QUANTIFYING SOIL AND NUTRIENTS LOSSES UNDER DIFFERENT SOIL AMENDMENTS AND CROPPING SYSTEMS ON A PLINTHIC VETIC LIXISOL IN GHANA

BY

JANVIER BASHAGALUKE BIGABWA

MAY, 2018

KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,

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SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF CROP AND SOIL SCIENCES

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JANVIER BASHAGALUKE BIGABWA

A Thesis submitted to the Department of Crop and Soil Sciences, Faculty of Agriculture, College of Agriculture and Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana in partial fulfillment of the requirement for the award of degree of

DOCTOR OF PHILOSOPHY

IN

SOIL SCIENCE

MAY, 2018

DECLARATION

I hereby declare that this submission is my own work toward the PhD and that, to the best of my knowledge, it contains no material previously published by other person nor material which has been accepted for the award of any other degree of the

University, except where due acknowledgement has been made in the text.

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Dr. Vincent Logah	……………......................	………….............
(Head of Department)	Signature	Date

DEDICATION

This thesis is dedicated to my parents Bonaventure Bigabwa and Ernestine M' Banywesize, my beloved Wife, Nicole Nshobole Migabo, our daughter, Emilienne Agisha Bashagaluke and all my primary school teachers. Thank you, God for your blessings and grace.

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ABSTRACT

Soil erosion coupled with soil nutrients depletion affect crop production in small-scale cropping systems of sub-Saharan Africa (SSA). Reducing both threats, based on sustainable practices is crucial to enhancing crop productivity in the region. The current study was designed to help address the twin problems based on the following objectives: (i) developing and validating a new numerical method for surface runoff assessment; (ii) determining the effect of crop and soil management practices on soil loss; (iii) analyzing soil nutrients loss due to soil erosion under different amendments and cropping systems; (iv) assessing the effect of soil amendments and cropping systems on soil properties; (v) assessing the effect of soil amendments on crop productivity. In achieving these objectives, a field experiment was carried out on runoff plots under different cropping systems (commonly practiced in Ghana) treated with soil amendments. The study was a two-factor experiment in split-plot arranged in a randomized complete block design for three consecutive cropping seasons (2016 major, 2016 minor and 2017 major seasons). The cropping systems (sole maize, maize intercropped with soybean, sole soybean and cowpea) constituted the main plots whereas the subplots comprised soil amendments (inorganic fertilizers (NPK), inorganic fertilizers combined with biochar (NPK+BC), sole biochar (BC) and control). For the model development and soil erosion characterisation, a total of 33 erosive rainfall events were observed. Different statistical parameters viz. p-values, R^2, RMSE, NSE and RSR were used to assess the quality of the model developed.

Parameters on the effects of the soil and crop management practices were analyzed in ANOVA and regression models. P value < 0.001 and R^2 ranging from 0.88 to 0.94 showed good accuracy of the model prediction. The dispersion between the predicted and observed values was low with RMSE varying from 1.68 to 2.66 mm. Moreover, the low variability between parameters was confirmed with the low values of RSR which ranged from 0.38 to 0.46 (with $0.00 \leq RSR \leq 0.50$ for good prediction). During the observation periods, NSE values ranged from 0.79 to 0.86 (≥ 0.75 being the threshold for excellent prediction). The sensitivity analysis showed that the model under high runoff generation (simulation including bare plots), was poorly adapted. Results for crop yield and soil properties showed positive impacts of the different interventions. Soil loss characteristics based on amount of soil loss, soil depth reduction and runoff coefficient were significant ($P < 0.05$). Among the different treatments, sole cowpea and inorganic fertilizers application were most effective in reducing soil erosion. Also, biochar, due to its multipurpose effect on soil properties, had positive

effects on soil erosion reduction compared to the control. Cumulative nutrients loss, enrichment ratios and monetary values of soil nutrients loss varied significantly under the amendments and cropping systems. Soil nutrients loss was more pronounced on the bare and the control plots than on the treated plots due to less soil erosion from the latter. All the nutrients had enrichment ratios (ER) greater than unity showing off-site nutrients deposition due to soil erosion; and this was more pronounced during the minor season than in the major seasons. The soil particles had ER greater than unity, except for the sand with values ranging from 0.77 to 0.88 and from 0.65-0.70 in the major and minor seasons, respectively. The economic effect of soil erosion based on the monetary values of soil nutrients loss was high for the control plots for each cropping system followed by the sole biochar (BC) treatment. Monetary loss under NPK and NPK+BC treatments was lowest due to their positive impacts on soil erosion reduction. The physical soil properties (bulk density and volumetric moisture content) were improved by the different practices and best values were observed under sole cowpea and sole biochar with respect to the cropping systems and soil amendments. Soil acidity increased slightly over time except under biochar treatments where a slight decline was observed. The legume-based cropping systems as well as the inorganic fertilizers applications improved soil organic carbon, total nitrogen, available phosphorus and exchangeable potassium contents slightly than the other treatments. For all the three crops evaluated (maize, cowpea and soybean), the productivity (grain and biomass yields) was better under the inorganic based treatments followed by sole biochar. Land equivalent ratio (LER) was greater than 1 under all the amendments under the maize-based systems. This emphasized the positive effect of the intercrop compared to the sole systems. With respect to cost effectiveness, VCR was greater than 2 for only sole NPK treatments under all the cropping systems and also for sole biochar treatment during the third season (2017 major). However, for NPK+BC, VCR > 2 was observed under the intercropped system throughout the study period. Indeed, sustainable nutrients management systems reduced soil loss and enhanced crop productivity and are recommended for small-scale farming activities in SSA.

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CHAPTER ONE

1. GENERAL INTRODUCTION

In sub-Saharan Africa (SSA), soil degradation due to water erosion is a major constraint to crop production as it greatly affects soil quality with a concomitant effect on crop yields. As a result, soil and water conservation have become very urgent now than ever to sustain agricultural production in the sub-region (Medrano *et al.*, 2015; Rinderer *et al.*, 2015). Soil and water are the two important factors for crop production. However, they are actually affected by acute forms of degradation, resulting from interaction of different factors.

Soil degradation in its several forms, is evident in all the agro-ecological zones of Ghana (Quansah *et al.*, 2000; Amegashie *et al.*, 2011) and in different other regions across the world (Kleinman *et al.*, 1998; Lal, 2001; and Rodriguez-Caballero *et al.*, 2013). Globally, about 10 million ha of croplands are lost due to soil erosion each year, which reduces their availability for food production (Pimentel and Burgess, 2013) as well as soil quality. Different methods and models have been used to assess the quantity of soil and nutrient losses (e.g. Wischmeier and Smith, 1978; Enters 1998; Hudson, 2005; Yang *et al.*, 2016; Vaezi *et al.*, 2017; Zhang *et al.*, 2017). However, most of them are not useful due to important but unrealistic parameters required for their calibration and validation.

Soil erosion measurement can be done with tipping buckets but this method is tedious and calls for development of more useful and adapted approaches. More so, the approach is limited in quantifying soil sediments for further investigation for which the new method proposed in this current study (runoff fractionation system) seeks to address. Most of the erosion studies carried out in the semi-deciduous forest zone of

Ghana focused on measurement of soil loss under specific soil conservation practices (Amegashie, 2014) with less attention on relevant cropping systems and soil nutrients management practices. Moreover, there is less research on nutrient losses as well as well as soil fertility erosion (Quansah *et al.*, 2000; Amegashie *et al.*, 2011; Amegashie *et al.*, 2012) compared to soil sediment and runoff assessment which have been widely studied across the world (Wang *et al.*, 2016; Bertol *et al.*, 2017). Not only is the soil loss nutrients assessment difficult (Bertol *et al*., 2017) but also the associated cost is high and this poses a major challenge in most of the soil erosion characterization studies (García-Díaz *et al*., 2017). The on-site effect of soil erosion decreases crop yields via fertility depletion (García-Díaz *et al.*, 2017;Vaezi *et al.*, 2017). The off–site effect on the other hand, is an environmental threat resulting in pollution of rivers, reservoirs and ground water (Prosdocimi *et al.*, 2015; Rice and Horgan, 2017). The problem of soil degradation in SSA are compounded by erratic rainfall patterns leading to poor soil moisture storage and poor agricultural productivity on smallholder farms in the era of climate change (Vaezi *et al*., 2017).

Cereals and legumes are staple crops in developing countries with good implication for food security on smallholder farms. In West Africa, maize and cowpea are among the basic food crops. Soybean, on the other hand, has progressively been included in cropping systems due to its multipurpose functions (Mathu *et al.*, 2010). However, the actual production level, for all these crops, is below the achievable yields of the different varieties released, due essentially to soil nutrients depletion and moisture stress among other factors. Thus, this requires integrated approaches for sustainable productivity (García-Díaz *et al.*, 2017). Organic amendments have been widely applied in small-scale farming systems to restore soil fertility by supplying nutrients, increasing soil organic matter, and improving soil physical properties (Pan *et al.*, 2017). These materials have been largely disseminated among farmers (Vanlauwe *et al*., 2001; Bationo, 2004). However, the interaction between biochar and cropping systems on soil and nutrient losses is not well documented.

This study hypothesizes that developing and adapting new tools for soil erosion characterization will give better opportunities and options in soil conservation which has been widely studied but with less adaptability under wide climatic conditions. Moreover, the use of sustainable cropping systems coupled with sustainable nutrient management will enhance resilience to soil erosion and increase crop productivity.

The main objective of this research was to increase productivity of cropping systems through enhanced resilience to soil loss. The specific objectives were to:

i. develop and validate a new approach for surface runoff assessment; ii. determine the effect of cropping systems and soil amendments on soil loss characteristics; iii. quantify the soil nutrients loss due to soil erosion under different amendments and cropping systems; iv. assess the effect of soil amendments and cropping systems on soil chemical and physical properties;

v. assess the effect of soil amendments under different cropping systems on crop yield.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Effect of soil erosion on soil properties and crop productivity

Soil erosion, counted among the most important threats to agricultural production in

SSA, affects strongly crop productivity and soil characteristics in different ways.

Globally, there is continuous erosion and deposition at different geomorphic settings (Okeyo *et al.*, 2014; Tamene and Le, 2015; Govers *et al.*, 2016). However, soil properties and farming systems that could reduce the negative impact of this threat are being strongly degraded by unsustainable land management practices (Montgomery, 2007).

The surface soil is subjected to vast inputs of energy from rainfall, runoff, wind, and solar radiation as well as a wide range of human and other biotic activities. Some of these energy fluxes are intercepted and absorbed by plants that use solar energy, soil nutrients, and atmospheric carbon for photosynthesis (Mandal and Sharda, 2013). By contrast with plants, the soil is incapable to absorb the large energy fluxes in a constructive manner and when the surface is exposed, the results can be highly degrading (Lal, 1998; Wilkinson *et al.*, 2015). Particularly in the case of energy from rainfall and runoff causing water erosion, the operative processes are destructive, both to soil structure, and to its capacity to sustain plant growth (Kurothe *et al.*, 2014). Soil erosion reduces strongly the agricultural values of the eroded lands. Moreover, rainfall drops and the shearing forces of runoff disintegrate soil particles (Nadeu *et al.*, 2012; Vaezi *et al.*, 2017) and transport the most fertile topsoil and organic matter away from eroded soil landscapes (Rice and Horgan, 2017). This reduces soil depth and plant nutrients with direct effect on other soil properties and crop productivity.

Some of the soil nutrients and organic matter are redistributed across the landscape whilst some are transferred into aquatic ecosystem (Bertol *et al.*, 2017), where they may contribute to eutrophication; and the rest deposited at different locations outside the farm (Park *et al*., 2014). The landscape formed with the sediment deposition are mostly of high agricultural value due to the characteristics of the eroded topsoils (Díaz *et al.*, 2011; Romero-Díaz *et al.*, 2016). Therefore, soil erosion effects are observed on the site where it is generated (on-site effect) as well as outside the eroded area of origination (off-site effect).

2.1.1 On-site effect of soil erosion

Rainfall erosivity, soil erodibility, topography, vegetative cover, soil management and conservation practices are the major factors affecting the magnitude of soil erosion on-site. Soil loss due to erosion varies under different land uses in addition to quality of soil and intensity of climatic parameters, especially rainfall and temperature (Bhandari, 2014). At the place where soil erosion is generated, it affects soil properties and crop production in different ways. The effects of soil water erosion extend beyond the removal of valuable topsoil which is the most important source of plant nutrients (Bhattacharyya *et al.*, 2007; Ojeda *et al.*, 2015).

Crop emergence, growth and yield are directly affected by the loss of natural soil nutrients and applied fertilizers. Seeds and plants can be disturbed or completely removed by erosion. Organic matter from the soil, residues and any applied manure are relatively lightweight and can be readily transported off the field. Pesticides may also be carried off the site with the eroded soil (Jendoubi *et al.*, 2015). Soil quality, structure, stability and texture can be affected by the loss of surface soil. The breakdown of aggregates and the removal of smaller particles or entire layers of soil or organic matter can weaken the soil structure and even change the texture (Valley *et al.*, 2017). Textural changes might occur which in turn affects the water-holding capacity of the soil, making it more susceptible to extreme conditions of drought (Janeau *et al.*, 2014). All these consequences affect soil quality by reducing its potential characteristics and the associated management practices and eventually crop productivity.

2.1.1.1 Soil nutrients loss through sediments and runoff

The transport of soil nutrients through erosion is affected by different factors, especially rainfall and soil characteristics. Zheng *et al.* (2005) found that lower rainfall amount and intensities (rainfall amount $\leq$ 15 mm or $I_{30} \leq$ 10 mm h^{-1}) generated lower runoff discharge as well as the corresponding transport capacity, resulting in lower sediment yield and erosion rate. Consequently, particles in eroded sediments are finer with higher nutrient contents (Alberts *et al.*, 2002), leading to higher nutrient enrichment (Smith *et al.*, 2016). As rainfall amount and intensity (rainfall amount >15 mm or I_{30} >10 mm h^{-1}) increased, Zheng *et al.* (2005) found that the amount of coarse particles (sand and silt) with lower concentration of nutrients increased. Berhe and Kleber (2013) demonstrated that fine particle content (<0.001 mm) in sediment decreased with erosion rate, while coarse particle content (> 0.005 mm) contrarily increased. According to Pardini *et al.* (2017), who studied relationships between runoff, erosion and nutrient movement in the inter-rill areas; the proportion of clay in sediment decreased with an increasing runoff rate while trends of total nutrient amount showed an opposite trend.

For a given soil, particle or aggregate size in eroded sediment depends on the detachment and transport capacities of the runoff. Walker and Young (2006) pointed out that nutrient enrichment ratios in eroded sediment decrease with an increase of sediment concentration in sheet erosion. The studies of Sharpley (1995) (equations 1.1 and 1.2) and McDowell and McGregor (1984) (equations 1.3 and 1.4), carried out under natural rainfall to assess nutrient loss due to erosion, showed also strong relation between soil nutrient contents in sediment and sediment concentration in runoff events.

$N = 0.03X^{-0.68}$ (1.1) $P = 0.72X^{-0.30}$ (1.2)

$N = 6675X^{-0.11}$ (1.3) $P = 4315X^{-0.18}$ (1.4) where:

N = concentration of nitrogen in sediment (mg kg^{-1}), P= concentration of phosphorus in sediment (mg kg^{-1}) and X = sediment concentration in runoff (g L^{-1}).

Regardless of the exponent differences in the above equations, the research results indicated that nutrient content in eroded sediment decreased with an increase in sediment concentration (Smith *et al.*, 2015).

2.1.1.2 Soil depth reduction due to soil loss under erosive processes

Soil loss on the field is expressed by soil depth reduction which is one of the outcomes of erosion. With soil depth reduction, water holding capacity is decreased with direct effect on soil moisture storage and soil structure stability. According to Okeyo *et al.* (2014), with topsoil detachment, water availability is affected by three processes. Firstly, when solum depth decreases, it reduces soil water storage capacity. Also, there is degradation of soil structure due to a reduction in organic matter and increased compaction, which reduces the soil water holding capacity. Lastly, there is detachment and transport of more clayey soil material, which can have a detrimental effect on the extent to which soil moisture is made available to plants. However, once the consequences of soil erosion are observed, there is already an effect on soil productivity. The consequences help in future planning and management to sustain crop productivity and the environment.

2.1.1.3 Effect of soil erosion on crop production

Crop production, expressed by growth and yield, is the result of plant genotype and environmental factors. Soil erosion is known to affect soil water holding capacity, soil structure, soil organic matter, plant nutrients, soil depth and soil biota. All these factors influence directly or indirectly soil productivity. Therefore, poor crop yield due to soil erosion is due to the degradation of soil physical properties, nutrient exportation through sediments and runoff. The extent to which crops respond to soil erosion depends on several variables, viz. crop type, soil properties, management practices and climatic characteristics (Nearing *et al.*, 2005).

Understanding the response of crop yields to soil erosion is of vital importance in assessing adequately the vulnerability of agriculture to erosion. The degree and extent of crop yields decrease will vary from soil to soil since the loss of topsoil depends on various factors specific to each site as well as external factors. Erosion reduces crop productivity so slowly that the impact may not be recognized until crop production is no longer economically viable. However, the use of good farming practices stabilizes production for some time under erosion risk. Improved and sustained cropping practices often mask the reduction in soil productivity by erosion, leading to increased rather than decreased yields. Also, the loss of topsoil via soil erosion is compensated by the formation of new soil through pedo-genetic processes. However, the soil formation process is very slow. The rate of soil formation has been reported to vary from < 0.025 mm yr^{-1} (in dry and cold environments) to >0.015 mm yr^{-1} in humid and warm environments (Bhattacharyya *et al*., 2008). Topsoil formation at the rate of

0.1 mm yr^{-1} is equivalent to an annual addition of 1.33 tons $ha^{-1}yr^{-1}$ (Pimentel and Burgess, 2013).

In conclusion, improved soil management practices and associated sustainable technologies such as soil conservation systems, cropping systems, soil nutrient management can help reduce soil erosion, improve land productivity and improve soil quality (Novara *et al.*, 2013; Mohawesh *et al*., 2015). Singh *et al*. (2001) and Alemu and Kidane (2014) reported that soil and crops which are interdependent variables should be managed simultaneously in order to reduce runoff and soil

erosion.

2.1.2 Off-site effect of soil erosion by water

The sediments detached from the field where soil erosion is generated, are transported through runoff outside the zone. The deposition of the sediments on the new area creates another ecosystem on the new landscape. According to Beck *et al.* (1995) and Rice and Horgan (2017), nutrients loss is not just costly and wasteful but can be a source of environmental concern when they reach lakes, rivers, and groundwater. During the movement of the soil particle and runoff, vegetation and other soil elements are destroyed according to the energy of the mass. The deposited elements may lose some of their physical protection and become exposed to advanced oxidative processes such that some of them go through stages of accelerated decomposition (Johnson *et al.*, 2007). For SOC, the emission of carbon dioxide to the atmosphere should increase at an estimated rate of 20 % greater annually than if erosion had not occurred (Lal, 2008). This is one of the relationships between soil erosion and global warming.

2.1.3 Enrichment ratio

The enrichment ratio (ER) is the ratio of nutrient concentration in the eroded materials to that in the original soil. It measures the magnitude of nutrient richness in the eroded materials (Quansah *et al.*, 2000; Amegashie *et al*., 2011). It is also an indicator of the selective removal of the finer, more fertile fraction of the soil subjected to erosion. Generally, the enrichment ratio is greater than unity which shows that the eroded sediments are richer in soil fertility constituents. This explains the agricultural importance of topsoil transported through runoff and sediment. The accumulation of sediment, rich in nutrients, increases eutrophication of water bodies and contamination of the new site where the sediments are deposited.

Studies by Quansah *et al*. (2000) and Amegashie *et al*. (2011) in Ghana in different watersheds, showed that for nitrogen, phosphorus, clay and silt particles, the ER values were greater than unity. However, the ER may be less than unity, emphasizing that the nutrients have been deposited on the same place where erosion has taken place, due to some specific factors such as soil roughness, slope curvature change, reduction of erosivity, land cover improvement. These factors may reduce the energy of runoff and the sediments deposed off-site are washed for most of the nutrients to remain on the eroded site. Amegashie *et al*. (2011) found that potassium enrichment ratio was less than unity for 3 sites out of the 6 sites studied. The solubility of the nutrients and the local condition of soil runoff restrictions can strongly affect the ER. The low solubility of a specific element may increase its transport by the runoff

(Haregeweyn *et al*., 2008).

2.2 Soil erosion estimation through different models

Due to the constraints of direct soil erosion quantification, different models have been adapted under different conditions to estimate soil loss. They require specific parameters for calibration and confirmation.

2.2.1 Type of models for soil erosion assessment

Different types of models and equations exist for simulating or assessing soil erosion patterns. In general, these models are grouped into three main categories, based on the physical processes simulated by each of them. These are empirical or metric/statistics conceptual and physically based models.

2.2.1.1 Empirical models

Empirical models are considered the simplest among the three model types. They are based primarily on the analysis of observations and seek to characterize response from data and therefore define the specific relationship among them (Wheater *et al.*, 2005). Compared to the conceptual and physical based models, the amount of data and computation required for empirical equations are less tedious. Most empirical equations are based on the analysis of catchment data using stochastic approaches, and as such are ideal tools for the analysis of data in catchments (Wheater *et al*., 2005). The parameters used in these model types may be obtained by calibration, but they are usually transferred from calibration to experimental sites.

For erosion characterization, empirical models are mostly used as a first step to identify the sources of sediments and nutrients generation. Empirical models are often criticized for employing unrealistic assumptions about the physics of the catchment system, ignoring the heterogeneity of catchment inputs and characteristics, such as rainfall and soil types, as well as ignoring the inherent non-linearity in the catchment system (Yu *et al.*, 1997). Such models are generally based on the assumption of stationary that underlying conditions remain unchanged for the duration of the study period. Empirical models also tend not to be event-responsive, ignoring the processes of rainfall-runoff in the catchment being modeled. Nevertheless, empirical equation are frequently used in preference to more complex models as they can be implemented in situations with limited data and parameter inputs (Yu *et al*., 1997, McIntyre *et al.*, 2014) and they give acceptable accuracy for soil erosion assessment on the field.

2.2.1.2 Conceptual models

Conceptual models are mostly based on the representation of a catchment as a series of internal storages. They usually incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure, representing flow paths in the catchment as a series of storages, each requiring some characterization of its dynamic behaviour. These model types tend to include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Cuomo *et al.*, 2015). This allows the models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data.

Generally, conceptual models lump representative processes over the scale at which outputs are simulated (Wheater *et al.*, 2005). The recent conceptual models developed have been assessed through the spatial distribution of the outputs and this is assumed to be one of the strengths of these models. Alternatively, lumped conceptual models may be applied in a semi-distributed manner by disaggregating a catchment into linked sub-catchments to which the model is applied. The parameters of the conceptual models are typically obtained through calibration against observed values (Abbott *et al.*, 1980). In general, the calibration techniques used under conceptual models of medium complexity (say more than six parameters) are capable of finding only local optima at best simulation. This means that there may be many possible 'best' parameter sets available. Randle *et al*. (2015) identified this problem in large simulation models stating that 'there is not a single point in the parameter space associated with good simulations. Pandey *et al.* (2016) concluded that the simpler conceptual models have fewer problems with model identification than more complex models.

Therefore, to increase the accuracy of the models due to problems of identification (Wheater *et al.,* 2005), recommanded reduction in the number of parameters to be simulated and identification of additional parameters using a priori knowledge of the system. The most complex models are more likely to provide a better fit to calibration data, although this does not necessarily extend to providing better predictions of future behaviour, as complex models run the risk of over fitting calibration data (Pandey *et al.,* 2016). The lack of uniqueness in parameter values for conceptual models means that the parameters in such models have limited physical

interpretability. Yet, this problem can also be observed with empirical and physicsbased models.

2.2.1.3 Physically-based models

Physically-based models are mostly focused on the solution of fundamental physical equations describing stream flow and sediment and associated nutrient detachment in a catchment. Most of the standard equations used in such models are the equations of conservation of mass and momentum for flow and the equation of conservation of mass for sediment (Bartley *et al*., 2006).

In theory, the parameters used in physically-based models are measurable and so are 'known'. In practice, the large number of parameters involved and the heterogeneity of important characteristics, particularly in catchments, mean that these parameters must often be calibrated against observed values (Wheater *et al.,* 2005). This creates additional uncertainty in parameter values for these types of equations. Where parameters cannot be measured in the catchment, they must be determined through calibration against observed data. Even in situations where parameters can be 'measured', errors in the measurement of important characteristics, and differences between the scale at which model algorithms are applied and the scale at which measurements are made, will create additional uncertainty as to the veracity of model outcomes (Pandey *et al.*, 2016). The derivation of mathematical expressions describing individual processes in physically-based models is subject to numerous assumptions that may not be relevant in many real world situations (Wilkinson *et al.*, 2015).

