.98	0.00
Sand	-2.16	0.09	-24.02	0.00
Silt	-1.38	0.11	-12.45	0.00

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