Moreover, in general, the equations governing the processes in physically-based models are derived at the small scale and under very specific physical conditions. However, in practice, these equations are regularly used at much greater scales, and under different physical conditions. The equations are derived for use with continuous spatial and temporal data, yet the data used in practice is often point source data taken to represent an entire grid cell in the catchment. The viability of lumping up small scale physics to the scale of the spatial grid used in many physically-based models is questionable (Chaplot, 2014). These are some of the limitation of physically-based equations for soil erosion characterization, although they are assumed more accurate and successful compared to the two other types.

2.2.2 Characteristics of some models used in soil erosion measurement

The rainfall- soil erosion relationships have been widely developed from several studies (e.g. Cohen *et al.*, 2005; Mekonnen *et al.*, 2015, Wang *et al.*, 2016 ; Rice and Horgan, 2017, etc) using different approaches based on natural rainfalls and rainfall simulation. But under field conditions, there has been a strong focus on easily measurable or widely-available parameters, in particular total rainfall amount and various intensities and their impacts on soil and nutrient losses using different equations and methods (García-Díaz *et al.*, 2017).

In recent years, much time has been devoted to the development of water erosion models. Some of them are physically based, empirical or conceptual and each of them has its accuracy and limitations for soil erosion assessment (Van Leeuwen *et al*., 2015). Installing erosion runoff plots for direct soil erosion assessment in the field is one of the scientific approaches used for soil erosion studies. The problem of time , labour and cost of runoff plots' management are not the only limitations but also the handling of the large amount of sediments collected (Pardini *et al*., 2017). Due to the limitations of the direct soil erosion measurement, different equations have been developed to assess the soil loss, runoff; nutrients and which are categorized within the three groups. Some of the models and their characteristics are presented in Table 2.1. Each of those equations requires specific data before calibration and validation. Also, the extrapolation of the predicted values to the large areas is less accurate compared to direct values. The developed equations require important basic factors which are not easy to get without specific background of the area.

Table 2.1. Characteristics of some models used for soil erosion assessment

Name	Description	Type	Scale	Input/Output	References
AGNPS	Agricultural Non-Point Source model	Conceptual	Small catchment	Input : High; Output: runoff volume; peak rate, N, P	(Young *et al*. 1987).
EMSS	Environmental Management Support System	Conceptual	Catchment	Input: Low ;Output: runoff, sediment loads, nitrogen loads and phosphorus loads	(Watson *et al*., 2001).
HSPF	Hydrologic Simulation Program Fortran	Conceptual	Catchment	Input : High; Output: runoff, flow rate, sediment load, nutrient concentration	(Johanson *et al*., 1980).
IHACRES		Empirical/Conceptual	Catchment	Input : Low; Output: runoff , sediments and nutrient and nutrients	(Azmera *et al*., 2016).
IQQM	Integrated Water Quantity and Quality Simulation Model	Conceptual	Catchment	Input: Moderate; Output : Many polluants including nutrients, sediments , dissolved oxygen, salt , algae	(Bellin *et al*., 2016).
LASCAM	LArge Scale CAtchment Model	Conceptual	Catchment	Input: High; Output : runoff , sediment; salt fluxes	(Viney and Sivapalan, 1999).
SWRRB	Simulator for Water in Rural Basins	Conceptual	Catchment	Input: High; Output : steam flow , sediment , nutrient and pesticide yields	(Behera and Panda, 2006).
GUEST	Griffith University Erosion System Template	Physical	Plot	High; Output: runoff, sediment centration	(Yu *et al*., 1997).
LISEM	Limburg Soil Erosion Model	Physical	Small catchment	High; Output: runoff, sediment yield	(Takken *et al*., 1999).
PERFECT	Productivity, Erosion *a*nd Runoff Functions to Evaluate Conservation Techniques	Physical	Field	High; Output : runoff, erosion, crop yield	(Littleboy *et al*., 1992).

TOPOG		Physical	Hillslope	High; Output: water logging, erosion ard, solute transport	(Croke and Nethery, 2006).
USLE	Universl Soil Equation Loss	Empirical	Hillslope	High ; Output: erosion	(Wischmeier and Smith, 1978).
WEPP	Water *Erosion* Prediction Project	Physical	hillslope/Catch ment	High; Output :runoff, sediment, characteristics m sediment loss	(Laflen *et al*., 1991).

2.3 Characteristics of some cropping systems

A cropping system refers to a component of crops on a land combined with different resources for an expected outcome or production (Ghosh *et al.*, 2006). In SSA, different cropping systems exist with specific characteristics due to the variability of the small-scale farmer conditions. The stakeholders use the most adapted practices to their environment with less risk to maximize the production and reduce ecosystem degradation. The selection of any technology or cropping practice is therefore based on different factors such as the availability of resources, the goal of the production and the environmental conditions.

2.3.1 Monocropping

For this system, the stakeholders grow one species or variety of crop on the land. The system is mostly practiced under agricultural intensification. However, it has been shown that this practice is not sustainable and increases the threat of pest and diseases and also increases soil degradation.

Soil degradation and reduction in crop production may occur when the system is not well managed through integrated nutrient and pest management approaches. But also, for most of the smallholder farmers in SSA, land availability is an important constraint to crop production (Wall *et al.*, 2013). In some areas of SSA, the land has been strongly degraded and is not any more suitable for farming activities. Thus, the small portion of land suitable for cropping is used with different crops for diversity of incomes and products and to sustain the ecosystem; although this is not the main goal of most of the farming activities (Mateus *et al.*, 2010). However, it is crucial to combine both, crop productivity and environment conservation approaches to enhance sustainability of cropping activities.

2.3.2 Intercropping

Intercropping is used when two or more crop species are planted on the same land at the same time. This system is used in both intensive and extensive agriculture with the aim of improving and increasing production whilst reducing ecosystem degradation. For small-scale farmers, with limited resources (farm size, inputs, etc), this system may increase land degradation due to competition of the crops on degraded soil (Chu *et al*., 2004; Hamzei and Seyyedi, 2016). However, the system is mostly sustainable by improving agricultural income, soil nutrients, pest and diseases control, as well as soil and water conservation**.**

Grain legumes intercropped with cereals is the most adapted and adopted intercrop system in SSA and which has many agronomic and environmental advantages (ChabiOlaye *et al.*, 2005). The type of species intercropped may vary for the two plant groups due to agro-ecological conditions of each farming zone. For the cereal-legume intercrop, the residual effect from the grain legumes and the nutrients requirement of each of the two categories of plants, make this intercropping one of the most sustainable systems in small-scale systems. Moreover, the constraint related to land tenure makes the system more useful for the smallholder farmers in the SSA (Egbe, 2010).

According to Wall *et al*. (2013), in the zone where land pressure is intense, famers are more interested in intercropping than rotation or mono-cropping. Mucheru-Muna *et al.* (2010) and Zerihun *et al*. (2013) reported that intercropping of annual cereals and grain legumes is a common practice in the tropics because the general income is enhanced compared to sole systems.

2.3.3 Crop rotation

This system refers to the allocation of different crops to the land at different consecutive periods. As it is the case for the sole systems, the land requirement may limit the success of this system. However, it is a very important practice for sustaining soil nutrients and soil water use efficiency through strategic crops succession on the farm. The principle of residual effect is very important such that legumes are recommended to be followed by the plant requiring more nitrogen (Shaalan *et al.*, 2014). For water use efficiency, plants with deeper root system will decrease the moisture stress for the next plant. Contrary to the mono-cropping, crop rotation reduces pest and disease incidences (Shaalan *et al*., 2014).

2.3.4 Alley cropping

Alley cropping is an agroforestry system where rows of crops are planted between trees. The system requires the use of leguminous trees for less competition on the associated crops and for soil nutrient improvement. Alley cropping has been widely reported to improve soil productivity and nutrient recycling in smallholder farming systems of the humid tropics (Kang *et al.*, 2007).

It has been recommended as one of the viable alternative approaches to the traditional shifting cultivation system (Kanmegne and Degrande, 2012). In SSA, several shrubs and trees (legumes) such as *Calliandra spp*, *Leucanea spp*, *Accacia spp*, *Tephrosia ssp*, etc; have been promoted by different scientific stakeholders under this system. These legumes are commonly called multipurpose species, not only because of their effect on soil but also for their use as good fodders and other social utilization (timber, wood, etc). The system had attracted more scientific interests due to its good and sustainable success. However, it is less successful in SSA for smallholder farmers with reduced land sizes. Moreover, the trees may compete with the crops, especially when the soil is highly degraded (Alemu and Kidane, 2014).

2.3.5 Shifting cultivation

This system involves the use of the land for a specific duration before leaving it under natural restoration after a decline in soil quality. Actually, this approach is not well practiced by small-scale farmers due to land availability constraints. The system works formally under forest conditions and where population density is low. It is a suitable approach of soil management which requires specific adaptation for good success (Bationo *et al.*, 2011). After the period of fallow, the soil becomes very suitable once again for crop production. The period for the soil fertility restoration is very long (15 to 20 years) such that in most smallholder farming systems in SSA, it is no longer applicable.

2.3.6 Improved fallow

This approach is an improved approach of shifting cultivation but with almost the same principal as the latter (Ajayi *et al.*, 2003). Under natural condition of shifting cultivation, the time and land size required for resource restoration was very important. Due to these challenges, researchers introduced improved fallow as one of the sustainable options to replenish and sustain soil fertility within the shortest possible time. According to Kwesiga and Coe (1994), improved fallow involves planting of fast growing plant species that are (usually) nitrogen-fixing, produce easily decomposable biomass compatible with cereal crops (mostly) in rotation and are adapted to the climatic and edaphic conditions of the farming zone. Different species have been found to be adapted in SSA. These include *Sesbania sesban* (L.) Merr., *Gliricidia Sepium* (Jacq.)Walp, *Tephrosia vogelii* (Hook), *Cajanus cajan* (L.) Millsp (Kaonga and Coleman, 2008).

2.4 Effect of cropping systems and soil management on soil properties Sustainable cropping systems are considered one of the important management options for tackling water induced erosion hazards, promoting in-situ water conservation and improving and stabilizing crop yields in rain-fed production systems of semiarid and subtropical regions (Kurothe *et al*., 2014). Therefore, soil conservation via suitable cropping systems are practices from which farmers might improve their productivity at affordable costs. Sustainable soil conservation technologies have positive impacts on the different production factors. Indeed, soil conservation improves crop production through the retention of organic matter and nutrients, water holding capacity improvement and soil and nutrient loss mitigation (Phillips *et al*., 2013).

2.4.1 Effect of cropping systems on soil loss

Sustainable soil and water conservation technologies are required to reduce the rates of soil loss up to tolerable levels and to conserve soil fertility and improve crop production in smallholder farming systems. One of the most affordable means to meet this demand is to identify effective and sustainable cropping systems that can reduce soil erosion (Faucette *et al.*, 2007; Prosdocimi *et al*., 2016) and improve crop production. In general, intercropping systems have been demonstrated to reduce soil loss and runoff when, compared to sole cropping systems; as this system provides adequate land cover (Laloy and Bielders, 2010; Kurothe *et al*., 2014).

Chamberlain *et al*. (2010) indicated that dense vegetation under strip intercropping slowed runoff and trapped moving soil particles. It was also demonstrated by Wall *et al.* (2013) that in maize based cropping systems, soil loss was significantly lower under maize intercropped with clover compared to both crops within the sole systems. Labrière *et al*. (2015) also recorded soil loss reduction by 50% when cassava was intercropped with alfalfa compared to sole systems. From their study in the semi-arid zone of Burkina Faso, Zougmore *et al*.

(2000) observed that intercropping sorghum with cowpea effectively reduced water runoff and soil erosion compared to the sole systems and the bare plots.

Rotational cropping systems have also been shown to reduce runoff and soil loss due to their role in soil organic matter (SOM) build-up and in enhancing soil aggregate stability (Alvey *et al.*, 2003; Shipitalo *et al*., 2013; Wei *et al*., 2014). This system increases soil infiltration due to improvement of soil physico-chemical properties which has good impact on soil loss reduction (Owens *et al*., 2012).

2.4.2 Effect of cropping systems on soil fertility

Under sustainable cropping systems, the surface soil is rougher compared to the bare surface and to crops on a degraded soil. The adapted and stable cropping systems reduce soil loss and runoff through positive impacts on soil infiltration rates. Moreover, with good plant development, leaf decomposition improves soil organic matter with good impact on soil physical, biological and chemical properties (Lee *et al*., 2013) and this reduces runoff and nutrients loss (Prosdocimi *et al*., 2016; Bertol *et al*., 2017).

Legume based cropping systems do not only improve soil nutrient status through nitrogen fixation but also biomass litter which is more consistent compared to cereals. Legumes will improve soil characteristics better than cereals during the development stage through leave decay (Van Leeuwen *et al*., 2015; Wilkinson *et al*., 2015).
However, cereals may develop good rooting systems with positive impact on soil loss, runoff and nutrient loss reductions. Under organic farming, sustainable cropping systems are important sources of soil nutrients for good crop production. Moreover, for smallholder farmers with poor external fertilizer use, sustainable cropping systems are good and alternative options of soil nutrients management and soil fertility improvement.

2.5 Soil fertility management for cereals and legumes production

Several technologies of soil management and improvement have been developed for different agro-ecological zones in SSA to improve crop productivity (Bationo *et al.*, 2003; Sanginga and Woomer, 2009). The developed ISFM technologies are expected to help farmers and other stakeholders to improve crop yields, especially based on local and available knowledge. Due to inability of smallholder farmers to apply mineral fertilizers at optimal rates based on multi-dimensional constraints, the combination of organic and mineral inputs has been proposed as a sound management principle to attain optimal crop yields (Bationo *et al*. 2003)

The expansion of soybean cropping systems is a great opportunity for most developing countries to improve soil nutrients status through biological nitrogen fixation (BNF) aside other nutritional and economic advantages of the crop. In most

African countries, soybean cropping is relatively new compared to other staple crops. Due to the multipurpose value of soybean (human nutrition, drought tolerance, income generation, fodder, market and industrial values and recently for bio-energy), its production is expected to increase very quickly under small-scale farming systems (Chianu *et al.*, 2009; Mugendi *et al*., 2010). However, in small-scale farming systems of SSA, soybean yields are still below the potential yields of released varieties, being averagely 3,000 - 3,600 kg ha^{-1} (Mucheru-Muna *et al.*, 2010).
Cowpea is an important source of protein in Africa but is also low yielding under small-scale farmer conditions. Different factors have been identified as the causes of the low yields in SSA: inherent poor and declining soil fertility, soil acidity, poor soil management practices and low use of agricultural inputs (Vanlauwe *et al*,. 2010).

Despite their potential of nitrogen fixation, several studies across the continent have shown the improvement of soybean and cowpea yields through external nutrients supply (e.g. Vanlauwe and Giller, 2006; Mucheru-Muna *et al*., 2010; Chiamaka, 2014 ; Janagard and Ebadi-Segherloo, 2016, etc).

Maize is the first cereal crop in SSA and it is adapted to different agro-ecological zones. Its production is also constrained by land degradation and poor resource management within the region. Across the continent, most of the ISFM technologies are mostly developed under maize based cropping systems. It is the test crop mostly used under soil nutrient management programs across the continent. Different types of inorganic and organic inputs and their combination are frequently recommended to improve and sustain maize production in SSA (Vanlauwe *et al.*, 2011). Its yield has been increased not only due to the sustainable nutrient technologies applied (Kintché *et al*., 2015) but also with its several breeding programs (Challinor *et al.*, 2016). Thus, maize has benefited immensely from the scientific progress observed in soil science and plant breeding during the 20 th and 21 th centuries (Kintché *et al*., 2015).

Soil nutrient management is a key factor for crop yield improvement in smallholder farming systems in SSA. Cereals and grain legumes require specific and sustainable nutrient managements under degraded soils of the tropics for yield increase.

2.6 Biochar

2.6.1 Principle of biochar production

Biochar is an organic compound produced by heating organic material under conditions of limited or no oxygen (Karhu *et al.*, 2011). Biochar, as soil amendment, is greatly affected by the type of organic matter (or feedstock) used as well as the conditions under which it is produced (Warnock *et al.*, 2010). Biochar production releases generally more energy than it consumes, depending on the moisture content of the feedstock (Lehmann and Rondon, 2006). Heat, oil, and gas that are released can be recovered for other uses, including the production of electricity (Hunt *et al*., 2010). Sadeghi *et al.* (2015) suggested a sustainable model of biochar production primarily by using waste biomass, such as green waste from municipal landscaping, forestry, or agriculture.

Biochar is a specialized form of charcoal suitable for use as soil amendment. The particular heat treatment of organic biomass used to produce biochar contributes to its large surface area and characteristic ability to persist in soils with very little biological decay (Deenik *et al.*, 2009; Jien and Wang 2013). This resistance to microorganisms attacks gives biochar an important value on soil carbon sequestration, which is among the environmental interests of this material.

2.6.2. Effect of biochar effect on soil properties and crop production

While other organic materials (e.g. compost, manures, etc.) supply relatively high amounts of available nutrients to plants and soil microorganisms, biochar serves as a catalyst that enhances nutrients and water uptake beside the low nutrients supplied directly for plant nutrition (Karhu *et al*., 2011; Uzoma *et al*., 2011; Amendola *et al*.,

2017). Compared to other soil organic amendments, its high surface area and porosity enable it to adsorb or retain nutrients and water and also provides a habitat for beneficial microorganisms to flourish (Deenik *et al.*, 2009).

Biochar has many direct and indirect advantages to crop production through different ways. Due to its positive effects on soil properties, crop productivity and environment protection (soil carbon sequestration), biochar is actually being promoted and integrated into soil management systems. Several studies from both tropical and temperate zones have shown biochar’s ability to increase plant growth, reduce leaching of nutrients, increase water retention, and increase microbial activity (e.g. Ojeda *et al*., 2015;

Amendola *et al.*, 2017, etc). Findings have shown that both biological nitrogen fixation and beneficial mycorrhizal relationships in common beans

(*Phaseolus vulgaris L.*) are enhanced by biochar applications (Amendola *et al*., 2017). With both biochar additions and mycorrhizal abundance subject to specific management practices, there are clearly opportunities for exploiting a potential synergism that could positively affect soil quality under poor available crop nutrient conditions (Ameloot *et al*., 2015). According to Elad *et al*. (2012), biochar can improve plant biotic stresses' resistance, especially diseases.

However, biochar application may have negative impact on crop performance. Knowles *et al*. (2011) and Zimmerman *et al*. (2011) observed that some of the situations where crop productivity decreased, with biochar application, could be due to temporal levels of pH, volatile or mobile matter (MM) and /or nutrient imbalance

(associated with fresh biochar). Indeed, with biochar application, its initial high pH (alkaline) can be more desirable and useful when used under acidic and degraded soils (Amendola *et al.*, 2017). However, if soil pH becomes too alkaline, plants' development can strongly be affected through nutrients unavailability. "Mobile matter" (MM) refers to tars, resins, and other short-lived substances that remain on the biochar surface immediately after production and which might inhibit plant growth. However, good cropping practices can decrease the rate of MM in the biochar. Soil microorganisms can decompose and transform the carbon-rich MM into nutrients which can be efficiently used by plants. However, in this process, the microorganisms require nitrogen and other soil elements, rendering them temporarily unavailable for uptake by plants. These transitional imbalances are later corrected as MM decays, pH neutralizes, and unavailable nutrients are released. Therefore, the long effect on crops' performance of biochar is mostly due to such factors (Amendola *et al.*, 2017).

The low microbial activity of biochar makes it more stable into the soil for many years. The findings of Zheng *et al*. (2012) from studies in Amazon Basin's Terra Preta soils and naturally occurring biochar from forest and grassland fires, shows that biochar can persist for millennia with very little decay. Apart from the agricultural advantage, this low decomposition of biochar gives more opportunities of biocharbased researches for soil carbon sequestration in the era of climatic change.

In conclusion, the production of biochar requires specific technologies and seems to be expensive compared to other organic amendments (composts, green manure, manures, etc.). This can constitute a constraint to its rapid adoption by smallholder farmers. Biochar is multipurpose compound which makes it very attractive for soil health improvement and in environmental studies. Key promising findings have been obtained but there are still new areas which need more scientific evidences and supports for the integrated use of this soil amendment.

2.7 Effect of land cover and soil nutrient management on soil characteristics

2.7.1 Land cover principle and its effects on soil erosion

There is strong interaction between land cover patterns and soil erosion and sediment yield in watersheds (Gyssels *et al*., 2005; Pardini *et al*., 2017; Pan *et al*., 2017) Generally, soil erosion is related to the different interactive factors: soil properties, topography, climatic characteristics, land use and its management and human activities. Soil properties and topography are relatively constant in the short term; and changes in land use and climatic features, influenced by human interventions, are the most dominant variables (Wei *et al.,* 2007). Soil erosion is strongly influenced by the absence of protective soil cover which should decrease runoff and rainfall erosivity (Bakker *et al*., 2008). The types of land cover are closely defined by human activities and which in turn determine the anthropogenic substances carried into erosion systems through soil detachment, runoff process, sediment transport, and deposition. Crop distribution on the ground is an important factor defining the fate of rainfall water. During a storm, a portion of water is intercepted by the plants and a new spatial distribution of rainfall drops takes place with less erosive energy (Smith *et al.*, 2007; Pan *et al*., 2017).

It is worth noting that a soil which is inherently prone to erosion may produce less erosion under improved soil management practices than a less erodible soil under poor management (Govers *et al.*, 2016 and Wang *et al.*, 2016). From a hydrological principle, plants can reduce soil erosion rates through: raindrop interception, soil infiltration improvement, surface roughness and soil organic matter improvement (Pan *et al.*, 2017). This emphasizes the importance of soil management practices on soil erosion control through improved plant performance. The impact of plants on soil loss is based on the above-and-belowground biomass. The root system improves soil resistance to soil transport by runoff and raindrops (Gyssels *et al.*, 2005). Moreover, the kinetic energy of the raindrops is intercepted by the aboveground biomass (plant canopies), which implies that split raindrops have less impact on soil loss and physical degradation. The soil cover and leaf litter produced with good plant development increases the surface soil roughness which slows down runoff through increased soil infiltration. To reduce soil erosion, the greatest ground cover must be reached during periods of maximum rainfall (Pan *et al.*, 2017).

According to Bhandari (2014), there are two basic ways in which soil erosion may be controlled through cropping systems: by minimizing the effects of raindrop impact on the soil surface and reducing the volume and/or velocity of run-off water. Also, the root systems create a network of passages in the soil which increase infiltration to reduce run-off. The effectiveness of vegetation or plant cover in reducing soil erosion depends on its characteristics (underground and aboveground biomass). The effectiveness also depends on the height and continuity of the canopy, density of ground cover and root density. The root system plays an important role in reducing erosion rate by binding the soil mass to increase its resistance to flow (Pan *et al*., 2017).

2.7.2 Effect of soil nutrients management on soil erosion

Poor soil management practices accelerate the degradation of soil properties with direct effect on land cover which has been demonstrated to influence soil erosion (Gyssels *et al*., 2005; Pardini *et al*., 2017). Managing soil nutrients will not only increase plant yields but will improve also the resistance of the soil to the impact of runoff and raindrops. Good plant performance, as result of sustainable soil nutrients management will positively impact soil loss reduction. However, during planting and establishment stage, the soil is exposed to runoff and sediment transport due to poor crop development at that stage. In the tropics where heavy storms are observed at the beginning of the cropping seasons, soil loss is important despite good soil nutrients management. Studies have shown significant amount of soil loss from bare soils and also the early stages of plant growth when most part of the soil is still bare (RuizColmenero *et al.*, 2013; Pan *et al*., 2017). Therefore, promotion of early soil cover is essential for reducing soil loss on arable farmlands to maintain soil productivity (Blanco-Canqui and Lal, 2008).

Thus, soil nutrient management practices are good options to partially reduce the impact of runoff on soil through improvement in crop performance. Good plant biomass increases soil organic matter, mechanical and physical resistance to runoff and raindrops.

2.8 Economic value of soil management technologies in smallholder farming systems

Agricultural profitability is a key component of soil fertility management practices in SSA. Crop yield improvement and profitability are strongly related to the availability of external fertilizers (Kihara *et al.*, 2016) and different cropping practices. Different approaches have been developed across the continent to improve agribusiness but good outcomes are still to be achieved to sustain agricultural productivity. In most of the SSA countries, fertilizer subsidies are not very effective as expected after the agreement of the heads of African states during the AGRA program launching in 2006 (Bationo *et al.*, 2013). Several other programs and projects have been developed at national and international levels to support the increase of fertilizer use but with low up-scaling. Different recommendations of soil nutrient managements are suggested but are not much adopted by the smallholder farmers, due to diverse reasons. As reported by Pypers *et al*. (2012) and Mucheru-Muna *et al*. (2014), the adoption of the actual recommendation of fertilizer types and rates in SSA, by smallscale famers, will be based on income improvement. Making agriculture more attractive in developing countries will emanate from income improvement and governments support through subsidies and other facilities.

In general, the SSA region has the lowest rate of inorganic fertilizer use (8 kg/ha) (Bationo *et al.*, 2013) and which presents important constraint to agricultural intensification. Prior to recommending specific soil amendments, scientists assess their profitability to convince the users for adoptions. Several methods have been used to assess this agricultural profitability, with the value cost ratio (VCR) being mostly applied. It is usually used to assess the profitability of the fertilizer, especially when there is absence of full cost data to use the cost benefit ratio (BCR) method. A VCR value greater than 1 but less than 2 means that cost of fertilizer is recovered while a

VCR of 2 or more represents 100 % return or more on the investment in fertilizers (Kihara *et al*., 2016).

For the VCR method, different factors are taken into account. These are, the type of crop grown (some crops are more responsive than others to inputs), agro-ecological factors (soil, climate favorable fertilizers response), access to market facilities and other infrastructures (roads, credits), cropping system and land management, postharvest management, storage and market technologies and institutions, government policies (Takeshima *et al.*, 2017).

Using the soil fertility replenishment method, nutrients lost through runoff and sediments can be converted to monetary value to understand the economic magnitude of this threat (Enters, 1998). Therefore, soil erosion effect can be assessed in monetary terms through economic analyses of the different nutrients lost during erosive events.

2.9 Summary of literature review

There is a diversity of cropping systems with specific advantages related to soil properties improvement and crops yield increase. Soil erosion has been cited as an important threat to crop productivity especially in the tropics. The climatic conditions occurring in these regions increase the susceptibility of the soil to erosive factors. Soil erosion has different impacts on soil and crop development. Different methods (models and equations) have been developed for quantifying soil erosion but with some limitations related to their specificity, accuracy, and applicability under general conditions.

Nutrients loss through runoff and sediments increases soil fertility depletion coupled with poor soil management techniques in smallholder farms of SSA. Strategic soil and nutrient management practices are required to improve the productivity while reducing soil erosion through good crops performance**.** Biochar is a multipurpose soil amendment which has agronomic and environmental advantages. However,

investment in crop nutrition requires economic profitability to make the technology more attractive to stakeholders. The monetary value of the different nutrients lost through soil erosion, needs further scientific evidences to support the sustainability of soil management practices.

The current study attempts to fill the stated gaps.

CHAPTER THREE

3. GENERAL MATERIALS AND METHODS

3.1 Description of study site

The field experiment was carried out at the Anwomaso Agricultural Research Station of the Kwame Nkrumah University of Science and Technology, Kumasi,Ghana. The site is located within the semi-deciduous forest zone of Ghana and lies on longitude 1.52581° W and latitude 6.69756° N. In this zone, farmers mostly cultivate maize, cowpea and cassava at the subsistence level. The experiment field was a one-year fallow which hitherto, was used for maize production under different tillage and soil management systems. The natural vegetation was dominated by guinea grass during the fallow period.

The zone is characterized by two cropping seasons: March to August as the major season and September to December being the minor season as a result of the bimodal rainfall regime. The annual rainfall of the semi-deciduous forest zone of Ghana ranges between

1300 and 1500 mm (Opoku-Ankomah and Cordery, 1994 ; Nkrumah and Adukpo, 2014). However, during the research period, the total rainfall at the experimental site was 387, 272 and 466 mm during the 2016-major, 2016-minor and 2017-major seasons, respectively. The mean monthly temperature ranged between 24 and 28° C and the soil type, according to the WBR classification is Plinthic Vetic Lixisol and Kotei series (Ghana classification) (Amegashie, 2014) .

3.2 Field experiment

This study was a two-factor experiment in split–plot arranged in a randomized complete block design (RCBD). Cropping systems constituted the main plot whereas soil amendments, the subplots**.**

3.2.1 Soil amendments

The following soil amendments (Table 3.1) were applied according to the requirement of each of the crops (OFRA, 2012; Hardie *et al.*, 2014; Mia *et al.*, 2014) **Table 3.1. Types and rates of the different amendments**

Crop type	Amendments (kg ha^{-1})			
	NPK	NPK+Biochar	Biochar	Control
Maize	90 N 60 P_2O_5 60 K_2O	45 N 30 P_2O_5 30 K_2O 2500 BC	5000	
Soybean	20 N 40 P_2O_5 30 K_2O	10 N 20 P_2O_5 15 K_2O 2500 BC	5000	
Cowpea	20 N 40 P_2O_5 30 K_2O	10 N 20 P_2O_5 15 K_2O 2500 BC	5000	

The biochar used was produced at the Soil Research Institute (SRI), Kwadaso from rice husks through a slow pyrolysis process. Based on the recommendations of Major *et al.* (2010) and Uzoma *et al.* (2011) on longer-term effect of biochar on soil properties, this was applied once (at the beginning of the first cropping season: two weeks before sowing) during the three different cropping seasons while the other amendments were applied each season for direct and seasonal plant nutrition. After crushing into small particles for homogeneity, the biochar was sieved via 2 mm mesh (Amendola *et al.*, 2017) before being applied by hand to the respective plots and watered slightly.

Straight inorganic fertilizers (Urea, TSP and KCl) were applied as sources of nutrients (N, P and K) based on the recommended rates for each crop (Table 3.1). Fertilizers were applied two weeks after sowing; with split application of urea for maize: 2/3 of the rate was applied two weeks after sowing and the 1/3 remaining, four weeks after sowing.

3.2.2 Cropping systems

Four cropping systems were evaluated in the study (Table 3.2). Each system was expected to have unique land cover characteristics with a given impact on soil conservation under natural rainfall regime.

Table 3.2. Cropping systems established in the study

2016-major season	2016-minor season	2017-major season
Sole Maize (MZ)	Sole Maize (MZ)	Sole Maize (MZ)

Sole Soybean (SB)	Sole Soybean (SB)	Sole Soybean (SB)
Maize + Soybean (MZ+SB)	Maize + Soybean (MZ+SB)	Maize + Soybean (MZ+SB)
Sole Cowpea (CW)	Sole Cowpea (CW)	Sole Cowpea (CW)

As an improved system of the conventional method of 1:1 intecropping, the MBILI (MBILI = two in Kiswahli and the acronym of "Managing Beneficial Interaction in Legume Intercrops") system was used for maize and soybean intercropping. Under this system, two lines of soybean were cropped between two lines of maize and with the same spacing as in the sole systems for both crops. The MBILI system allows more legume population, compared to the conventional system of 1:1 but without changing the plant population for the maize and is more profitable (Okalebo *et al.*, 2006; Woomer 2007 ; Mucheru-Muna *et al.*, 2010).

3.2.3 Field layout

The treatments were replicated three times. Each replication had 16 plots under cultivation for the 16 treatments (4 x 4) plus 1 bare plot as erosion check or control. Each individual plot measured 12 m x 3 m separated from the subsequent plot with aluzinc sheets fixed 0.5 m deep and 0.75 m high at the surface to avoid any runoff contamination from the neighbouring plots. The observation was carried out during three consecutive growing seasons (2016-major, 2016-minor and 207-major) and the field was under natural rainfall regime. With the three replications, the experiment consisted of 51 plots (Plate 3.1) with 48 plots under cropping plus 3 bare plots (Plate 3.2 and Table 3.3). The field was divided into three slope classes namely 3, 6 and 10 % for slope 1, slope 2 and slope 3, respectively.

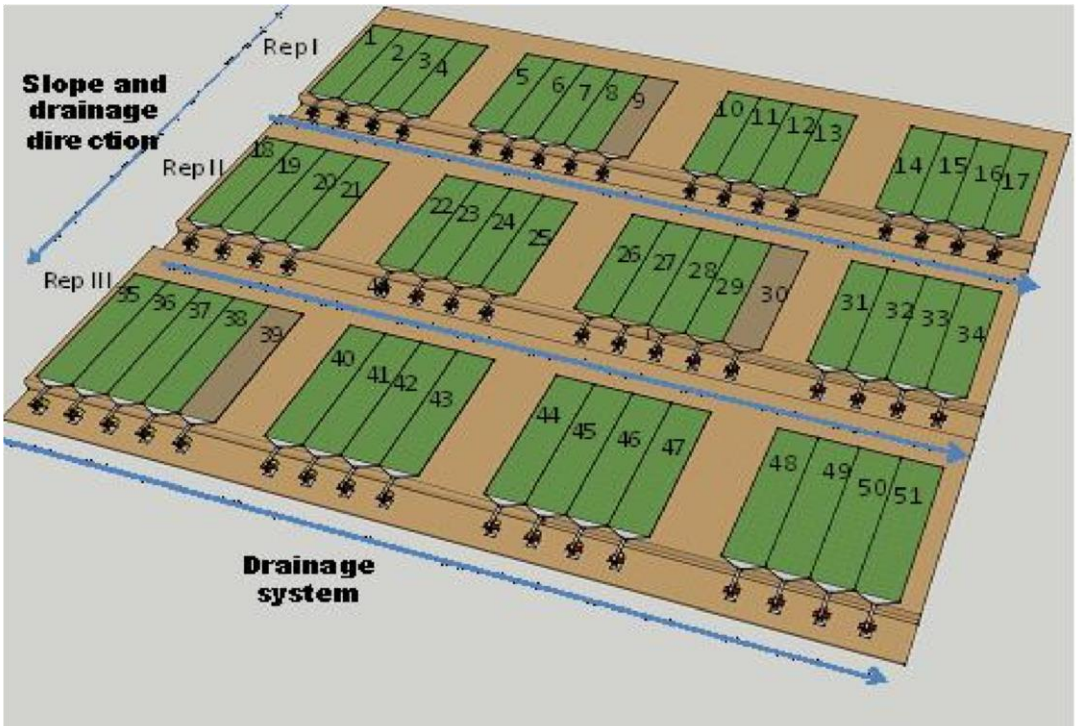

Plate 3.1. Field layout showing the different treatment

Table 3.3. Field layout and allocation of the different treatments

Cropping systems	Soil amendments	Plots number
Sole Maize	NPK+BC	10, 29 and 42
	NPK	12, 27 and 43
	BC	13, 28 and 40
	Control	11, 26 and 41
Soybean	NPK+BC	8, 18 and 44
	NPK	5, 20 and 47
	BC	6, 21 and 46
	Control	7, 19 and 45
Maize+Soybean	NPK+BC	3, 22 and 49
	NPK	1, 22 and 50
	BC	4, 25 and 48
	Control	2, 23 and 51
Cowpea	NPK+BC	17, 31 and 35
	NPK	14, 34 and 37
	BC	15, 33 and 36
	Control	16, 32 and 38
Bare plot	No amendment	9,30 and 39

Plate 3.2. Bare plots associated with different cropping systems (sole cowpea, sole soybean and sole maize)

3.2.4 Land preparation and sowing

The field was slashed and hoed (because it was under fallow). For the subsequent cropping seasons, the plots were only hoed before sowing.

All the crops were sown the same day during each season. The maize seeds were sown at 80 cm x 40 cm (for both sole and intercropping systems) at 3 seeds/ hill and thinned to two plants per hill one week after germination. Two soybean seeds were sown per hill at a spacing of 40 cm x 10 cm for both systems. For the intercropping system, the plant population remained unchanged for the maize while the soybean was half population density per area. Cowpea was sown at 60 cm x 20 cm spacing at two seeds per hill. Overall, plant stands for sole maize, soybean and cowpea were 31,250, 250,000 and 83,334 stands ha^{-1} respectively and 125 000 stands ha^{-1} for the soybean in MBILI intercropping system (the maize population was constant in the intercropping system).

3.2.5 Characteristics of the crops varieties

For each of the three test crops, one early maturing variety was used: maize (var. Omankwa), cowpea (var. Asontem) and soyabean (var. Soung-pungun). The seeds for these varieties were obtanined from the Crops Research Institute (CRI), Femesua, Kumasi. The germination percentages ranged between 85-95, 95-100 and 85-95 for the maize, cowpea and soybean, repectively. The repective potential yields are 3-4.7 Mg ha^{-}

[1]; 1.8 Mg ha^{-1} and 3 Mg ha^{-1} with their resepctive emegernce and physiological maturity periods as 4-6 and 82-90 DAS; 3-4 and 75-80 DAS and 3-5 and 85-90 DAS.

3.2.6 Agronomic practices

3.2.6.1 Weeds and pests control

Pests and diseases are among the important constraints to crop production in SSA, even when sustainable nutrient management tecnhnologies are applied. During the experiments, insect pests were controlled using Lambda Masat 2.5 EC (25 g lambda cyhalothrin) and Cymethoate Super at the rates of 80 mL 30 L^{-1} of water and 100 mL /30 L water, respectively. The insects obseved were thrips, pod borers, aphids, betteles for the cowpea; stalks borers for the maize and aphids and pod borers for soybean. For weed control, hoeing and hand pulling were emplyed.

3.2.6.2 Water drainage

Water collected from each plot was drained out of the experimental field through a common drainage system for each block. The drainage channel was slightly slopy so that water can flow from the last plot to the first one before draining out of the experimental field by gravitation.

3.3 Soil sampling and laboratory analyses

3.3.1 Soil sampling

Initial soil samples were taken randomly at the depth of 20 cm. From each block, three samples were taken and bulked to obtain one composite sample for each block. In total, three composite samples were taken for initial characterization. These samples were then subjected to analysis after air – drying, crushing and sieving through a 2 mm sieve.

Chemical and physical properties were determined following specific procedures for each parameter as described in sections 3.3.2 and 3.3.3.

For moisture and hydrological parameters, fresh and undisturbed soil samples were taken at of 0-20 cm depth at the end of the third season of cropping. The specific procedures are described from section 3.3.3

For chemical and particles size analyses, soil sampling was done at harvest during each cropping season. Four sub-soil samples were collected at 0-20 cm from each plot and thoroughly mixed to obtain one composite sample, representative of each plot.

These were then subjected to analysis as per sections 3.3.2 an 3.3.3.

3.3.2 Determination of soil physical parameters

3.3.2.1 Particle size analysis

The hydrometer method was used for this analysis. This method relies on the differential settling velocities of different particle sizes within a water column. The settling velocity is also a function of liquid temperature, viscosity and specific gravity of the falling particle (Okalebo *et al*., 1993). A 51 g soil sample was weighed into a

'milkshake' mix cup. To this, 50 mL of 10% sodium hexametaphosphate (calgon) along with 100 mL distilled water were added. The mixture was shaken for 15 minutes after which the suspension was transferred from the cup into a 1000 mL measuring cylinder and distilled water added to reach the 1000 mL mark. The mixture was inverted several times until all soil particles were in suspension. The cylinder was placed on a flat surface and the time noted. The first hydrometer and temperature readings were taken at 40 seconds. After the first readings, the suspension was allowed to stand for 3 hours and the second hydrometer and temperature readings were taken. The first reading indicated the percentage of sand whilst the second reading was percentage clay. The percentage of silt was determined by the difference. Equations 3.1, 3.2 and 3.3 were used for the computation of % sand, clay and silt respectively.

Calculations:

% Sand = 100 – [H_1 + 0.2 (T_1 – 20) – 2.0] * 2 (3.1)

% Clay = [H_2 + 0.2 (T_2 – 20) – 2.0] * 2 (3.2)

% Silt = 100 – (% sand + clay) (3.3) where:

H_1 = Hydrometer reading at 40 seconds;

T_1 = Temperature at 40 seconds;

H_2 = Hydrometer reading at 3 hours;

T_2 = Temperature at 3 hours;

0.2 (T – 20) = Temperature correction to be added to hydrometer reading; -

2.0 = Salt correction to be added to hydrometer reading.

3.3.2.2 Bulk density

Undisturbed soil samples were taken at 20 cm depth using a core sampler (20 cm of height and 12 cm of diameter). The fresh soil samples were dried at 105 °C to a constant weight for 48 h and weighed. The bulk density (ρb) was calculated using equation 3.4.

$$\rho b = \frac{Ms}{Vt} \quad (3.4)$$

where:

Ms = Oven dry weight of soil (g)

V_t = total volume of sampling core ($\pi r^2 h$: π=3, 14; r = radius of the cylinder, h = height of the cylinder).

3.3.2.3. Gravimetric moisture content

This method was based on soil moisture removal by oven–drying at 105 °C for 48 h to a constant weight. The gravimetric moisture content (ϴg) was calculated based on equation 3.6.

$$\Theta g\ (\%) = \frac{W_3 - W_1}{W_2 - W_1} * 10 \quad (3.6)$$

where:

ϴg = gravimetric moisture content ;

W_1 = Weight of empty core; W_2

= Weight of core+ fresh soil;

W_3 = Weight of core + dried soil.

3.3.2.4 Volumetric moisture content

This parameter was calculated by multiplying the gravimetric moisture content by the bulk density as per equation 3.7.

$$\Theta v\ (\%) = \frac{\theta g}{\rho w} * \rho b \quad (3.7)$$

where:

Θv= volumetric water content ;

Θ_g = gravimetric moisture content ;

ρb = bulk density Mg m^{-3};

ρw = density of water Mg m^{-3} (assumed to be 1).

3.3.3 Chemical analyses

3.3.3.1 Soil pH

Soil pH was determined with a pH meter in a soil: water ratio of 1:1. Ten grams soil sample was weighed into a beaker. To do this, 10 mL distilled water was added and the suspension stirred continuously for 60 minutes and allowed to stand for 15 minutes. After calibrating the pH meter with buffer solutions of pH 4.0 and 7.0, the pH was read by immersing the electrode into the soil suspension.

3.3.3.2. Organic carbon

The modified Walkley and Black procedure as described by Okalebo *et al*. (1993) was used in the determination of organic carbon. One gram of soil sample was weighed into an Erlenmeyer flask. A reference sample and a blank were included. Ten milliliters of 1.0 *N* (0.1667 *M*) potassium dichromate was added to the sample and the blank. Concentrated sulphuric acid (20 mL) was carefully added to the soil from a measuring cylinder, swirled and allowed to stand for 30 minutes in a fume cupboard. Distilled water (250 mL) and 10 mL concentrated orthophosphoric acid were added and allowed to cool. A diphenylamine indicator (1 mL) was then added and titrated with 1.0 *M* ferrous sulphate solution.

The organic carbon content was calculated from equation 3.8:

$$\text{Carbon } (\%) = \frac{M*(V_b - V_s)*1.33*0.003*100}{Wt} \tag{3.8}$$

where:

M = molarity of ferrous sulphate used in titration;

V_b=blank titrated with 0.5 ferrous sulphate;
V_s = sample titrated with 0.5 ferrous sulphate;

0.003 = milliequivalent weight of C expressed in grams (12/4000) ;

1.33 = correction factor used to convert the wet combustion C value to the true C value since the Wet combustion method is about 75 % efficient in

estimating C value (i.e. 100/75 = 1.33);

Wt = weight of air-dry sample in gram.

3.3.3.3 Total nitrogen

The total nitrogen content of the soil was determined using the Kjeldahl digestion and distillation procedure as described by Okalebo *et al*. (1993) . Ten grams of soil was weighed into a 500 mL Kjeldahl digestion flask and one spatula full of copper sulphate, sodium sulphate and selenium mixture followed by 30 mL of concentrated H_2SO_4 were added. The mixture was heated strongly to digest the soil to a permanent clear green colour. The digest was cooled and transferred to a 100 mL volumetric flask and made up to the mark with distilled water. A 10 mL aliquot of the digest was transferred into a Tecator distillation flask and 20 mL of 40 % NaOH solution added. The ammonium distilled was collected into a 250 mL flask containing 15 mL of 4 % boric acid with mixed indicator of bromocresol green and methyl red. The distillate was titrated with 0.1 *N* HCl solution. A blank digestion, distillation and titration were carried out without soil as a check against traces of nitrogen in the reagents and water used.

$$\% \text{ N} = \frac{(a-b) * 1.4 * N * V}{S * t} \tag{3.9}$$

where:

a = mL HCl used for sample titration; b

= mL HCl used for blank titration;

1.4 = 14 * 10^{-3} * 100 % (14 = atomic weight of N);

N = normality of HCl; V = total volume of digest; s =

mass of air dry soil sample digested in grams (10.0 g); t =

volume of aliquot taken for distillation (10.0 mL).

3.3.3.4 Available phosphorus

This parameter was determined using the Bray P1 method (Okalebo *et al.*, 1993). The method is based on the production of a blue complex of molybdate and

orthophosphate in an acid solution. Standard series of 0, 0.8, 1.6, 2.4, 3.2, and 4.0 µg P/mL were prepared by diluting appropriate volumes of 10 µgP/mL standard substock solutions. These standards were subjected to colour development and their respective transmittances read on a spectronic 21D spectrophotometer at a wavelength of 520 nm. A standard curve was constructed using the readings.

A 2.0 g soil sample was weighed into a 50 mL shaking bottle and 20 mL of Bray-1 extracting solution added. The sample was shaken for one minute and then filtered through No. 42 Whatman filter paper. Ten milliliters of the filtrate was pipetted into a 25 mL volumetric flask and 1 mL each of molybdate and reducing agent was added for colour development. The percent transmission was measured at 520 nm wavelength on a a spectronic 21D spectrophotometer. The concentration of P in the extract was obtained by comparison of the results with the standard curve.

Calculations:

$$P\ (mgkg^{-1}) = \frac{(\text{reading Graph}*20*25)}{w*10} \qquad (3.10)$$

Where:

w = sample weight in grams; 20

= mL extracting solution; 25 =

mL final sample solution;

10 = mL initial sample solution.

3.3.3.5. Exchangeable cations determination

Exchangeable bases (calcium, magnesium, potassium and sodium) in the soil were determined in 1.0 *N* ammonium acetate extract and the exchangeable acidity (hydrogen and aluminium) in 1.0 *M* KCl extract (Okalebo *et al.*, 1993)

Determination of calcium and magnesium

For calcium and magnesium analyses, a 25 mL aliquot of the extract was transferred into an Erlenmeyer flask. To this was added 1 mL each of hydroxylamine hydrochloride, 2.0 % potassium cyanide, 2.0 % potassium ferrocyanide and 10 mL ethanolamine buffer and also 0.2 mL Eriochrome Black T solution. The solution was titrated with 0.01 *M* EDTA (ethylene diamine tetraacetic acid) to a pure turquoise blue colour.

Determination of calcium only

A 25 mL aliquot of the extract was transferred into a 250 mL Erlenmeyer flask and the volume made up to 50 mL with distilled water. After this, were added 1 mL each of hydroxylamine, of 2.0 % potassium cyanide and of 2.0 % potassium ferrocyanide solutions. After a few minutes, 5 mL of 8.0 *M* potassium hydroxide solution and a spatula of murexide indicator were added. The resultant solution was titrated with

0.01 *M* EDTA solution to a pure blue colour.

The concentration of calcium + magnesium or calcium were calculated using the following equation:

$$\text{Ca} + \text{Mg (or Ca) (cmolc/kg soil)} = \frac{0.01*(Va-Vb)*1000}{w} \qquad (3.11)$$

where:

w = weight (g) of air – dried soil used;

V_a = mL of 0.01 *M* EDTA used in sample titration;

V_b = mL of 0.01 *M* EDTA used in blank titration;

0.01 = concentration of EDTA.

Determination of exchangeable potassium and sodium

Potassium and sodium in the soil extract was determined by flame photometry. Standard solutions of 0, 2, 4, 6, 8 and 10 ppm K^+ and Na^+ were prepared by diluting appropriate volumes of 100 ppm K^+ and Na^+ solution to 100 mL in volumetric flask using distilled water. Photometer readings for the standard solutions were determined and a standard curve constructed. Potassium and sodium concentrations expressed in (cmolc kg^{-1}soil) were read from the standard curve and calculated using the equation 3.12 and 3.13, respectively.

$$\text{Exchangeable } K^{+}(\text{cmolc/kg soil}) = \frac{Graph\ reading*100}{39.1*W*10} \qquad (3.12)$$

$$\text{Exchangeable } Na^{+}(\text{cmolc/kg soil}) = \frac{Graph\ reading*100}{23*W*10} \qquad (3.13)$$

where:

w = air-dried sample weight of soil in grams;

39.1= atomic weight of potassium;

23 = atomic weight of sodium.

Determination of exchangeable acidity

For the exchangeable acidity, the soil sample was extracted with unbuffered 1.0 *M*

KCl solution. Ten grams of soil sample were weighed into a 200 mL plastic bottle and 50 mL of 1.0 *M* KCl solution added. The mixture was shaken on a reciprocating shaker for 2 hours and filtered. An aliquot of 25 mL of the extract was pipetted into a

250 mL Erlenmeyer flask and 4-5 drops of phenolphthalein indicator solution added. The solution was titrated with 0.025 *N* NaOH until the colour just turned permanently pink. A blank was also included in the titration.

Calculation:

$$\text{Exchangeable acidity (cmolc kg}^{-1}\text{ soil)} = \frac{(a-b)*M*2*100*mcf)}{w} \quad (3.14)$$

where: a = mL NaOH used to titrate with sample; b

= mL NaOH used to titrate with blank;

M = molarity of NaOH solution; w = weight (g) of air-

dried sample; 2 = 50/25 (filtrate/ pipetted volume); mcf =

moisture correcting factor (100 + % moisture)/100.

3.3.3.6 Effective cation exchange capacity

This parameter was calculated by summation of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and exchangeable acidity (Al^{3+} and H^+).

3.4 Characterization of biochar and plant samples

The biochar which was applied as soil amendment was characterized through chemical analyses. A representative sample was taken, dried in the oven at 40 °C and ground to pass through a 1 mm sieve before imposing the treatments.

The grain and above ground biomass of each crop (maize, soybean and cowpea) were milled into finer particles for chemical analyses. The sub-samples of grains and biomass were taken from the total yield of each plot as described in section 8.2.1 of Chapter 8.

3.4.1 Total nitrogen

Total nitrogen content of biochar and plant samples were determined by the Kjeldahl digestion method in which the organic materials were oxidized by sulphuric acid, hydrogen peroxide with selenium (catalyst), as described in section 3.3.3.

3.4.2 Phosphorus and potassium

A 0.5 g of organic material (biochar, grains and crops residues) was ashed in muffle furnance and dissolved in 1.0 *M* HCl of solution and filtered. The filtrate was diluted to 100 mL with distilled water.

3.4.2.1 Phosphorus

A 5 mL aliquot of the filtrate was taken into a 25 mL volumetric flask. Five millilitres of ammonium vanadate solution and 2 mL of stannous chloride solution were added. The volume was made up to 25 mL with distilled water and allowed to stand for 15 minutes for full colour development. A standard curve was developed concurrently with phosphorus concentrations ranging from 0, 5, 10, 15 to 20 mg P/kg organic material. The absorbance of the sample and standard solutions were read on a spectronic 21D spectrophotometer at a wavelength of 470 nm. The absorbance values of the standard solutions were plotted against their respective concentrations to obtain a standard curve from which phosphorus concentrations of the samples were determined.

3.4.2.2 Potassium

Potassium in the leachate was determined using a Gallenkamp flame analyzer. A standard solution of potassium was prepared with concentrations of 0, 20, 40, 60, 80 and 100 mg L^{-1} of solution. The emission values which were read on the flame analyzer were plotted against their respective concentrations to obtain standard curves.

3.5 Runoff off sample analyses

3.5.1 Total nitrogen

Nitrogen measurement was based on Okalebo *et al.* (1993) method. A 10 mL runoff sample was measured and transferred into a 500 mL digestion flask. One spatula full of Kjeldahl catalyst (sodium sulphate + copper sulphate + selenium powder mixture) and 20 mL concentrated H_2SO_4 were added to the digestion flask. The solution was digested until it became colourless and was allowed to cool before decanting it into 50 mL volumetric flask and topped –up to the mark. A 10 mL aliquot of the digestate was measured into a distillation tube and 20 mL of NaOH was added. The tube was connected to Kjeldahl system. The mixture was distilled for 5 minutes and the distillate collected in 10 mL boric acid which was also connected to the Kjeldahl apparatus. A final volume of 100 mL distillate containing boric acid and mixed indicator was obtained. The titration of the solution was done against the standard acid (0.1 *N* HCl) until the appearance of a permanent pink colour. A blank titration was run with equal volume of distilled water.

The percentage of nitrogen was calculated as follows;

$$N\ (mg\ L^{-1}) = \frac{14 * (A - B) * N * 1000}{1} \quad (3.15)$$

where: A = volume of standard HCl used in the sample titration

B = volume of standard HCl used in the blank titration

N = Normality of standard HCl

NB: Weight of l mL sample used, considering the dilution and the aliquot taken for distillation

$$= \frac{10\ mL\ x\ 10\ mL}{100\ mL} = 1\ mL$$

3.5.2 Determination of phosphorus and potassium

3.5.2.1 Sample preparation

Out of a thoroughly mixed and homogenized water sample, 50 mL was measured and mixed with 30 mL and 10 mL of HCl and HNO_3, respectively in the ratio of 3:1 in a Kjeldahl flask. The mixture was digested until it became clear. The digested mixture was allowed to cool after which it was decanted into a 50 mL volumetric flask and topped up to the mark with distilled water. The digestate was transferred and stored in a clean bottle for the quantitative estimation of phosphorus and potassium.

3.5.2.2 Phosphorus determination

Based on the Okalebo *et al.*(1993) method, a vanadomolybdate reagent was prepared by dissolving 22.5 g of ammonium molybdate in 400 mL of distilled water and 1.25 g of ammonium vanadate in 300 mL of boiling distilled water. The vanadate solution was added to the molybdate solution and cooled to room temperature. A 250 mL of analytical grade HNO_3 was added to the solution mixture and diluted to 1 litre with deionized water. The standard phosphate solution was also prepared by dissolving 0.2195 g of analytical grade KH_2PO_4 in 1000 mL distilled water. This solution contains 50 µg P/mL. A standard curve was prepared by pipetting 1, 2, 3, 4, 5 and 10 mL of standard solution (50 µg P/mL) in 50 mL volumetric flasks. A 10 mL of vanadomolybdate reagent was added to each flask and the volume made up to 50 mL. This gave a P content of the flasks as 1, 2, 3, 4, 5, and 10 µg P/mL. These concentrations were measured on a spectronic 21 D spectrophotometer to give absorbance measurements at a wavelength of 420 nm. A plot of absorbance against concentration was used to prepare the calibration curve. Ten milliliters of the sample solution were transferred into a 100 mL volumetric flask and 10 mL of vanadomolybdate reagent was added and volume made up to 100 mL. The sample was kept for 30 minutes for colour development. A stable yellow colour was developed. The sample was then read on the spectronic 21 D spectrophotometer at 420 nm. The observed absorbance was used to determine the P content from the standard curve. The mg L^{-1} P was calculated as:

$$P\ (mg\ L^{-1}) = \frac{C * df * 1000}{1000} = \frac{C * 10 * 1000}{1\ 000} \quad (3.16)$$

where : C = concentration of P (µg mL^{-1}) as read from the standard curve;

df = dilution factor and 1 000 = factor for converting µg to mg.

3.5.2.3 Potassium determination

Potassium was determined using a flame photometer. A 1.908 g of analytical grade KCl previously dried in an oven for 4 hours at 105° C was dissolved in 200 mL of deionised water and volume made up to 1000 mL. This gave a standard of 1000 ppm. A calibration curve (standard curve) of 200, 400, 600 and 800 ppm was plotted. All the absorbance readings were taken using the flame photometer. The sample solutions from the HCl and HNO_3, were read on the flame photometer. From the standard curve, the concentration of K was calculated using the particular absorbance observed for the sample.

Calculation:

K content (µg) per mL of water sample = C x df (3.17)

$$K\ (mg\ L^{-1}) = \frac{C * df * 1000}{1000} \quad (3.18)$$

where:

C = concentration of K (µg mL^{-1}) as read from the standard curve

df = dilution factor and

1000 = factor for converting µg to mg.

3.6 Statistical analyses

Before the analysis of variance (ANOVA) using GENSTAT v. 12, the normal distribution, for soil and plant data as affected by the different treatments, was checked using residual plots. Significant effect between the treatments was confirmed at F probability < 0.05 and the means separation done using the Least Significant Difference (LSD) method at 5 % level of probability.

For the model goodness and accuracy assessment, specifics statistic parameters (R^2, RMSE, NSE and RSR) as well as the QQ diagnostic plots were performed using R statistics (R 3.4).

CHAPTER FOUR

4. NEW METHOD FOR RUNOFF ESTIMATION UNDER DIFFERENT SOIL MANAGEMENT PRACTICES

Abstract

Soil erosion measurement has been widely carried out using different approaches based on models, direct runoff and sediment collections. However, most of the methods are poorly applied by the different stakeholders due to the cost, the accuracy and the tedious interventions. This study aimed to develop and test a new method for runoff characterization which may be more applicable and adaptable to different situations of soil and crop managements. An experiment was therefore carried out on runoff plots under different cropping systems (sole maize, and maize intercropped with soybean) and soil amendments (NPK, NPK + Biochar, Biochar and Control) in the semi-deciduous forest zone of Ghana. The study was a two-factor experiment laid out in split – plot and arranged in a randomized complete block design (RCBD). Cropping systems constituted the main plot whereas soil management, the subplot. To assess the quality of the developed method, different statistical parameters were used: p-values, coefficient of determination (R^2), Nash –Sutcliffe efficiency (NSE), root mean square (RMSE) and root square ratio (RSR). The inorganic amendments associated with biochar treatments under each cropping system were more effective in reducing surface runoff. At $p < 0.001$, R^2 ranged from 0.88 to 0.94 which showed good accuracy of the method developed. The dispersion between the predicted and observed values was low with RMSE varying from 1.68 to 2.66 mm which was less than 10 % of the general mean of the runoff. Moreover, the low variability between parameters was confirmed by the low values of RSR ranging from 0.38 to 0.46 (with

$0.00 \leq RSR \leq 0.50$ for perfect prediction). During the observation periods, NSE values varied from 0.79 to 0.86 (≥ 0.75 being the threshold for excellent prediction). The sensitivity analysis showed that the method under high amount of runoff (simulation including bare plots) was poorly adapted. This suggests that dimensions of runoff plots should be based on runoff coefficient of the region by analyzing the possible limits of an individual rainfall amount of the site. These findings provide good opportunity for scientists and other stakeholders involved in soil conservation and crop production to monitor soil degradation.

Keywords: cropping systems, erosion, sediment, soil amendment, soil degradation

4.1 Introduction

Characterizing soil erosion on the field is a critical option to sustain crop productivity due to its effect on the environment and on crop development (Lal, 1998). Describing and quantifying the rate of soil erosion in a watershed over spatial and time scales are major constraints to direct soil erosion assessment due to the limitations in field measurement (Pandey *et al*., 2016) and the significant amount of sediments and runoff to handle. Adapted interventions are therefore clearly required to investigate the effect of climate and land use change, as the driving factors of rainwater fate on erosion rates towards the recommendation of sustainable land management practices.

Due to the constraints to the direct soil loss quantification, different and specific models and equations have been widely used to predict soil erosion over a wide range of conditions (e.g. Wischmeier and Smith, 1978; Hudson, 2005; Djuma *et al.*, 2017; Vaezi *et al.*, 2017, etc). Most of the developed models are site-based equations, making them more applicable to specific agro-ecological conditions (Yu *et al.*, 1997) without a general adaptation to each ecosystem. They vary significantly in terms of their capability and complexity, input requirement, representation of processes, spatial and temporal scale accountability, practical applicability and with the types of output they provide (Pandey *et al.*, 2016). For the applicability, each desirable model of soil erosion rate assessment should satisfy specific conditions of universal acceptability; reliability;

robustness in nature; ease of use with minimum data; and ability to take account of changes in land use, climate and conservation practices (Pandey *et al.*, 2016). Apart from the modeling by prediction, direct soil erosion measurement involve the use of big containers to harvest the runoff but with poor success (Olson *et al*., 2014; Mohawesh *et al*., 2015; Ngetich *et al*., 2015).

On the other hand, the use of automatic tipping buckets is one of the options for direct quantification of soil runoff and sediments with good accuracy (Khan and Ong, 1997; Amegashie, 2014) However, this method is perceived as very tedious and costly for adoption by the different stakeholders involved in soil and water conservation practices. Indeed, soil erosion measurement using direct and indirect approaches have been challenging in different studies due to the accuracy of the method and the important parameters which are required for both methods (Azmera *et al.,* 2016; Bellin *et al.*, 2016). Due to the various constraints to the tipping buckets and other methods of soil erosion characterization, there is need to develop more useful and adapted means based on numerical method which provides new options of assessing accurately soil runoff. This study therefore aimed to develop and test a new method to measure surface runoff on the field to reduce the constraints related to direct and indirect measurements.

4.2 Materials and Methods

The methods and procedures used for the calibration of the tipping bucket, model assumptions and other specific processes related to the new method of runoff measurements are described in this section of specific methodology in connection with the first objective of the overall study. The experiment with the different soil and crop management practices described in sections 3.1 and 3.2.

4.2.1. Surface runoff measurement with tipping buckets

The runoff amount from the plots was collected at the base of each runoff plot with the tipping bucket device (Plate 4.1).

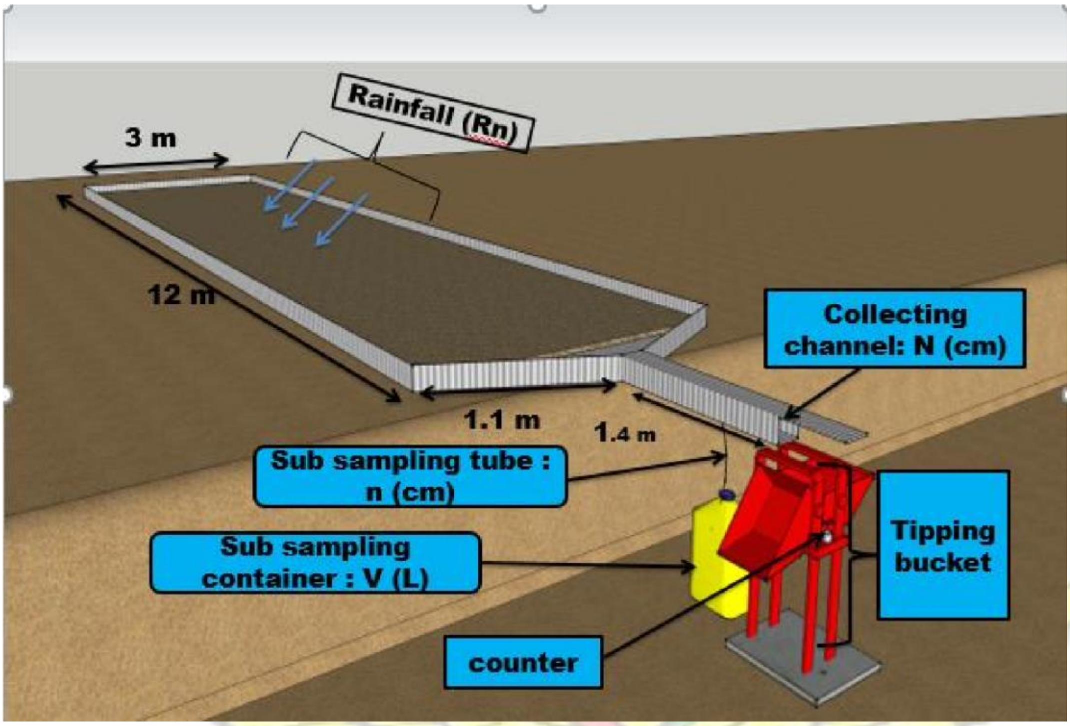

Plate 4.1. Layout of runoff plot with the tipping bucket device for runoff and soil erosion assessment

The tipping bucket device consisted of a collecting trough, tipping bucket and counter as described below:

Collecting trough: After the last row of crops, there was trapeze surface (covered by aluzinc sheets) to retain the first portion of runoff and sediments from the plot whilst the rest of the water and the loads were passed through a mesh of 0.1 cm diameter for collection with the tipping bucket (Plate 4.2).

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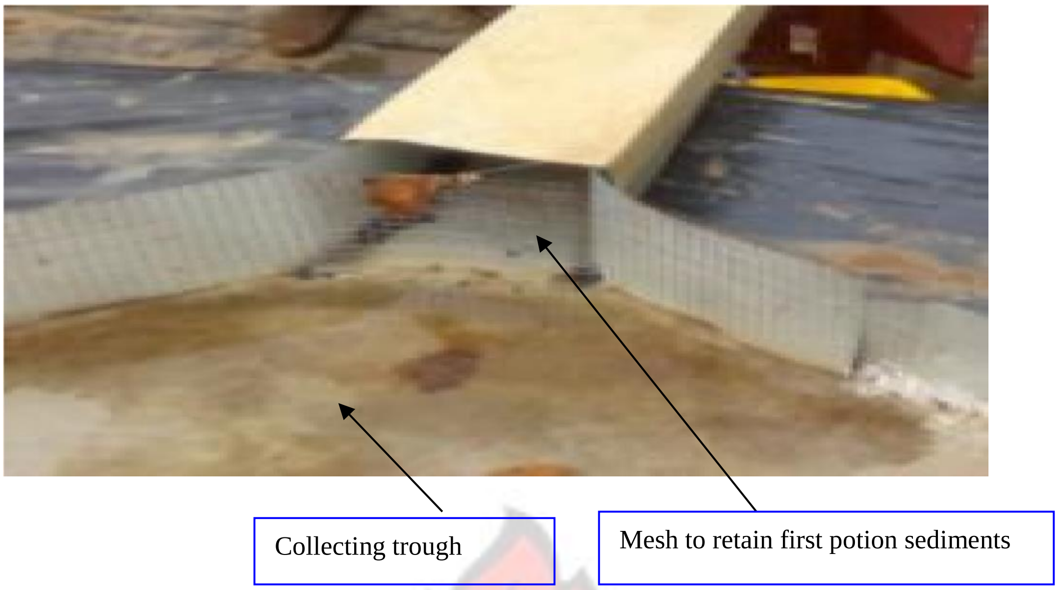


Plate 4.2. Collecting trough with aluzinc sheet at the end of each runoff plot and the mesh fixed between the channel and the collecting trough to retain the first portion of the runoff loads

Tipping bucket devices and counter: After the mesh, the rest of water and its loads were passed through a channel of diameter 22.5 cm, ending into a tipping bucket with two specific buckets (sides) with a known tipping volume for each (Plate 4. 1). Once a bucket was filled with water or at the tipping volume, it tipped automatically and this was recorded from a counter fixed to the system. As a result, calibration of each of the devices was done each cropping season to confirm the tipping volumes (Plate 4.3 a). The number recorded from the counter multiplied by the tipping volume of each bucket gave the volume of runoff collected from each plot. A bucket may tip at different volume from the other or before full volume (Plate 4.3 b). The volume of each bucket, obtained during the calibration process, was therefore used to calculate the total amount of runoff from each plot passing through the tipping bucket using equation 4.1.

Plate 4.3 (a). Seasonal calibration to determine the tipping volume of each bucket. (b)Tipping bucket devices installed at the end of a runoff plot with the counter and the tipping volume of each bucket: 1.20 L and 3 L $Ø = m_1 * \alpha + m_2 * \beta$

(4.1) where: Ø (L) = Total amount (volume) of runoff passed through the tipping buckets ; m_1 (L) = Tipping volume of the first bucket and m_2 (L) = tipping volume of the second bucket. The tipping volume of each bucket was obtained at the tipping point during the calibration process carried out during each season;

α and β: number of tipping times from the counter for the first and second buckets, respectively.

Equation 4.2 was used to determine the total amount of runoff after subtracting the amount of water from the direct rainfall.

$$mi = Ø + \gamma - \rho \qquad (4.2)$$

$$m = \sum_{i=1}^{k} mi \qquad (4.3)$$

where: mi (L) = total amount (volume) of runoff for an individual erosive rainfall;

m (L) = total amount (volume) of runoff during k rainfall events; k = number of erosive rainfall events; γ (L) = volume of runoff collected from the small container (gallon) placed under the channel (sub-sample);

Ø (L) = amount of runoff from the tipping buckets and ρ (L) = the volume of water from the direct rainfall in the collecting trough determined using the equation 4.4.

$$\rho = A * r * 10^6 \quad (4.4)$$

where:

A (mm²) = area of the collecting trough which is trapezoidal; r (mm) = rainwater amount during each erosive storm and

10^6 = conversion factor for water of mm^3 into L).

4.2.2. Development of the new method for soil runoff measurement

The new method developed was based on mathematical equations described in sections 4.2.2.1-4.2.2.2.

4.2.2.1. Procedures and theoretical approaches

After each sampling, a specific order was designed for all the tipping buckets: wherein buckets for the whole field with highest tipping volumes were related to the first runoff of the next erosive storms. This enabled the determination of the values of α or β since only one number was read on the counter. In case of equal tipping volume

($m_1 = m_2$) for both buckets, there was not any specific order to follow since $m_1 = m_2$. When the counter reads even number, this number was divided by two to obtain the values of α and β. But for the uneven number, $\alpha = \beta + 1$ (assuming that α is the number of records of the bucket of the highest volume). This means that the uneven number minus one and divided by two should give β value.

By using the installed devices of tipping buckets, the total amount of runoff from each plot was collected through a uniform channel, with **N (cm)** as its diameter, and connected to the end of the plot (Plate 4.1). A line level was used for a good horizontality of the channel to ensure that the water was uniformly distributed to each space of N_i cm of the channel; and to be sure that the channel is not slopy and that all the parts are on the same level of elevation. A small tube with known diameter **n (cm)** was then fixed on the uniform channel to collect small portion of runoff into a small container (gallon) of **v** (L) as the volume.

The diameter of the channel; the small tube and the volume of the gallon for sub-sampling should depend on the rainfall characteristics of the zone. Knowing the maximum individual rainfall of the zone, this can help to decide on the sizes of the three parameters (N, n and v). This allowed for avoidance of any loss if the small container gets full before the sampling during the specific rainfall event. Mathematically, this is represented by equation 4.5 and this condition should be respected to avoid any flooding during the erosive rainfall. Thus, by using the principle of runoff coefficient, the container will never be full because the plot cannot lose the total amount of water received from the rainfall; even if the land is bare and very slopy. The runoff coefficient depends on soil properties, soil moisture content, land cover, the slope and rainfall characteristics (Viglione *et al.*, 2009; Pektaş and Cigizoglu, 2013) as well as the interaction between groundwater and surface water flows (Mahmoud *et al.*, 2014) .

$$\frac{N}{n} > \frac{Rn}{v} \qquad (4.5)$$

where: N (cm) = Diameter of the collecting channel;

n (cm) = Diameter of the tube fixed on the channel;

Rn (L) = Maximum amount of an individual rainfall of the study zone (this can be taken from the previous meteorological data during some years) that can be collected on a specific area; v (L) = volume of the small container for sub sampling the- runoff.

4.2.2.2. Runoff estimation or prediction

Following the above conditions and assumptions, the total amount of runoff for each erosive rainfall event (**pi**) and the total runoff during specific period of k rainfall events were determined by equations 4.6 and 4.7 respectively:

$$pi = \frac{N \times w}{n} \qquad (4.6)$$

$$p = \sum_{i=1}^{k} pi \qquad (4.7)$$

where:

N (cm) = diameter of the collecting channel; n (cm) = diameter of the small tube fixed on the channel; w (L) = volume of runoff in the small container; pi (L)= individual predicted runoff for a specific erosive rainfall event; p (L)= total volume of runoff predicted during a period of k erosive rainfall events k = number of rainfall events during the

study period.

4.2.3. Evaluation of method quality and statistical analysis

Different statistical parameters were used for quality assessment of the method. The goodness of fit between predicted and measured values was assessed using the statistical prediction errors. The coefficient of determination (R^2), Nash –Sutcliffe efficiency (NSE), root mean square (RMSE) and root square ratio (RSR) were the parameters used to assess the quality of the method (Kisi *et al*., 2013; Rezaei *et al*,.

2016). The R^2 and NSE allowed to assess the predictive power of the model while RMSE indicates the error in model prediction (Miao *et al*., 2016). The RSR incorporates the benefit of error index statistics and includes a scaling/normalization factor, so that the resulting statistics and values can apply to various constituents (Moriasi *et al*., 2007).

$$R^2 = \left[\frac{\sum_{i=1}^{k}(mi-m)(pi-p)}{\sqrt{\sum_{i=1}^{k}(mi-m)^2 \sum_{i=1}^{k}(pi-p)^2}}\right]^2 \quad (4.8)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{k}(mi-p)^2}{\sum_{i=1}^{k}(mi-m)^2}\right]^2 \quad (4.9)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{k}(mi-pi)^2}{k}} \quad (4.10)$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{k}(mi-pi)^2}}{\sqrt{\sum_{i=1}^{k}(mi-m)^2}} \quad (4.11)$$

where:

mi and pi = the measured and predicted values, respectively;

m = the mean of measured values; p = the mean of predicted values and k = the number of observations (erosive rainfall events).

The data used for testing the models were measured from 51 runoff plots in three consecutive cropping seasons: 2016-major, 2016-minor and 2017-major with 11, 9 and 13 erosive rainfall events, respectively. High number of observations allows for model accuracy (Traore *et al,*. 2017). Therefore, a total of 561, 459 and 663 direct observations were recorded during the three consecutive cropping seasons for the model evaluation.

The different parameters used for the assessment were compared to their standards and ranges of acceptability as described by equations 4.8, 4.9, 4.10 and 4.11. For RMSE, lower values indicate better model agreement with predicted values. The coefficient of determination (R^2), between measured and predicted values, range from 0 to 1, with higher values indicating better model prediction. NSE ranges between - ∞ and 1 (1 included) and the values between 0 and 1 are generally considered as acceptable levels of performance. Negative values of NSE indicate that the mean of observed values is a better predictor than the simulated value, which indicates unacceptable performance of the model (Moriasi *et al.*, 2007). RSR varies from optimal value to 0 which indicates zero RMSE or residual variation and therefore perfect model simulation. Lower RSR values emphasize better model simulation performance. According to Moriasi *et al.* (2007), the values are categorized as : 0.00 ≤

RSR ≤ 0.50; 0.50<RSR ≤ 0.60; 0.60< RSR ≤ 0.70; RSR >0.70 for very good, good, satisfactory and unsatisfactory simulation, respectively.

4.3 Results

4.3.1 Characteristics of the new method for runoff estimation

The comparison between measured and predicted values for runoff is shown in Table 4.1. In general, all the factors of goodness presented excellent trends for a good model performance. The R^2 and p-value between the predicted and measured were $R^2 = 0.94$ and $p < 0.01$ in 2016–major; $R^2 = 0.94$ and $p < 0.01$ in 2016-minor and $R^2 = 0.89$ and $p < 0.01$ in 2017-major seasons. The model showed good performance as the R^2 values were close to 1 for all the three cropping seasons where 33 seasonal and cumulative erosive rainfall events were analyzed. The RMSE and RSR between measured and predicted runoff showed perfect thresholds with values of 2.67 and 0.40; 2.05 and 0.38 and 1.69 and 0.45 for the 2016-major, 2016-minor and 2017major seasons, respectively. This showed that there was not much dispersion between measured and predicted values of runoff throughout the study period. For all the cropping seasons, NSE values ranged from 0.79 to 0.86 which qualified the prediction as excellent. The model showed good fit for runoff prediction through diagnostic plots of the linear model (Figs 4.1a-4.1c).

The accuracy of the runoff prediction under different slopes is presented in Figs. 4.1a4.1c and the measured parameters (R^2 and p-value) showed good performance and almost the same with the three slope classes (3, 6 and 10%). This confirmed that the current developed method can be applied to different landscapes based on slope steepness for soil erosion characterization

Table 4.1. Performance indices between the predicted and measured runoff during different cropping seasons

Index	2016-major season	2016-minor season	2017-major season
R^2	0.94	0.94	0.89

Slope	0.60	0.64	0.59
RMSE	2.67	2.05	1.69
RSR	0.40	0.38	0.46
NSE	0.84	0.86	0.79
P- value	<.001	<.001	<.001

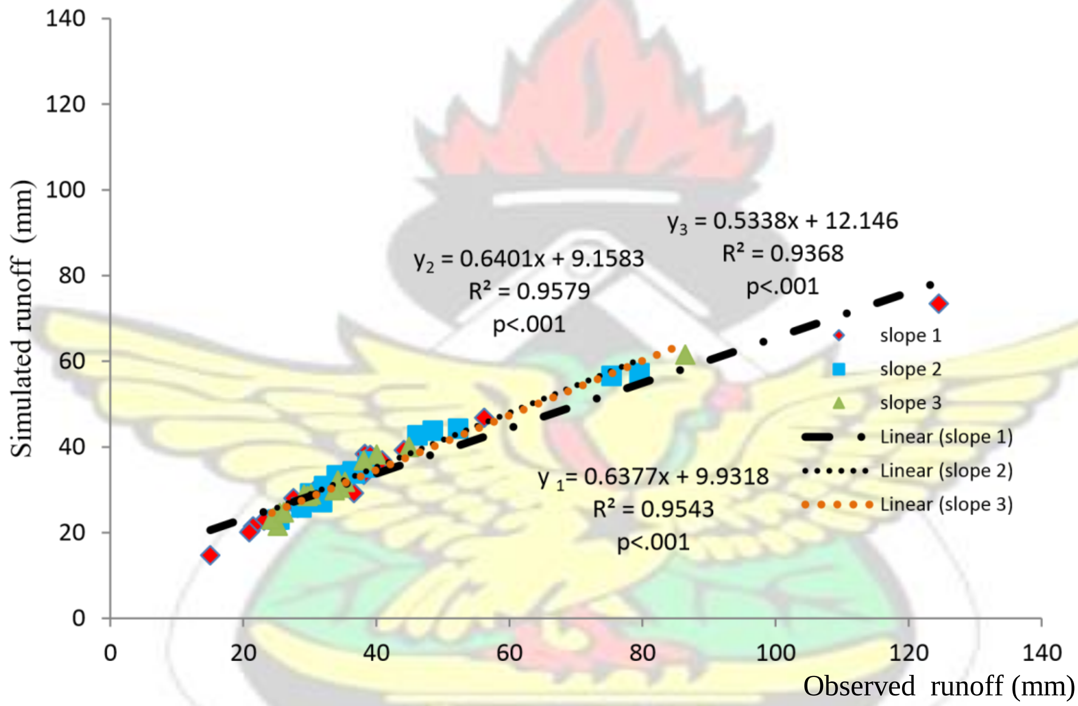


Figure 4.1 a. Effect of slope on model prediction under cropping systems and soil amendments during the 2016-major season

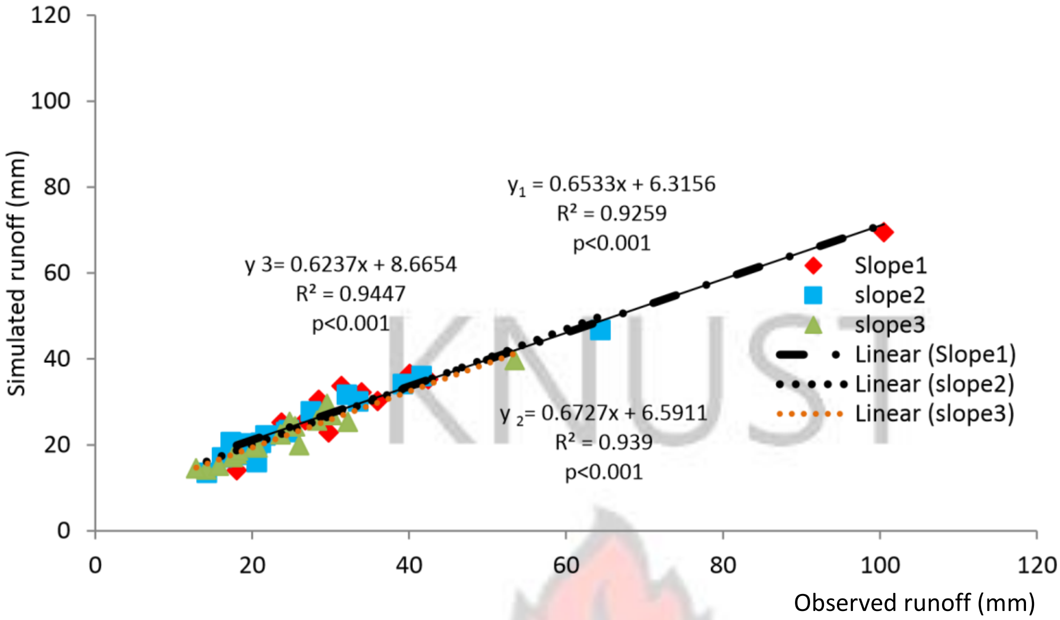


Figure 4.1 b. Effect of slope on the model prediction during the 2016-minor cropping season

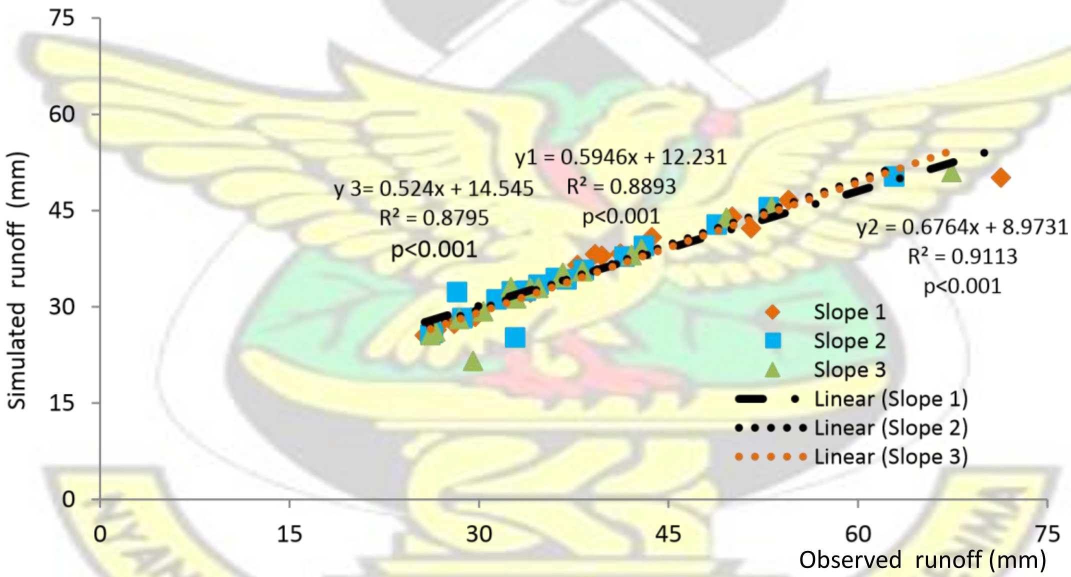


Figure 4.1 c. Effect of slope on the model prediction during the 2017-major cropping season

4.3.2 Sensitivity to different management and application of the model

The accuracy of the prediction is a function of the materials used for sub-sampling the runoff which depend also on the climatic factor and the soil status as result of specific management practices and inherent properties. In Figs. 4.2b, 4.2d and 4.2f, the rainfall induced important amounts of runoff on poorly managed soils (bare plot).

From equation 4.5, the variables N, n and v should be defined according to the rainfall characteristics (potential maximum daily rainfall amount) of the area for good accuracy of the simulation. Figures 4.2 a-4.2 f showed good sensitivity of the model to predict runoff under cropped and bare plots. The results showed good simulation as per the statistical parameters of goodness assessment (Table 4.1). All the figures without the bare plots (Figs 4.2 a, 4.2 c and 4.2 e) gave better accuracy of the prediction compared to the cropped plots mixed with the bare ones. Therefore, the bare plots induced more runoff loss compared to the cropped land such that the estimation using the current method was poor for those three bare plots as marked with their respective peaks (**) in Figs. 4.2b, 4.2d and 4.2f. The runoff was underestimated for the uncropped plots due to the high rate of the runoff generated and unsupported by the sampling tools. Under such circumstances, where high runoff occurs (Eq 4.5), the dimensions of the N, n and v should be adjusted to avoid losses due to overflow. The plot numbers are related to the different soils and crop management practices (Table 3.3)

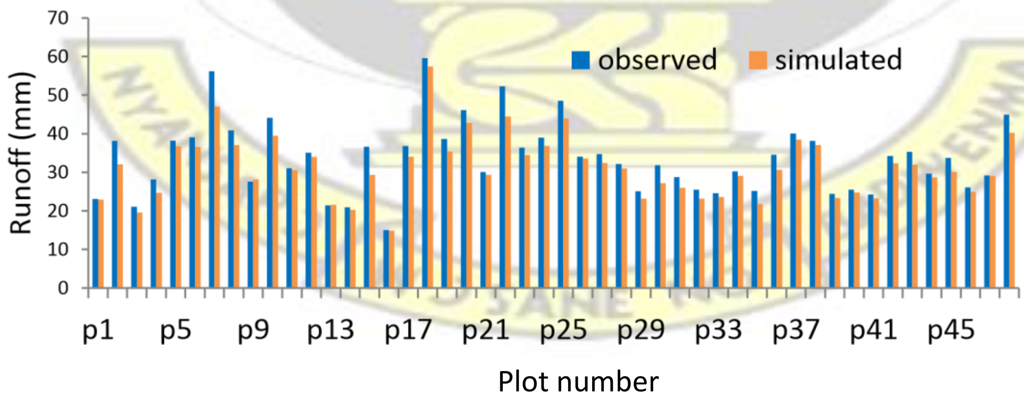


Figure 4.2a. Runoff simulation and measurement sensitivity without bare plots during 2016-major cropping season

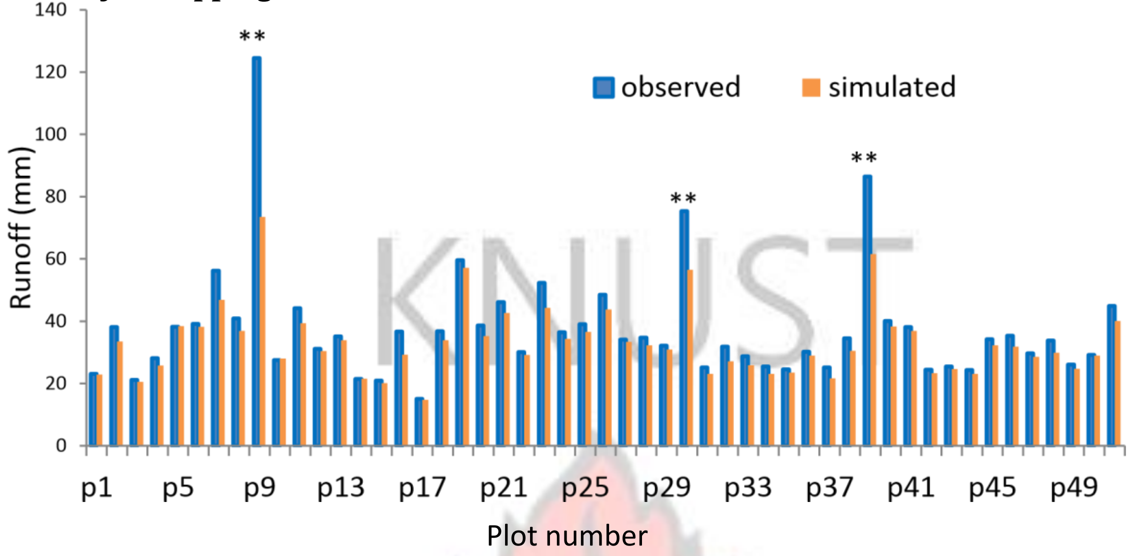


Figure 4.2b. Runoff simulation and measurement sensitivity with bare plots during 2016-major cropping season. The ** on the three peaks of the bare plots show under-prediction when the flow is important compared to the cropped plots.

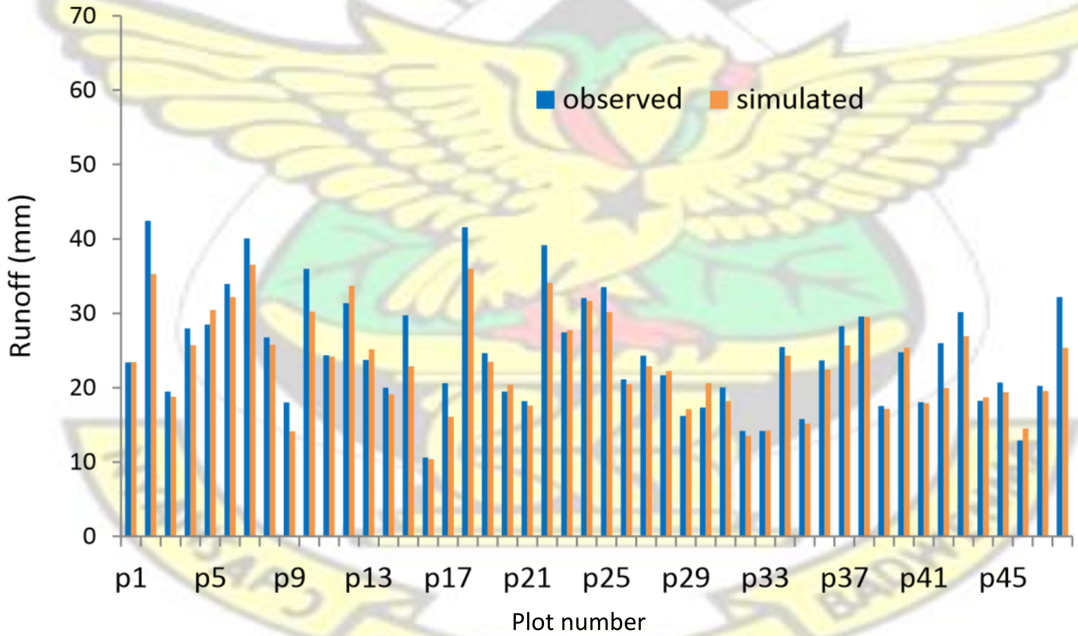


Figure 4.2c. Runoff simulation and measurement sensitivity without bare plots during 2016-minor season.

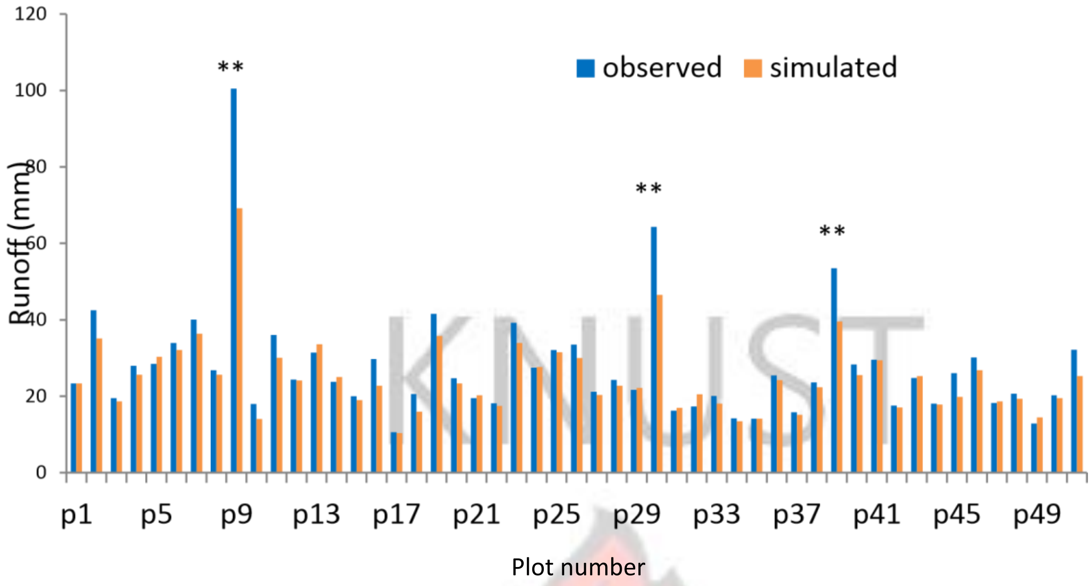


Figure 4.2d. Runoff simulation and measurement sensitivity with bare plots during 2016-minor season. The ** on the three peaks of the bare plots show under-prediction when the flow is important compared to the cropped plots.

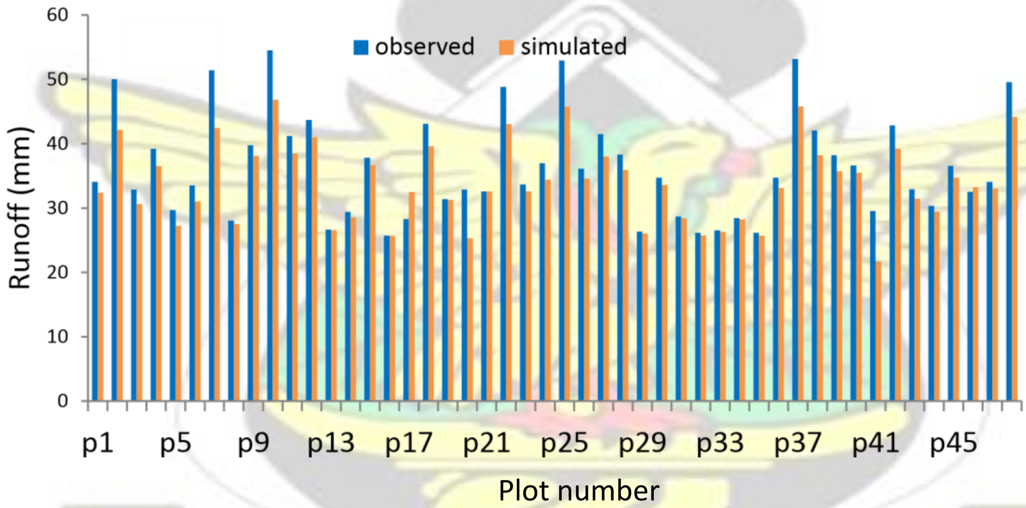


Figure 4.2e. Runoff simulation and measurement sensitivity without bare plots during 2017-major cropping season.

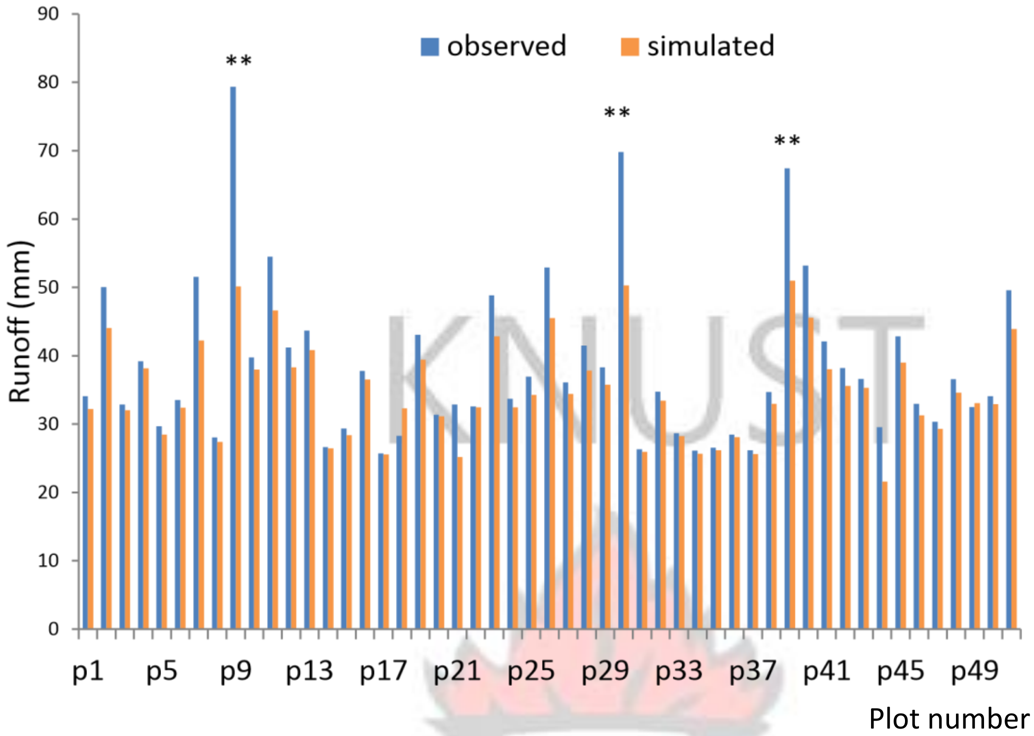


Figure 4.2f. Runoff simulation and measurement sensitivity with bare plots during 2017-major season. The ** on the three peaks of the bare plots show under-prediction when the flow is important compared to the cropped plots.

4.4 Discussion

4.4.1 Accuracy assessment of the developed method

Several studies have used different models to measure and predict soil erosion and runoff in assessing the impact of soil and crop management practices on soil and water management (De Vente and Poesen, 2005; Laloy and Bielders, 2009; Ramos *et al*., 2015). The selection of a specific model depends on the objective of the study, the minimum data set and calibration and the implicit uncertainty in interpreting the results obtained. However, the traditional physically-based, conceptual, and empirical or regression models have not been able to describe all processes involved due to insufficient knowledge and unrealistic data requirement. Thus, the application of most methods is limited to specific areas and studies. Moreover, the tipping bucket method is a tedious and expensive approach and this reduces its success as one of the accurate models of soil erosion characterization.

The accuracies under the three slopes followed the same trends with good values for coefficient of determination ($R^2 > 0.8$) (Moriasi *et al*., 2007 for each of the slope class as observed across the different cropping seasons Figs 4.1a- 4.1c). This confirmed the adaptability of the model to different landscapes with different angles (slopes) as was also shown by the RSR values which exhibited low variability among the different soil amendments. Thus, this gives a large applicability of the proposed approach for soil erosion characterization based on runoff determination within different landscape types. The adaptability of a model to different environments by keeping the same thresholds is one of the conditions to assess good model quality for soil erosion measurement (Pandey *et al.,* 2016).

Under the different cropping systems, apart from the bare plots, the prediction was accurate under the different soil management measures. The method satisfied the statistical thresholds of accuracy for runoff prediction as defined by Moriasi *et al.* (2007) and the replicability under different soil management sytems based on the principles of Pandey *et al*. (2016).

4.4.2 Model application, advantage and limitation

The application of the actual model is mostly based on the factors developed under equation 4.5 and the principle described by equations 4.6 and 4.7. Soil runoff quantified will therefore be used to assess the amount of soil and nutrients lost through erosion before suggesting sustainable practices for soil management and crop productivity improvement. Soil fertility restoration strategies will be based on measured values of soil and nutrient loss to sustain agricultural production (Kleinman *et al*., 1998; Quansah *et al*., 2000). The advantage of the proposed method of runoff sub-sampling is based on the following criteria: high accuracy under land management systems by defining the sampling parameters (Equation 4.5); applicability to different conditions including spatially varying and surface characteristics. Moreover, the method is less expesnsive and with less runoff and sediment to hangle. Indeed, the costs of the tipping bucket and counter for each plot are significantly reduced in the new method where only a simple container is required to sample a fraction of runoff from each designed runoff plot. Therefore, this make this new method more affordable for soil erosion quantification. As suggested by Pandey *et al.* (2016), a model with large conditions of adaptability and not specifically limited to certain situations are recommendable for soil erosion characterization under field and watershed scales. The current method is adapted and useful for soil erosion characterization on field scale basis. Contrary to other methods and models for soil runoff characterization where soil erosion is assessed after a long period of observation, as reported by numerous studies (e.g. Wischmeier and Smith, 1978; Hudson, 2005; Olson *et al.*, 2014; Pandey *et al*,. 2016; Djuma *et al.*, 2017; etc), the current method can assess runoff for an an individual erosive storm. However, this new method of runoff assessment is limited with the design and size of the runoff plot to avoid any rainwater loss before sampling as shown in Plate 4.1. Moreover, the method also requires regular monitoring of the site for sampling after each erosive storm which might be tedious and time demanding but with less volume of runoff to handle compared to the classic ones.

4.5 Conclusion

The developed model for soil runoff measurement was assessed using five statistical parameters of accuracy and goodness. These different parameters showed excellent thresholds and confirmed that the model performance for runoff prediction was accurate. All the five factors used for the assessment (p-values, R^2, RMSE, NSE and

RSR) gave excellence trends and as such the approach was qualified for soil erosion characterization. The model was assessed under different slope classes and showed good trends confirming its adaptability to different types of landscape. This gives a new opportunity for soil erosion measurement under field conditions. Despite the excellent predication of the method, the accuracy was poor for the plots with high rates of runoff (bare plots). Thus, the rainfall characteristics (runoff coefficient) of the study site should be considered to fix the characteristics the runoff plot.

Further test under different agro-ecological zones should be considered to assess the adaptability and the environmental effect on the accuracy of this method although the statistical parameter based on RSR showed large adaptability trends.

CHAPTER FIVE

5. SOIL LOSS AND RUNOFF CHARACTERISTICS UNDER DIFFERENT CROPPING SYSTEMS AND SOIL AMENDMENTS

Abstract

Under small-scale farming systems, soil erosion is one of the common constraints to crop production. Several methods based on mechanical and biological approaches have been promoted to control this threat but with poor success. Soil management practices based on biochar/inorganic inputs interaction under common cropping systems in the tropics have been scarcely studied within the framework of soil erosion control. The current study aimed to assess the effect of different soil and crop management practices on soil loss characteristics. A field experiment was therefore carried out on runoff plots under different cropping systems treated with soil amendments. It was a two-factor experiment laid out in split – plot and arranged in a randomized complete block design

(RCBD). Amendments (inorganic fertilizers (NPK), inorganic fertilizers + biochar (NPK+BC), sole Biochar (BC) and control) and cropping systems (sole maize, sole soybean, sole cowpea and maize intercropped with soybean) were the two factors investigated. Cropping systems constituted the main plot factor whereas soil management; the subplot. Observations were made on the runoff plots during three consecutive cropping seasons based on soil loss parameters. The results showed that the seasonal soil loss ranged from 9.75-14.5 Mg ha^{-1} ($\leq$ 3 Mg acr^{-1} yr^{-1}, being the tolerable rate) for the bare plots. Soil loss was minimal under cowpea cropping system compared to sole maize where the highest rates were observed. The soil management options; beside their direct role in plant nutrition, affected soil loss significantly. The least soil loss (1.23 – 2.66 Mg ha^{-1}) was observed under biochar + NPK fertilizer treatments across the different cropping seasons. Sole biochar treated plots showed good performance of soil erosion reduction than the control plots. The coefficient of runoff ranged from 21.04 to 29.27% on bare plots while cropped plots had values ranging from 5.42 to 20.01 % under soil management practices and control, respectively. Soil depth followed the same trend as soil loss such that it reduced on control plots (0.16 - 0.34 mm) more than amended plots (0.09 – 0.19 mm). The different cropping systems, sustainably managed with soil amendments could be useful in small-scale farming systems for soil erosion reduction.

Keywords: biochar, erosion, nutrient, sediment, soil degradation

5.1 Introduction

Soil erosion is a serious threat to global food production. Annually, more than 10 million hectares (ha) of croplands are lost due to soil erosion, thus reducing their availabilities for world food production (Pimentel and Burgess, 2013). Globally, there will be a need of 200 million ha of croplands to meet the requirement of the increasing population, over the next 25-30 years (Barreiro-Lostres *et al.*, 2017). It is thus very crucial to develop and adapt sustainable soil management options to reduce and protect the soil against further degradation (Pandey *et al.*, 2016) and to improve crop productivity in smallholder farming systems (Ghosh *et al.*, 2006; Aminifar *et al.*, 2016; Traore *et al.*, 2017). The actual status of smallholder cropping systems in subSaharan Africa (SSA) coupled with demographic factors increases soil degradation, arising essentially from erosion and nutrients depletion (Rodríguez-Caballero *et al.*, 2013).

Cropping systems in the sub-region are predominantly rainfed based systems at the smallholder level. However, erratic weather patterns, as a result of climate change compound the challenges faced by smallholder farmers in producing enough food to feed the ever growing population of the region (Karamage *et al.*, 2017; Tesfaye *et al.*, 2017). While the situation requires remedial measures, there is need for scaling-up adaptation and adoption of appropriate practices that can help improve crop yields and resilience to climate change. Sustaining cropping systems, especially cereal-legume based systems with good soil management practices is advisable to reduce the actual soil fertility degradation as observed in most of the agro-ecological zones in SSA.

On the other hand, the weather conditions in this region, characterized by high rainfall intensities and temperature, increase the effect of soil erosion on croplands. Despite the high rainwater observed in the tropics, water shortage is cited among the most limiting factors to crop production while the excess cause soil erosion (Lal, 2007). The poor storage capacities of soil, increase soil loss through runoff causing double constraints to the soil: soil moisture stress for crops development and soil erosion due to the excess of water. With soil erosion, not only soil nutrients are affected but also physical, biological and other chemical properties, which have important implications for crop production. The nutrients and sediments deposited off-site are also considered important environmental threats. Sustainable and specific practices are required for soil quality restoration and crop productivity improvement.

The exportation of surface soil layer through runoffs causes the soil to become poor in organic carbon and plant nutrients contents associated with low holding capacities and soil depth reduction (Schoumans *et al.*, 2014). Excessive soil degradation may reach the point of non-responsive soils and this can reduce totally the agricultural value of eroded land (Sahoo *et al.*, 2015). The classic methods of soil management and erosion control have been studied with results indicating good impacts on crop production and improvement in soil properties (Bonsu and Quansah., 1992; Quansah *et al*., 2000; Amegashie *et al.*, 2011; Chaghazardi *et al.*, 2016; Wang *et al.*, 2016); but with less attention on crop intensification effects on soil and water conservation (Govers *et al*., 2016). These studies were mostly carried out on-station and in specific agro-ecologic zones which makes them less reliable to other zones with different climatic characteristics. But also, within the small-scale farmer conditions, the recommendations are poorly applied due to the complexity of the technologies developed and the limited resources available for adoption. This is mostly the case of soil erosion control methods using vegetative barriers which may even have negative impact on crop production (Sesmero *et al*., 2015). Cropping systems enhanced by specific nutrient management practices may reduce soil erosion with less negative impact on soil properties and crop productivity more than the traditional soil erosion control techniques viz. terraces, hedgerows, etc. Within the farming systems, most of the methods of water and soil conservation have been developed based on three principles: mulching, minimum tillage and crop rotation (Lal, 2001; Vanlauwe *et al*., 2013; Kurothe *et al.*, 2014) but their adoption by the smallholder farmers is a challenge (Wildemeersch *et al.*, 2015). However, it has been recognized that, in order to sustain crop production and soil water conservation in SSA, a fourth principle based on nutrient supply needs to be added into the system (Vanlauwe *et al.*, 2013). Therefore, soil nutrient supply through external inputs will have good impact on soil and water conservation while it has also direct impact on crop performance.

The current study assessed the sensitivity of the soil to erosion under different amendment practices in selected cropping systems. Among the different soil amendments, biochar was included to assess its effect on erosion characteristics under different cropping systems. Its interaction with inorganic fertilizers under specific cropping systems on soil characteristics is not well documented from previous studies in sub-Saharan Africa.

Soil and water conservation under smallholder cropping systems is a multipurpose strategy which can reduce soil degradations. Moreover, good crops performance due to suitable cropping systems and soil amendments may have direct effect on soil erosion reduction.

5.2 Materials and Methods

The methods and procedures used to measure soil erosion characteristics are described in this section in relation to the second specific objective of the overall study. The experiment layout and the different soil and crop management options have been described in sections 3.1 and 3.2 of Chapter three under general methodology.

5.2.1 Total amount of soil loss

The total amount of soil loss (S) was derived from the sediment concentration in the runoff and from the direct amount of soil retained on the collecting trough fixed at the end of each plot.

A 500 mL sample was taken from the total runoff sub-sampled within the small container (gallon) fixed on the collecting channel to quantify the total amount of soil (S_1) lost through runoff. The second portion of soil (sediment) was taken from the total amount of sediment retained by the mesh on the collecting trough and oven dried at 105 °C for 48 h to quantify direct sediment (S_2).

The total amount of soil loss (S) under each treatment was computed using the empirical equation 5.1.

Total amount of soil loss (S) = $S_1 + S_2$ (5.1)

Each of the factors (S_1 and S_2) was determined by specific procedures described in sections 5.2.1.1 and 5.2.1.2.

5.2.1.1 Soil loss in runoff

The total amount of sediment concentrated into the runoff was computed using the equation 5.2:

$$S_1 = \frac{C_1}{C_2} * R_t \quad (5.2)$$

where:

S_1 (g) = the total amount of dry soil in total runoff;

C_1 (g) = the dry soil concentration from the runoff sample taken into the laboratory;

C_2 (mL) = volume sample of the runoff measured in situ (field) and R_t

(mL) = the total volume of runoff measured in situ (field).

5.2.1.2 Soil on the trough

The equation below (5.3) was used to determine the direct amount of soil retained on the collecting trough.

$$S_2 = \frac{C_4}{C_3} * S_t \quad (5.3)$$

where :

S_2 (g) = the total amount of dry soil retained by the the mesh on the collecting trough in situ;

C_3 (g) = soil sample measured in situ and taken to the laboratory for oven drying at 105 °C for 48 h;

C_4 (g) = dry weigh of C_3 and

S_t (g) = fresh weigh of the soil collected on the collecting trough and meaured in

5.2.2. Soil depth reduction

The soil loss by erosion from the plot reduces soil depth which affects its productivity. Equation 5.4 was used to assess the depth reduction due to soil loss during the erosive events and this was an indicator of degradation:

$$S = \rho * v \quad (5.4)$$

where:

S (kg) = amount of soil loss from the plot; ρ

(Mg m^{-3}) = bulk density of the soil;

V= volume of the soil (m^{-3}); defined by equation 5.5

$$V = Ar * dr \tag{5.5}$$

where:

Ar (m^2) = the area affected by the erosion (plot size) and dr (m) = depth reduction from the plot due to soil loss by erosion. ;

From equations 5.4 and 5.5, the value soil depth reduction was calculated as follows:

$$dr = \frac{S}{\rho * A} \tag{5.6}$$

5.2.3 Runoff coefficient

The runoff coefficient (RC) estimates the rate of rainwater loss through runoff. Soil characteristics and land cover affects this coefficient as well as the climatic conditions of the area. It was calculated using equation 5.7.

$$RC\ (\%) = \frac{\text{Runoff depth (mm)}}{\text{Rainfall depth(mm)}} * \ 100 \tag{5.7}$$

5.3 Results

5.3.1 Soil loss under different cropping systems and soil amendments

Soil loss under different the cropping systems, soil amendments and their interactions are shown in Table 5.2. The cropping systems varied significantly ($P < 0.05$) in soil loss with the least values of 2.16, 1.47 and 2.75 Mg ha^{-1} observed under sole cowpea whereas the highest values of 3.99, 2.66 and 3.77 Mg ha^{-1} were obtained under sole maize in 2016- major, 2016-minor and 2017- major seasons, respectively. As observed throughout the three cropping seasons, soil loss followed the patterns: MZ > MZ+SB > SB > CW.

There were significant variations ($P < 0.05$) among the different soil amendments and the control in soil loss. The highest amount of soil loss was observed under the control treatment (where no amendment was applied) with values of 4.44, 3.27 and 4.56 Mg ha^{-1} in 2016- major, 2016- minor and 2017- major seasons, respectively. On the other hand, the least soil loss was observed under biochar + NPK with the seasonal values as 2.66, 1.23 and 2.75 Mg ha^{-1} in 2016- major, 2016- minor and 2017- major seasons, respectively.

Cropping systems and the amendments interacted to significantly ($P < 0.05$) affect soil loss. The highest loss was associated with maize cropping systems with no amendment whereas cowpea amended with NPK+BC conserved more soil. The values ranged from 1.14 to 5.94 Mg ha^{-1} for CW x NPK+BC and MZ x Control,

respectively during the entire period of study.

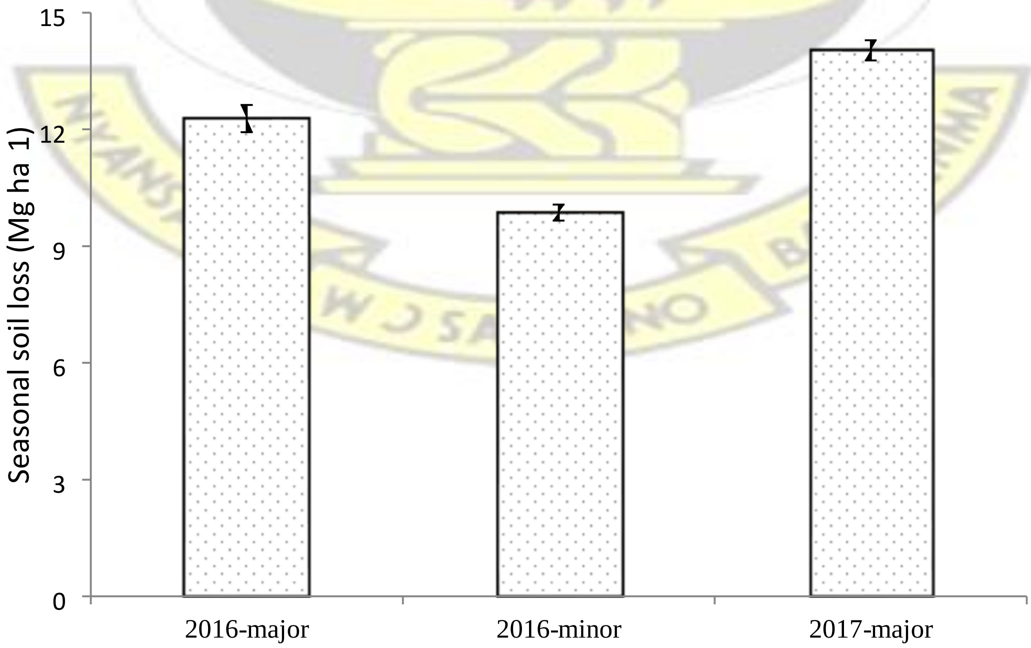
The rate of soil loss from the bare plots during the three cropping seasons was very high (Fig 5.1) ranging from 2 to 15 times soil loss observed under cropped plots (Table 5.2). The erosive storm characteristics, defined in Table 5.1, determined the soil erodibility under the different rainfall regimes.

5.3.2 Effect of cropping systems, soil amendments and their interaction on soil depth reduction

Soil erosion characterized by soil particle detachment and transport, induces soil depth reduction which affects other soil properties and crop development. In this study, there were significant differences ($P < 0.05$) among the different cropping systems based on soil depth reduction due to erosion (Table 5.3). The values ranged from 0.14 to 0.26 mm in 2016- major cropping season, 0.08 to 0.15 mm in 2016- minor cropping season and 0.20 to 0.28 mm in 2017- major cropping season under sole cowpea and sole maize, respectively (Table 5.3). Significant differences were also ($P < 0.05$) observed among the different soil amendments with values ranging from 0.17 to 0.28 mm in 2016- major cropping season, 0.09 to 0.16 mm in 2016minor cropping season and 0.20 to 0.34 mm in 2017- major cropping season for NPK

+BC and control, respectively. On the other hand, the interaction effect of the different soil amendments and cropping systems was also significant ($P < 0.05$) with the least and highest values observed under cowpea x NPK+BC and sole maize x

control, respectively.



Cropping seasons

Figure 5.1. Seasonal soil loss under the bare plots (the error bars represent standard deviation)

Table 5.1. Erosive rainfall characteristics during the different cropping seasons at Anwomasso

Cropping Seasons	No. of rainfall events	No. of erosive events	Interval of rains (days)	Highest drought duration (days)
2016 -major season	28	11	3.2	10
2016- minor season	19	8	4.7	53
2017- major season	29	13	3.1	9

Table 5.2. Effect of soil amendments, cropping systems and their interaction on cumulative soil loss

Treatments	Cumulative soil loss (Mg ha^{-1})		
	2016-major	2016- minor	2017- major
	Cropping seasons		
Cropping systems			
Cowpea (CW)	2.16	1.47	2.75
Maize (MZ)	3.99	2.63	3.77
Soybean (SB)	2.76	1.65	3.35
Maize+Soybean (MZ+SB)	3.65	2.82	3.36
CV (%)	10.1	10.9	12
LSD (5%)	0.74	0.42	0.39
Soil amendments			
Control	4.44	3.27	4.56
Biochar (BC)	2.89	1.82	3.12
Inorganic fertilizer (NPK)	2.75	1.53	2.75
NPK+BC	2.66	1.23	2.65
CV (%)	18.3	8.7	9.1

LSD (5%)	0.35	0.31	0.62

Soil amendments x C ropping systems			
MZ x Control	5.94	2.37	4.13
MZ x BC	3.11	2.18	3.66
MZ x NPK	3.71	2.06	3.02
MZ x NPK+BC	3.38	0.93	4.25
M Z+SB x Control	4.53	3.05	5.04
MZ+SB x BC	2.75	2.09	3.20
M Z+SB x NPK	2.70	1.98	2.13
MZ+SB x NPK+BC	2.66	1.65	2.66
SB x control	3.99	2.70	4.37
SB x BC	2.45	2.07	3.38
SB x NPK	2.76	1.20	3.50
SB x NPK+BC	2.45	1.23	2.31
CW x Control	2.76	1.20	3.50
CW x BC	2.45	1.23	2.31
CW x NPK	3.14	2.03	4.64
CW x NPK+BC	1.63	1.56	2.22
CV (%)	1.79	1.17	2.37
LSD (5%)	2.12	1.14	1.79

Table 5.3. Effect of soil amendments, cropping systems and their interaction on cumulative soil depth reduction

	Soil depth reduction (mm)		
Treatments	2016-major	2016- minor	2017- major
	Cropping seasons		
Cropping systems			
Cowpea (CW)	0.14	0.08	0.20
Maize (MZ)	0.26	0.15	0.28
Soybean (SB)	0.19	0.10	0.24
Maize+Soybean (MZ+SB)	0.20	0.13	0.24
CV (%)	10.1	6.8	12.0
LSD (5%)	0.004	0.001	0.003
Soil amendments			
Control	0.28	0.16	0.34
Biochar (BC)	0.19	0.11	0.23
Inorganic fertilizer (NPK)	0.18	0.10	0.20
NPK+BC	0.17	0.09	0.20

CV (%)	12.3	10.9	9.1
LSD (5%)	0.002	0.001	0.002

Soil amendments x C ropping syst	ems		
MZ x Control	0.38	0.21	0.31
MZ x BC	0.20	0.12	0.27
MZ x NPK	0.24	0.14	0.22
MZ x NPK+BC	0.22	0.14	0.21
M Z+SB x Control	0.29	0.18	0.37
MZ+SB x BC	0.18	0.12	0.24
M Z+SB x NPK	0.17	0.12	0.16
MZ+SB x NPK+BC	0.17	0.11	0.19
SB x control	0.27	0.15	0.32
SB x BC	0.16	0.10	0.22
SB x NPK	0.18	0.09	0.19
SB x NPK+BC	0.16	0.09	0.17
CW x Control	0.20	0.11	0.26
CW x BC	0.11	0.08	0.16
CW x NPK	0.11	0.07	0.17
CW x NPK+BC	0.10	0.06	0.14
CV (%) 14.2 13.8 17.1			
			4.48
Bare plot	0.54± 0.004	0.40±0.004	0.585±0.006
LSD (5%) 5.74 3.05			

Values after ± represent the standard deviation

5.3.3 Effect of different cropping systems, soil amendments and their interaction on runoff coefficient

The fate of rain water is defined by different factors within a rainfed farming system. The rate of rain water lost through runoff is defined by the coefficient of runoff and its magnitude is also determined, apart from the rainfall characteristics, by soil properties as well as land management practices.

It was observed that the different factors studied influenced significantly the RC ($P < 0.05$) (Table 5.4) throughout the study period. Sole cowpea produced the lowest RC while sole maize had the highest in all cropping seasons. The least RC was observed under biochar +NPK treatment whilst the control plot generated more RC throughout the different cropping seasons. The interaction effect was significant and the combination of two treatments poorly adapted treatments (maize and control) produced the highest RC (varying from 10.03 to 18.34 %) whereas cowpea+ NPK+BC gave the least RC (varying from 4.14 to 6.94 %).

In general, the coefficient of runoff was higher during the major seasons than in the minor season. The bare plots had higher RC than cropped plots and the values ranged from 21.04 to 29.27% (Fig. 5.2).

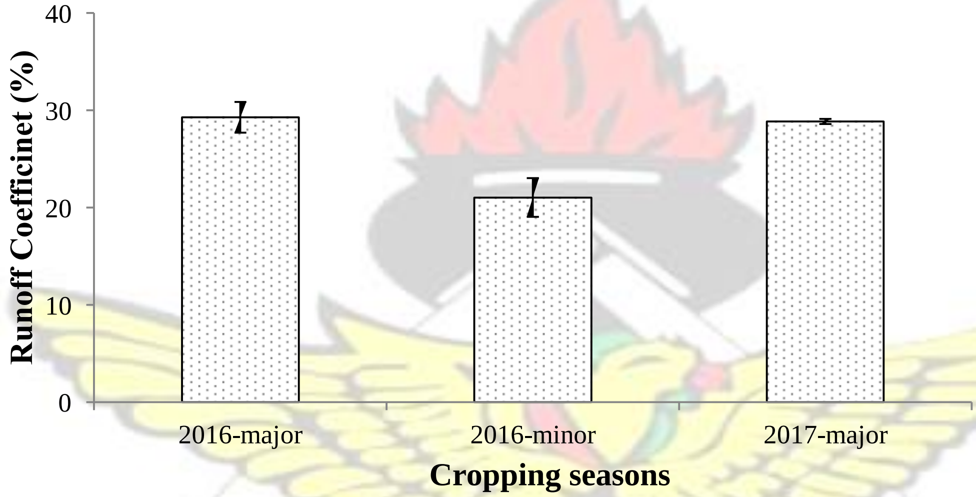


Figure 5.2. Runoff coefficient of the bare plots during the different cropping seasons. Error bars represent standard deviation.

Table 5.4. Runoff coefficient under different cropping systems and soil amendments

	RC (%)		
Treatments	2016-major	2016- minor	2017- major
	Cropping seasons		
Cropping systems			
Cowpea (CW)	8.57	5.84	8.98
Maize (MZ)	13.37	8.86	12.24
Soybean (SB)	10.78	8.30	10.59
Maize+Soybean (MZ+SB)	11.13	8.03	11.78
CV (%)	14.30	10.0	2.40
LSD (5%)	3.35	1.61	0.26
Soil amendments			
Control	14.48	10.00	13.62
Biochar (BC)	10.99	7.83	11.42
Inorganic fertilizer (NPK)	9.45	6.73	9.85
NPK+BC	8.93	5.42	9.70
CV (%)	12.1	10.8	1.20
LSD (5%)	1.40	0.92	1.06
Soil amendments x C ropping systems			
MZ x Control	18.34	10.03	15.29
MZ x BC	12.81	8.50	14.15
MZ x NPK	10.85	7.11	11.65
MZ x NPK+BC	11.50	5.79	11.89
M Z+SB x Control	14.02	11.52	15.18
MZ+SB x BC	11.78	8.17	11.52
M Z+SB x NPK	9.72	7.20	10.41
MZ+SB x NPK+BC	9.02	5.11	10.02
SB x control	14.50	11.32	13.05
SB x BC	10.82	8.04	11.17
SB x NPK	9.50	7.20	9.27
SB x NPK+BC	8.28	6.64	8.86
CW x Control	11.50	7.15	10.96
CW x BC	8.56	6.63	8.85
CW x NPK	7.73	5.43	9.07
CW x NPK+BC	6.94	4.14	8.04
CV (%)	14.2	14.6	11.4
LSD (5%)	1.92	2.10	2.20

5.4 Discussion

5.4.1 Soil loss under different cropping systems and soil amendments

Globally, the rate of soil loss annually (about 10 million ha) due to soil erosion is very high, such that more adapted technologies are required to sustain agricultural productivity in small-scale farming systems (Pimentel and Burgess, 2013). During the last two decades, several water-harvesting and soil conservation technologies such as tillage, stone rows, hedgerows, earth bunds and dikes have been used to reduce soil loss due to improvement of soil water infiltration and storage (Wang *et al*., 2016) but more studies are still needed to provide sustainable practices for crop production and soil conservation (Prosdocimi *et al*., 2015; Vaezi *et al*., 2017). Developing and adapting new approaches, based on local and sustained cropping systems that are ecologically sound and economically viable will be useful to the small-scale famers.

The efficiency of vegetative barriers on soil conservation depends on the aerial vegetative growth, undergrowth (root system), surface soil management and performance of the associated crops (Pansak *et al*,. 2008; Guto *et al*,. 2011; Fan *et al*,. 2015). For this study, there were no vegetative barriers for controlling erosion but plant performance under the different practices was tested. Several studies had found that reduced runoff and soil loss from arable farms depended not only on the presence of vegetative barriers and other mechanical methods but also improvement of the cultivated crops' performance which can be affected by specific and sustainable soil management practices (e.g. Pansak *et al*., 2008; Guto *et al*., 2012). Conventional and improved cropping systems associated with soil amendment practices can be used as alternatives for soil conservation as proven by the current study. Soil conservation and plant yield improvement can be positively correlated and this might improve the adoption by smallholder farmers due to the multipurpose nature of the cereal-legume based cropping systems. Soil conservation technologies will be more useful for farmers when good responses are observed based on crop performance and

productivity.

Soil loss of less than 3 Mg acre^{-1} yr^{-1} is considered tolerable under farming activities (Pardini *et al*., 2017). In 2016 (the cumulative amount for the two seasons), the erosion rates exceeded this acceptable rate, for all the treatments under the cropping systems except sole cowpea and sole soybean where the average soil losses were 3.63 and 4.41 Mg ha^{-1} yr^{-1}, respectively (Table 5.2). During the two seasons, all the soil amendments had values below the ranges of soil loss tolerance compared to the control plots where the annual loss in 2016 was of 7.71 Mg ha^{-1}. The bare plots had very high seasonal values (Fig 5.1) (which were already beyond the annual acceptable soil loss rate) which confirms the importance of soil and crop management for soil erosion reduction.

With the four cropping systems (sole maize, sole soybean, sole cowpea and maize intercropped with soybean), the principle was based on rainfall interception by the aerial biomass to reduce the impact of rainwater on soil. Sole maize poorly covered the soil and therefore was not effective in reducing the physical and mechanical raindrop impact on soil, compared to the other cropping systems. On the other hand, maize leaves are not very decomposable during the growing season to improve soil organic matter content in the short term. As suggested by Mugendi *et al. (*1999) and Guto *et al*. (2012), the role of cropping systems in soil erosion control are based on two principles: minimizing the effects of rainfall on the surface soil and reducing the volume and velocity of runoff. Moreover, apart from the high vegetative biomass for mechanical effect on raindrops, leaves of legumes might litter during the growth period with a positive effect on soil infiltration through soil porosity and structure improvement (Govaerts *et al.,* 2009). The two legumes (soybean and cowpea) within the sole systems decreased the soil loss compared to the sole maize and the intercrop system (Table 5.2). The seasonal leaves decomposition of the legumes, for soil organic matter improvement and the mechanical raindrops impact reduction with important crop cover reduced drastically the rates of soil erosion under these legumes. Sole soybean had low rate of soil loss compared to the maize-soybean intercropped firstly because soybean plant population was lower (half) in the intercropping system, which might have reduced the portion of litter and organic matter from leaves decomposition compared to the sole soybean system.

Pimentel *et al.* (1995) and Jordán *et al.* (2010) from their study, found that the efficiency of different anti-erosion barriers depended on the species used to form the barrier and the soil management practices carried out between them. The spaces between the vegetative barriers are normally under specific crop management practices which impact on soil stability. But for the current study, the barriers comprised the cropped plants under different soil amendments. Thus, the vegetative barriers were formed with multipurpose species: crop production and soil erosion control. The barriers formed under each cropping system might have increased water infiltration and reduced soil loss and this was specifically related to the aerial biomass, the root systems, and the soil organic matter from leaf litter, etc.

For the soil amendments, soil loss was higher under control plots, compared to the others where external inputs (biochar and/or inorganic fertilizers) were applied due to poor crop performance that reduced soil cover and root development. This is mostly the case with most tropical soils in SSA with low nutrient contents for crop development.

Therefore, external nutrients will not only increase the yield, as the main goal for nutrient application in farming systems, but also impact positively on soil and water conservation (Vanlauwe *et al*., 2013; Vanlauwe *et al*., 2015).

The effect of BC on soil loss reduction were significant ($P < 0.05$) compared with the control during the three cropping seasons (Table 5.2). Similar trends were found in the studies of Doan *et al*. (2015) and Lii *et al*. (2017) where it was observed that BC induced a significant reduction in soil loss compared with the untreated plots. The low rate of soil loss under BC is mostly due to the improvement of soil physical properties that increases water infiltration (Jien and Wang, 2013; Wang *et al*., 2017). According to Wang *et al*. (2017), biochar is more useful for soil and water conservation than a soil fertilizer due to the low nutrient content and its long term stability in the soil. Compared with other organic amendments commonly used in soil conservation and soil fertility management (mulch, residues, green manure, farmyard manure), biochar mineralization rate is very low for good rate of nutrients supply to the soil (Matter *et al.,* 2017). The high C-N ratio of biochar is not favourable for microbial activities for its decomposition for plant nutrients release. However, it has liming characteristics which can improve soil microbial activity which is useful also for soil organic matter decomposition (not itself) (Ameloot *et al.*, 2015).

On the other hand, apart from soil properties improvement, biochar is important in soil carbon sequestration in the era of climate change. Thus, the multipurpose agricultural effects of biochar give more reasons to invest in it as soil amendment and soil carbon sequestration option.

Combining local soil erosion management practices (soil roughness by stone rows, vegetation, etc) with nutrient management approaches (application of organic matter, fertilizers), is an interesting option to improve water infiltration and plant water use efficiency (Sahoo *et al.*, 2015; Oduor *et al.*, 2016). However, with the poor fertilizer application by most of the smallholder farmers in SSA, coupled with erosive nature of the rainfall in the region, soil erosion remains an important crop production constraint which requires integrated and sustainable approaches for its control.

Using the vegetative barriers or stone rows for soil erosion control as recommended by earlier studies (e.g. Zougmore *et al.*, 2009, Guto *et al*., 2011) is less adaptable to most of the smallholder farming systems due to the high labour demand, maintenance costs and equipment required while their agricultural improvement value is still poor.

However, sustainable cropping systems are optional solutions for soil erosion control. Indeed, it is necessary to change the land-use and add supporting practices in order to reduce soil loss rates to a tolerable level (Beskow *et al.*, 2009). Sustainable land management practices, as shown by the current study, reduced soil erosion rate. Therefore, soil nutrient management with direct impact on crop performance is an option to reduce the impact of runoff and sediment transport under different cropping systems. Vanlauwe *et al.* (2013) and Masvaya *et al.* (2017) reported from their studies that, soil and water conservation required a fourth principle (a part from the three classic ones: crop rotation, minimum tillage and mulching) based on integrating inorganic fertilizers in the system to promote sufficient organic matter production for soil and water conservation. This will be viewed as an attractive potential solution to reversing soil degradation and increasing land productivity in SSA contrary to the previous approaches where the three components of conservation agriculture (CA) were considered as a panacea (Giller *et al.,* 2009). Plant nutrition is therefore a full component of soil and water conservation system for sustainable soil degradation management and crop yield improvement.

5.4.2. Soil depth reduction due to soil erosion under different soil amendment and cropping systems

Soil loss through erosion, results progressively in reduction of topsoil layers. The onsite effect of soil erosion includes loss in production potential due to the reduction of soil thickness with the associated physical and chemical degradation. The topsoil transported through runoff and sediment is the most important layer of the soil supporting plant development.

The cumulative depth reduction observed under the bare plot during the three consecutive cropping seasons (1.63 mm) was very high when compared to the average for the cropped plots (0.56 mm) during the same period of study (Table 5.3). This emphasizes the importance of soil protection because even during a short period, the impact of soil erosion may be very high under bare or poorly covered soils.

The average 0.2 mm soil loss only during just one cropping season signifies a very important constraint to soil productivity. The natural replacement of this soil layer through pedogenetic processes may take decades (Lal, 1984). The top soil layers lost are the most fertile and have good impact on plant nutrition. In SSA, Bationo *et al.* (2007) reported that over 15 year, maize yield decreased by 12 to 21 % due to pronounced soil degradation by erosion. This therefore suggests that improving crop cover and soil moisture storage through sustainable use of inorganic and organic amendments hold promise for increased crop productivity, especially in smallholder farming systems.

For the soil amendment, the control plots were the most affected amongst all the treatments. The poor biomass development on bare soil accounted for the high soil depth reduction observed. On the other hand, the best soil amendment for soil erosion control based on reduced soil depth was observed under inorganic fertilizers associated with biochar. This is due to the soil physico-chemical improvement from each component. Thus, soil fertility degradation, which needs sustainable management, is an important constraint affecting not only crop production but also stability of soil layers. Inorganic fertilizers are one of the options to improve soil nutrients status, especially when they are associated with organic amendments. The latter are mostly recommendable for soil physical properties restoration. When nutrient reserves are depleted by erosion, plant growth is stunted and crop yield declines. Schoumans *et al.* (2014) observed that, under tolerable soil loss, maize yield decrease ranged from 25 to 50 % without any amendment but with fertilizer application, the yield reductions ranged from 11 to 17 %.

5.4.3 Effect of different cropping systems and soil amendments on runoff coefficient

Rainfall amounts are high in SSA to meet the plant water requirement for sustainable crop production. However, its temporal and spatial distributions, characterizing most of the agro-ecological zones in the region reduces soil moisture storage with important unproductive water loss. Water stress is among the major constraints to crop production in SSA. On the other hand, soil degradation due to water erosion is also is very pronounced in this region. This characterizes small-scale farming systems in SSA. In this sub-region, 95 % of the cultivated land is under rainfed systems (Biazin *et al.*, 2012). Rain water is mostly lost through runoff causing erosion on the already nutrient depleted soils. This is especially due to the poor capacity of the soil to store the excess water; thus, increasing the nonproductive loss of water by runoff

(Ngetich *et al.*, 2014). To reduce these negative impacts, soil and water conservation strategies based on adapted cropping systems and soil amendments are suitable options (Bayabi *et al.*, 2015).

Several studies (e.g. Jeffery *et al.*, 2011; Abel *et al*., 2013; etc) have reported the improvement of soil physical properties by organic amendments coupled with inorganic inputs to make rainwater more valuable for crop production. The current study found differences between the cropping systems and nutrient management options through the runoff coefficient due to their different effect on soil properties as well as on crop performance. The coefficient of runoff varied from 4.14 to 18.34% and from 21.04 to 29.27 % for cropped and bare plots, respectively and this accords to the findings of Araya *et al*. (2010), that nonproductive rainfall water loss, due to runoff, may reach up to 30% in SSA farming systems. The crops under the different nutrient management options improved the rainfall use efficiency strongly and good performance was observed under treated plots compared to the control plots under each cropping system (Table 5.4). The mineral fertilizers with and without biochar reduced runoff drastically (RC varying from 5.42 to 9.85%) as well as sole biochar (RC varied from 7.83 to 11.42%) under all the cropping systems in this study (Table 5.4). The good plant performance due to nutrients supply and soil properties improvement under biochar and mineral fertilizers, has positively affected soil water storage expressed by the low RC. The low RC observed under biochar compared to the control plot is due to its improvement of soil properties which increased water infiltration rate and plant growth for more land cover impact on rainfall drops (Mia *et al.*, 2014; Lone *et al.*, 2015).

The cropping systems with sole cowpea had the lowest RC (varying from 5.84 to 8.98 %) compared to the other systems (RC ranged from 8.03 to 13.37 %), not only due to the high biomass production but also due to early land cover compared to the other species (soybean and maize) with poor land cover during the first month whereas the erosive energy is already high at this stage.

The high RC values observed on the bare plots showed the importance of crops to reduce unproductive rainwater loss. The unprotected soils without vegetation cover are strongly affected by raindrops kinetic energy and this might increase soil structure degradation (Reza *et al.*, 2017) leading to important rainwater loss as observed in this current study (Fig. 5.2). Both sustainable nutrient management and cropping systems are necessary for small-scale farming systems to improve land cover and reduce the rate of unproductive water loss.

5.5 Conclusion

Soil erosion characteristic based on soil loss, soil depth reduction and coefficient of runoff, were strongly influenced by the cropping systems and soil amendments. The plots without any amendment were more sensitive to erosion under each cropping system. The treatment with inorganic fertilizers (associated with or without biochar) improved soil stability, based on soil erosion characteristics, compared to the sole biochar which also gave good improvement than the control. Legume based cropping systems were the most effective practices for soil erosion control. The bare plots resulted in high amount of soil loss and runoff (expressed by RC) than all the cropped plots. Rainwater loss through runoff was also pronounced under poor managed plots (control and bare) compared to the cropped ones with external inputs.

These findings give a new opportunity of soil and water conservation by highlighting the importance of sustainable cropping systems under specific soil management

options to reduce soil and water loss in SSA.

CHAPTER SIX

6. SOIL NUTRIENTS LOSS VIA EROSION: IMPACT OF DIFFERENT CROPPING SYSTEMS AND SOIL AMENDMENTS

Abstract

Soil erosion is a multifactor threat to crop production and the environment. Most studies on soil erosion characterization scarcely focused on soil nutrients loss associated with the process. This study aimed to quantify the magnitude of nutrients loss through soil erosion under different cropping systems and amendments to inform agronomic practices in sub-Saharan Africa (SSA). The field experiment was carried out on runoff plots with different cropping systems (sole maize, sole cowpea, sole maize and maize intercropped with soybean) as main plots and soil amendments (control, biochar, NPK, NPK + biochar) constituting the subplots in a randomized complete block design. The study was carried out in three consecutive cropping seasons in the semi-deciduous forest zone of Ghana. Results showed that plots with low crop and soil management measures were the most sensitive to nutrients loss. The bare plots followed by the control plots had the highest amounts of nutrients eroded. Plots treated with inorganic fertilizer resulted in the least nutrients loss due to their mitigative impact on soil erosion through improved crop performance. Sole maize produced the highest rate of nutrients loss compared to all the other cropping systems evaluated. The legume-based cropping systems under inorganic fertilizer management effectively reduced nutrient loss more than all other treatment combinations. The offsite effect of soil erosion expressed as enrichment ratio (ER) was higher for all plots which received inorganic fertilizer inputs. Higher ERs were observed during the minor rainy season (September-December) than in the major season (April – July) possibly due to low nutrients solubility under poor moisture conditions in the former.

The ERs of fine soil particles were greater than 1 (ranging from 1.14 to 3.6) being relatively higher than that of coarse particles (sand) with values below 1 (ranging from 0.62 to 0.88). Soil erosion has direct impact on soil nutrient depletion; however,

sustainable soil and crop management practices can be alternative options to reducing its effects on nutrients loss from croplands in SSA.

Keywords: Cropping systems, enrichment ratio, nutrient loss, runoff, sediment, soil amendments

6.1 Introduction

Soil erosion reduces the agricultural value of lands via physico-chemical degradations. Soil nutrients loss through erosion processes viz. runoff and sediment, is a major driver for soil fertility decline (Kurothe *et al.*, 2014 and Sahoo *et al.*, 2015). The eroded sediments and runoff are highly concentrated with crop nutrients which are washed away from farmlands. With soil loss, the fine particles transported from the surface layers are the richer in organic carbon and crop nutrients. Erosion -based constraints coupled with unfavorable climatic conditions define significantly the productivity of farming systems in sub-Saharan Africa (SSA).

Soil erosion leads to extreme losses of economic and environmental resources which affects the national economy for the concerned regions (Govers *et al.*, 2016 ;Vaezi *et al.*, 2017). The consequences on-site are directly observed on crop production as well as soil properties. This adversely affects the ability of the soil to respond to fertilizers applications and other sustainable management practices with time. The amount of nutrient elements transported from croplands depends on the agro-ecology and the farming systems. The amount of nutrients transported during plant harvest (yield and crop residues) coupled with nutrient loss through erosion (runoff and sediment) are important threats to soil nutrient depletion in SSA and defines the state of the soils within the region. As a result, soils within the tropics are highly degraded, requiring specific integrated management options.

The nutrients lost to soil erosion process can be expressed economically to reflect the impact of erosion on fertilizer investment. The loss of soil nutrients through erosion indicates significant cost because the nutrients must be replaced for plant use for the sustainability of the cropping system. In small-scale farming systems, this cost is not taken into account due to lack of relevant information (García-Díaz *et al.*, 2017). Thus, its quantification can help the different stakeholders to adopt the most effective soil and crop management practices to reduce soil nutrient loss and improve crop productivity (Bertol *et al.*, 2017). Quansah *et al.* (2000) found that the seasonal cost of N, P and K lost through erosion under a maize monocrop grown under excessively tilled land was US$ 7.1 per hectare. According to World Bank *et al.* (2006), the estimated cost of land degradation ranges from 1.1 to 2.4 percent of Gross Domestic

Product (GDP), corresponding to 2.9 to 6.3 percent of Agricultural Gross Domestic Product (AGDP).

For developing countries in SSA, whose economies depend heavily on the agricultural sector, the loss of agricultural productivity particularly through erosion, implies loss of revenue for the socio-economic development (Bonsu and Quansah 1992). However, only few studies are devoted to economic implication of soil fertility erosion under different cropping systems and fertility management practices (Amegashie *et al.*, 2011) compared to other soil erosion characteristics such as sediment and runoff (García-Díaz *et al.*, 2017). To bridge this gap in knowledge, sediment and runoff losses from different soil amendments and cropping systems were analyzed for nutrient losses. The aim of the study was to quantify soil nutrient losses and the associated costs due to erosion under specific crop and soil management practices typical of SSA.

6.2 Materials and Methods

The research area, the experiment and the different soil and crop management practices related to this Chapter have been described in sections 3.1 and 3.2 of Chapter three of general methodology. The methods and procedures used to measure the different components of the soil nutrients loss characteristics are described in the current section of specific methodology.

6.2.1 Nutrient loss

During erosion process, plant nutrients are transported in runoff and sediments. The surface layers are the most affected and where most of soil nutrients for plant nutrition are concentrated (Quansah *et al.*, 2000)**.** To assess the nutrient loss (equation 6.1)**,** samples of runoff (100 mL) and sediment (100 g) were taken from the total runoff and direct sediment respectively from the collecting trough fitted to each treatment plot.

Total amount of nutrient lost (N) $= N_1 + N_2$ (6.1)

where:

N_1 = Nutrient loss through the runoff;

N_2 = Nutrients loss through sediment.

6.2.1.1 Nutrient loss through the runoff

Nutrients concentration in the runoff, N_1 was computed using equation 6.2 below:

$$N1 = n_1 * Rt \quad (6.2)$$

where:

N_1 (g) = total amount of each nutrient lost through runoff; Rt (L) = the total amount of runoff measured in situ and n_1 (g L^{-1}) = concentration of each element in the runoff determined as described under section 6.2.4.

6.2.1.2 Nutrients loss through sediment

The amount of each nutrient lost through the sediment was determined using equation 6.3.

$$N_2 = n_2 * S_2 \qquad (6.3)$$

where:

N_2 (g) = the total amount of each nutrient lost in the sediment collected on the trough;

S_2 (g) = the total amount of direct soil sediment collected on the trough; n_2 (g g^{-1}) = the concentration of each nutrient in the sediment determined as described under section 6.2.4.

6.2.2. Enrichment ratio

Soil erosion affect not only the site were it is generated but also the soil and the ecosystems outside the eroded area. This is expressed as the accumulation of sediments and nutrients on the new site of deposition and has negtaive impacts on plants and other living organims as well as soil properties. The magnitude of sediment richness in plant nutrients is defined by enrichment ratio (ER) (equation 6.4)

(D'Elia *et al*., 1986; Amegashie *et al.,* 2011). Enrichment ratio greater than one indicates that the sediment is richer in nutrients than the parent soil (which correponds to the soil remaining on the field after the erosion process).

$$ER = \frac{\text{nutrient concentration in sediment}}{\text{nutrient concentration in parent soil}} \qquad (6.4)$$

6.2.3. Economic value of the different nutrients lost through runoff and sediment

In this study, the replacement cost method was used to estimate the cost of fertility erosion. This involved converting nutrient loss to existing fertilizer forms to assess the monetary value of the nutrients lost through erosion (Enters, 1998) under the different soil and crop management practices. For this study, the inorganic fertilizers applied were: urea, TSP and KCl with the concentration of 46%, 46% and 60% for N, P_2O_5 and K_2O respectively. Therefore, the three macronutrients (N, P, and K) analyzed from the runoff and sediment were converted into monetary values based on the three straight inorganic fertilizers (Urea, TSP and KCl) applied under using the factors of 0.44 and 0.8 for converting P and K to P_2O_5 and K_2O, respectively.

By using the concentration of each fertilizer indicated above, it was possible to determine the monetary value of soil nutrients lost through erosion under each treatment. The prevailing market price of each fertilizer was used to compute monetary value of soil fertility erosion. The local currency (Ghana cedis) was converted into US dollars and the exchange rates were 4.0 4.0 and 4.2 Ghana cedis for 1 US$ in 2016-major, 2016-minor and 2017-major seasons, respectively.

6.2.4. Laboratory analysis

For the sediment and runoff analyses, total nitrogen (TN), available phosphorus (P), exchangeable potassium (K) were determined using the methods described by

Okalebo *et al.* (1993). The different analyses were done in the Soil Science Laboratory of the Department of Crop and soil Sciences of the Kwame Nkrumah University of Science and Technology, Kumasi.

6.3 Results

6.3.1 Cumulative soil nutrient loss through erosion during three consecutive cropping seasons

The cumulative amount of nutrients lost under the different cropping systems and soil amendments are presented in Table 6.1. The nutrients assessed were the N, P, and K which were applied via chemical fertilizers in combination with biochar.

The cropping systems, soil amendments and their interactions showed significant differences ($P < 0.05$) in N, P, K eroded at the end of all three cropping seasons. Among the cropping systems evaluated, sole maize was the most sensitive to fertility erosion with the highest amounts of N, P and K losses (19.71; 8.12 and 7.27 kg ha^{-1} respectively) while sole cowpea had the lowest values (12.38; 6.67 and 5.81 kg ha^{-1}) for all three nutrient elements. The highest rate of nutrients loss was observed on the control plots while the least were recorded on plots which received external inputs especially the inorganic fertilizer treatments associated with biochar. The respective average values of N, P and K were 20.43; 8.42 and 7.87 kg ha^{-1} for the control plots and 14.15; 5.58 and 5.94 kg ha^{-1} for NPK + biochar amended plots.

For the interaction effect, each cropping system without any external amendment produced the highest rate of nutrients loss whilst the lowest rates were observed under cropping systems associated with inorganic inputs (Table 6.1). The bare plots showed the highest rate of nutrients loss compared to the cropped plots (Fig. 6.1).

Table 6.1. Cumulative soil nutrient loss through erosion during three consecutive cropping seasons

Treatments	Nutrients loss (kg ha^{-1})		
Cropping systems	N	P	K
Cowpea (CW)	12.38	6.67	5.81
Maize (MZ)	19.71	8.12	7.27
Soybean (SB)	16.75	6.81	6.61
Maize+Soybean (MZ+SB)	17.12	7.49	6.75
CV (%)	11.9	18.1	11.2
LSD (5%)	5.23	1.08	1.30
Soil amendments			
Control	20.43	8.42	7.87
Biochar (BC)	18.83	6.82	6.47
Inorganic fertilizer (NPK)	15.33	5.78	6.15
NPK+BC	14.15	5.58	5.94
CV (%)	15.1	12.7	12.0
LSD (5%)	4.44	0.64	0.68
Soil amendments x Cropping system s			
MZ x Control	22.45	9.55	8.15
MZ x BC	19.08	7.16	7.00
MZ x NPK	16.49	6.93	6.05
MZ x NPK+BC	14.60	6.80	5.82
M Z+SB x Control	21.13	8.82	7.92
MZ+SB x BC	19.08	7.92	7.24
M Z+SB x NPK	17.56	8.12	6.12
MZ+SB x NPK+BC	16.08	7.63	5.42
SB x control	20.80	7.32	7.79
SB x BC	20.56	7.05	6.40
SB x NPK	16.83	6.17	6.08
SB x NPK+BC	14.04	6.68	5.86
CW x Control	17.31	6.54	7.34
CW x BC	18.48	6.24	5.47
CW x NPK	14.48	5.65	5.98
CW x NPK+BC	13.89	5.04	5.17
CV (%)	12.4	17.9	14.9
LSD (5%)	6.88	1.44	1.63

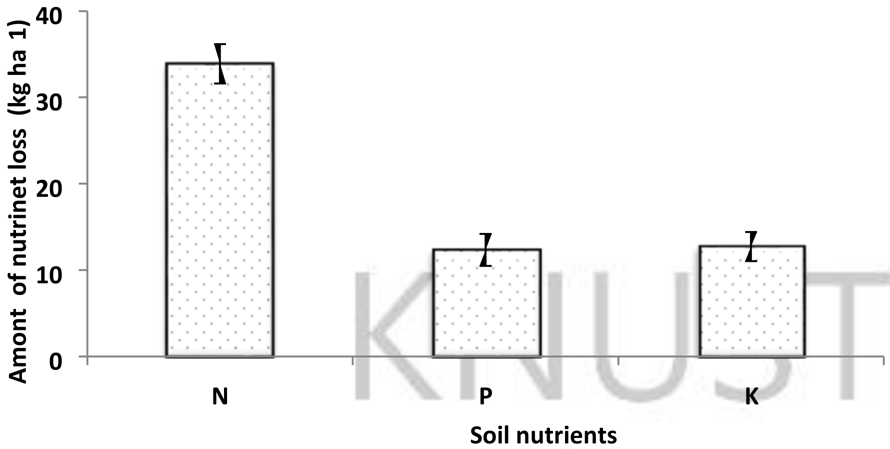


Figure 6.1. Cumulative soil nutrients loss on bare plots (the error bars represent standard deviation)

6.3.2 Enrichment ratio of soil particles and nutrients eroded under the different soil amendments and cropping systems

Tables 6.2, 6.3 and 6.4, Figures 6.2, 6.3 and 4 show the different ERs for the selected soil properties during the three cropping seasons. The chemical parameters (N, P and K) had ER greater than 1 for the individual factors and their interaction. In general, for all the crop nutrients, the ERs were higher during the minor season than in the two major seasons. for all plots with inorganic soil amendments. Moreover, all the amended plots had slightly higher ERs than the unamended plots.

During the cropping seasons, clay and silt particles had higher ERs (greater than unity) with higher values in the minor season than in the major seasons. The sand particles had ER less than unity for all the three growing seasons, but slightly higher for the major seasons compared to the the minor (Fig. 6.2).

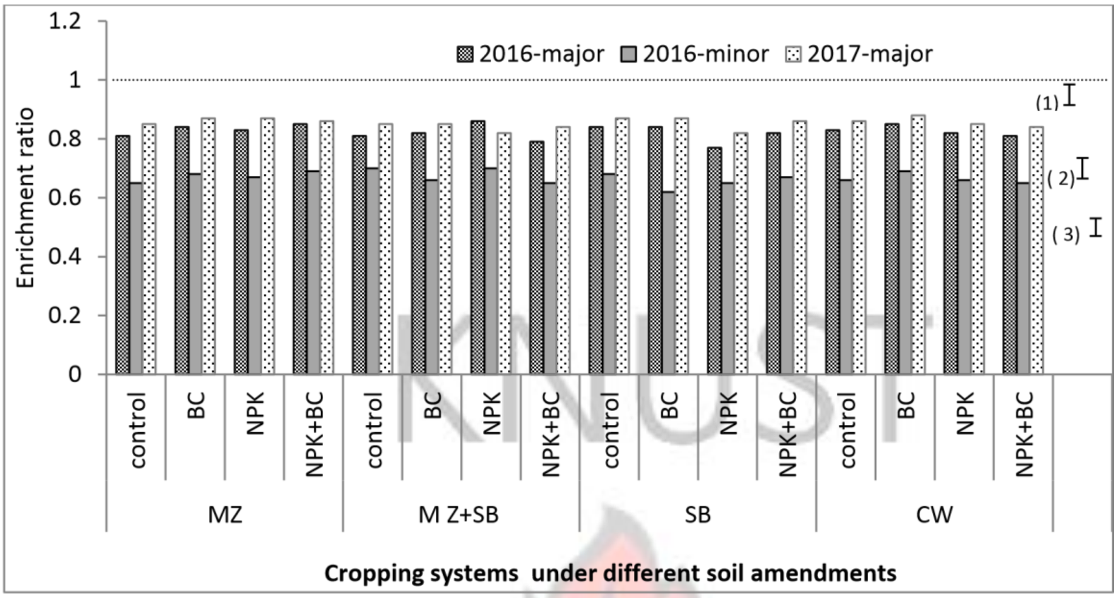


Figure 6.2. Sand enrichment ratio during the three cropping seasons. The bars (1), (2) and (3) are LSD (5%) for 2016-major, 2016-minor and 2017-major 2017 Seasons, respectively, MZ= sole maize, SB= sole soybean, CW = sole cowpea and MZ+SB = maize and soybean intercrop

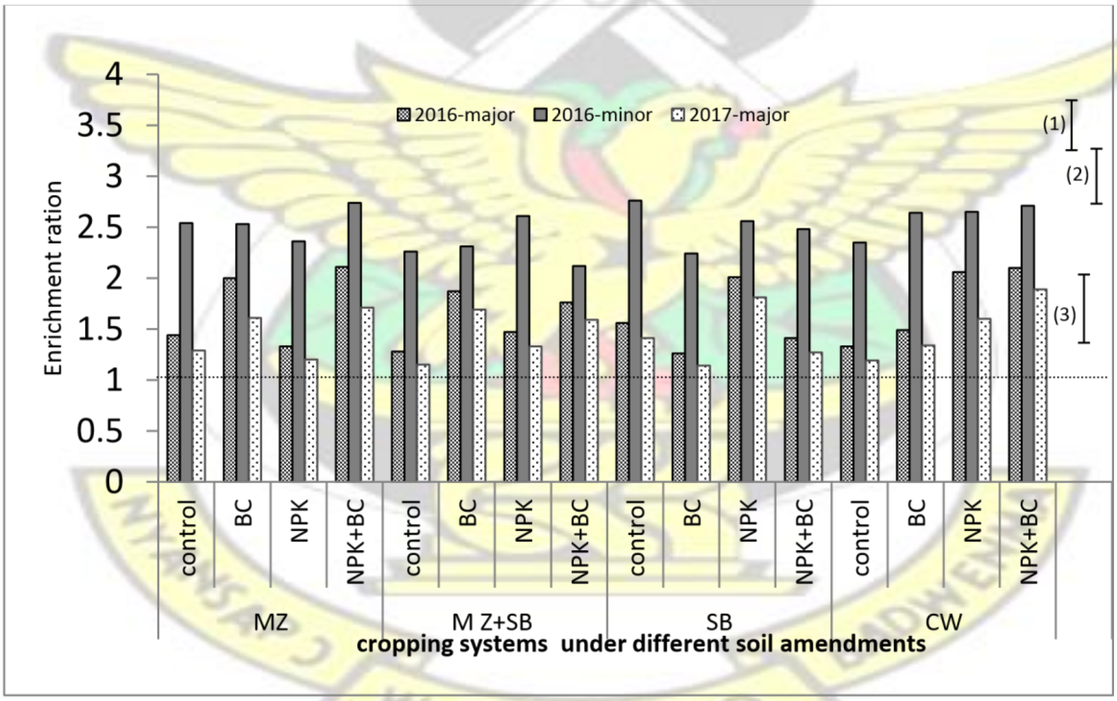


Figure 6.3. Silt enrichment ratio during the three cropping seasons. The bars (1), (2) and (3) are LSD (5%) for 2016-major, 2016-minor and 2017-major seasons, respectively; MZ= sole maize, SB= sole soybean, CW = sole cowpea and MZ+SB = maize and soybean intercrop

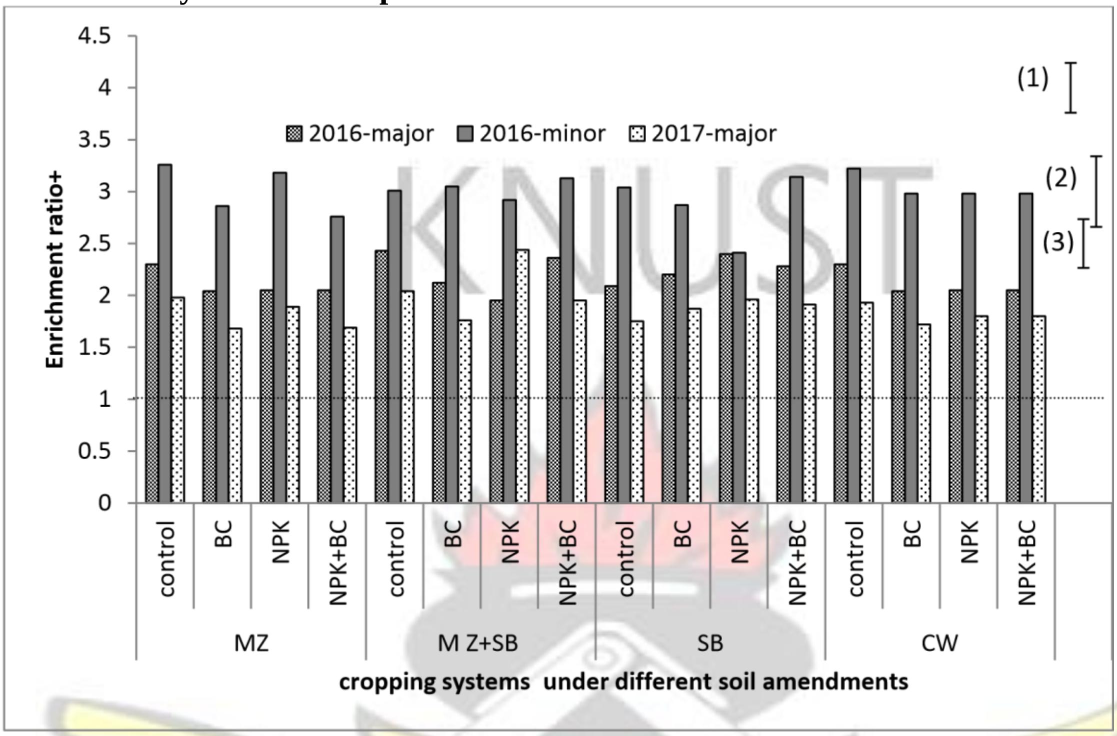


Figure 6.4. Clay Enrichment ratio during the three cropping seasons. The bars (1), (2) and (3) are LSD (5%) for 2016-major 2016-minor and 2017-major seasons, respectively; MZ= sole maize, SB= sole soybean, CW = sole cowpea and MZ+SB = maize and soybean intercropped

Table 6.2. Effect of soil amendments, cropping systems and their interactions on nitrogen enrichment ratio

Treatments	N enrichment ratio		
	Cropping seasons		
Cropping systems	2016- major	2016-minor	2017-major
Cowpea (CW)	1.54	2.20	1.30
Maize (MZ)	1.85	2.91	1.60
Soybean (SB)	1.79	2.44	1.72
Maize+Soybean (MZ+SB)	1.58	2.63	1.57
CV (%)	2.8	7.30	6.70

LSD (5%)	0.16	0.40	0.15
Soil amendments			
Control	1.73	1.46	1.59
Biochar (BC)	1.56	1.85	1.45
Inorganic fertilizer (NPK)	1.86	3.10	1.69
NPK+BC	1.62	3.09	1.47
CV (%)	4.9	7.6	5.00
LSD (5%)	0.45	0.64	0.38
Soil amendments x C ropping syste ms			
MZ x Control	1.60	2.06	1.37
MZ BC	1.65	2.45	1.41
MZ x NPK	2.22	3.74	1.90
MZ x NPK+BC	1.94	3.44	1.72
M Z+SB x Control	1.53	1.31	1.51
MZ+SB x BC	1.82	3.33	1.81
M Z+SB x NPK	2.32	3.04	1.79
MZ+SB x NPK+BC	1.95	2.81	1.19
SB x control	1.31	1.33	1.32
SB x BC	1.35	2.27	1.38
SB x NPK	1.94	2.75	1.81
SB x NPK+BC	1.73	3.43	1.53
CW x Control	1.60	1.11	1.33
CW x BC	1.43	2.20	1.19
CW x NPK	1.93	2.86	1.27
CW x NPK+BC	1.79	2.65	1.40
CV (%)	11.7	19.9	9.5
LSD (5%)	0.79	1.15	0.67

Table 6.3. Effect of soil amendments, cropping systems and their interactions on available phosphorus enrichment ratio

Treatments	P enrichment ratio		
Cropping systems	2016- major	2016-minor	2017-major
Cropping seasons			

Cowpea (CW)	1.64	2.38	1.39
Maize (MZ)	2.00	1.95	1.79
Soybean (SB)	1.44	2.63	1.40
Maize+Soybean (MZ+SB)	1.46	2.09	1.48
CV (%)	17.9	14.4	17.8
LSD (5%)	0.87	1.08	0.80
Soil amendments			
Control	1.55	1.58	1.33
Biochar (BC)	1.39	1.96	1.18
Inorganic fertilizer (NPK)	1.68	2.94	1.84
NPK+BC	1.67	2.58	1.70
CV (%)	19.9	12.2	16.5
LSD (5%)	0.61	0.58	0.58
Soil amendments x C ropping syste ms			
MZ x Control	1.35	1.44	1.67
MZ BC	1.46	1.98	1.25
MZ x NPK	2.43	2.50	1.78
MZ x NPK+BC	2.18	1.94	1.98
M Z+SB x Control	1.40	1.78	1.38
MZ+SB x BC	1.32	1.63	1.31
M Z+SB x NPK	1.60	2.26	1.63
MZ+SB x NPK+BC	1.51	2.67	1.58
SB x control	1.23	1.70	1.24
SB x BC	1.13	2.35	1.16
SB x NPK	1.85	3.14	1.84
SB x NPK+BC	1.54	3.37	1.38
CW x Control	1.21	1.44	1.01
CW x BC	1.22	1.87	1.01
CW x NPK	1.93	3.88	1.66
CW x NPK+BC	2.22	2.33	1.88
CV (%)	19.3	14	15.9
LSD (5%)	1.12	1.16	1.21

Table 6.4. Effect of soil amendments, cropping systems and their interactions on potassium enrichment ratio

Treatments	K enrichment ratio		
Cropping systems / Cropping seasons	2016- major	2016-minor	2017-major
Cowpea (CW)	1.65	1.86	1.38
Maize (MZ)	2.36	2.64	2.15
Soybean (SB)	1.84	2.06	1.75
Maize+Soybean (MZ+SB)	2.18	2.17	2.15
CV (%)	20.8	12.2	13.0
LSD (5%)	0.53	0.44	0.46
Soil amendments			
Control	1.85	1.51	1.69
Biochar (BC)	2.03	1.67	1.88
Inorganic fertilizer (NPK)	2.17	3.06	1.98
NPK+BC	1.98	2.48	1.93
CV (%)	14.1	21.5	12.9
LSD (5%)	0.21	0.30	0.36
Soil amendments x C ropping syste ms			
MZ x Control	1.95	1.53	1.66
MZ BC	2.11	2.23	1.89
MZ x NPK	2.88	3.67	2.12
MZ x NPK+BC	2.60	3.13	2.17
M Z+SB x Control	2.15	1.79	2.08
MZ+SB x BC	2.02	1.45	1.95
M Z+SB x NPK	2.39	3.02	2.28
MZ+SB x NPK+BC	2.14	2.41	2.23
SB x control	1.60	1.48	1.54
SB x BC	2.21.	1.48	2.18
SB x NPK	1.82	2.96	1.79
SB x NPK+BC	1.71	2.30	1.64

CW x Control	1.72	1.24	1.42
CW x BC	1.76	1.54	1.56
CW x NPK	1.98	2.58	1.77
CW x NPK+BC	1.88	2.10	1.73
CV (%)	14.1	18.3	13.9
LSD (5%)	0.84	1.44	0.74

6.3.3 Economic value of nutrients lost due to soil erosion

The monetary values of soil nutrient loss under different soil amendments and cropping systems in Ghana (for each season and cumulatively) are presented in Table 6.5. Indeed, the highest monetary values of soil nutrients lost through erosion were observed on the control plots and the least on plots treated with inorganic fertilizers (sole or in association with biochar) throughout the study period. During the two major growing seasons, higher values were recorded for all the treatments compared to the minor rainy season. Under all the cropping systems, the inorganic fertilizers treated plots had the lowest monetary values of soil nutrient loss compared to sole biochar and control plots. In general, legume-based cropping systems were the most economically viable compared to the maize based systems in terms of the monetary value of soil nutrients lost.

The sole maize had higher values compared to the intercropping system which was slightly higher than the sole soybean. In general, sole cowpea was better than all the other cropping systems with regards to economic value of nutrients lost.

With respect to the interaction between the soil amendments and cropping systems, the cumulative values ranged from 30.82 to 67.21 US$ ha^{-1} for cowpea x NPK and sole maize x control, respectively (Table 6.5). The specific economic loss observed under the different treatments is normally related to their ability to control soil erosion and nutrient transport through runoff and sediments during the growing season.

Table 6.5. Monetary values of the primary macronutrients lost under different cropping systems and soil amendments.

Cropping systems	Amendments	Economic nutrients loss (US$ ha^{-1}/season)			
		Cropping seasons			
		2016-major	2016-minor	2017-major	Cumulative (3 seasons)
Sole Soybean	NPK+BC	15.42	10.83	12.38	38.32
	NPK	17.22	12.67	14.49	44.58
	BC	20.94	12.27	14.03	47.64
	Control	22.20	15.30	19.49	56.99
Maize+Soybean	NPK+BC	17.64	13.60	15.54	46.02
	NPK	17.87	13.17	17.34	48.19
	BC	16.98	12.95	17.09	47.01
	Control	19.40	15.53	22.17	57.10
Sole maize	NPK+BC	16.85	13.67	15.63	46.75
	NPK	16.67	15.22	17.40	48.29
	BC	24.20	15.75	18.00	57.85
	Control	24.41	19.98	22.83	67.21
Sole cowpea	NPK+BC	9.29	10.05	11.49	30.62
	NPK	17.05	10.02	11.41	36.50
	BC	16.32	12.17	13.91	42.40
	Control	18.48	17.30	17.8[2]	53.63
		2.43			

[1] .4 Discussion

[2] .4.1 Cumulative soil nutrient loss through erosion under the different cropping systems and soil amendments

Soil erosion has been reported in several studies (e.g. Koning and Smaling 2005; Zougmore *et al*., 2009, etc.) as one of the major drivers of nutrients depletion in SSA. Environmental and land management factors influence the rate of soil erosion under

LSD (5%)		2.83	3.21	6.12
CV (%)	12.5	17.4	15.1	14.3

(Bertol *et al.*, 2017). Therefore, the low rates of nutrients loss observed under the more stable cropping systems (sole cowpea > sole soybean > intercrop > sole maize)

(Table 6.1) could be explained by the decrease in soil loss under these treatments. Several soil conservation practices have been developed and promoted in SSA but sustainable crop management practices can serve a multipurpose and a better option for crop production improvement as well as soil erosion control. The bare plots, due to the absence of land cover and its attendant soil physical degradation, were more affected by nutrient loss than the other plots under crop management practices (Fig. 6.1 and Table 6.1). The rate of soil nutrients loss observed on each plot was most probably related to the high rate of soil erosion generated and not the amount and type of fertilizers applied. Consequently, the control and the bare plots were the most affected despite application of external nutrients via fertilizer. McHugh *et al.* (2007) from their study, concluded that high rate of nutrient loss under unfertilized plots might be attributed to the beating action of rain drops which causes breakdown of aggregates and clay dispersion as a result of poor soil cover by the crops. This, subsequently, leads to soil surface sealing and decreased infiltration with high rate of runoff and soil loss (McHugh *et al*., 2007). During the cropping seasons, plant nutrients losses were lower under biochar treatment than the control plots (Table 6.1). Lii *et al*. (2017) observed similar trends in a study carried out in China based on biochar effect on soil and nutrient loss and indicated that

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farming activities. The amount of nutrient loss to erosion is often related to the rates of runoff and sediment produced. Soil management practices which reduce soil erosion, may increase nutrient stability in the soil to enhance crop use efficiency the cumulative values of total nitrogen (N) and phosphorus (P) losses were substantially minimized by the biochar treatment compared with the un-amended plots.

Despite the high concentration of soil nutrients in the sediments and runoff, soil erosion rate was strongly reduced with soil nutrient management (Table 6.1.). Soil nutrients application via external fertilizer improves crop performance and increases surface roughness to reduce runoff velocity (Zougmore *et al.*, 2003). The higher amounts of N, P and K lost under sole maize (Table 6.1) are related to the poor land cover with increased soil sediment transport containing plants nutrients. With good land cover and direct impact on soil organic matter, sole cowpea was the cropping system with the least rate of plant nutrients loss. In a study carried out in sorghum based cropping systems in Burkina Faso, Zougmore *et al.* (2009) found also that nutrient loss was lower for the plots where urea fertilizer was applied compared to the control plots.

As reported by Adimassu *et al*. (2017), most soil physical and water conservation practices such as contour and stone bunds are very effective in reducing runoff, soil erosion and nutrient losses. However, their direct effect on physical soil and water conservation practices on crop yield may be negative due to the reduction of effective cultivable area under these interventions (Zougmore *et al.*, 2009; Guto *et al.*, 2012) suggesting the need for agronomic masures.

6.4.2 Enrichment ratios under soil amendments and cropping systems

During the cropping seasons, all the nutreints assessed had ERs gretaer than 1, showing the ability of soil erosion to tranport the most fertile soil layers out of cropped area. The higher ERs of soil nutrients observed during the minor season (Tables 6.2, 6.3 and 6.4) was due to the rainfall characteristic which probably was less erosive in the former than in the latter. Therefore, the total amount of runoff was high for the two major seasons leading to high amounts of soil nutrient losses (Table 6.1), while in the minor seaon, due to the low moisture content, nutrients solubitliy was probably low (Bertol *et al*., 2017) resuslting in increase in nutrients concentration in the runoff and sedimens. The detached top-layers are highly concentrated in soil nutrients (Garcia-Diaz *et al*., 2017) which might strongly compromize agricultural activities due to acute nutrient depletion under eroded soils. The major seasons were characterized by runoff overloaded with soil sediments but with high nutrients solubility leading to lower ERs of the different nutrients evaluated (Sidibé, 2005). Although the total amounts of nutrients lost through erosion was higher on the unamended plots than the the treated plots (Table 6.1), the latter generally, had higher ERs than the former under the different cropping systems (Tables 6.2, 6.3 and 6.4). This shows that the nutrients supplied from the different amendments were washed away and were highly concentrated into the runoff and sediments compared to the control plots. The plots with inorganic fertilizers had generally higher ERs compared to those with sole organic amendment. Thus, fertilizers applied on erodible lands might be lost through runoff and sediment and increase off-site effects (e.g. eutrophication of water bodies) with nutrients accumulations. However, sustainable soil and water conservation practices associated with integated nutrient management technologies are advisable to reduce the impact of these losses.

The soil particles during the eroison process had different ‘behaviour’ towards the erosive factors. The ER > 1 observed for the clay and and silt patricles (Fig 3 and 4.) showed that eroded materials were richer in fine particles. Due to the selectivity nature of the process, the fine soil particles and the rich in plant nutrients were the most eroded. Generally, the soil sediments contain higher amounts of soil nutrients in available forms than the soil from which it is eroded (Quansah *et al*., 2000 ; Pan *et al*., 2016). This nothwithsatnding, the higher ERs for sand observed only during the two major seasons compared to the minor season, was probaly due to the storms characteristics.

6.4.3 Economic value of soil nutrients loss due to erosion

Globally, due to soil erosion, the annual amount of fertilizers mobilized is equivalent to 34 US$ billion for N and 80 US$ billion for P which is an important financial loss; while the global agricultural food production is valued at US$ 4000 billion (Govers *et al.*, 2016). One of the objectives of soil amendments is to restore the different nutrients lost through different pathways (e.g., plant up take, soil erosion). This may be achieved through application of inorganic fertilizers from the markets.

Nutrients loss through runoff and sediment transport converted into monetary values showed that soil nutrient management is an important component of sustainable soil conservation beyond direct crop nutrition effect (Sidibé, 2005). The reduced monetary values in terms of nutrients loss observed under the soil amendments and each cropping system (Table 6.5.), explained the effect of fertilizer application on soil erosion management. Under poor soil and crop management practices, the rate of soil and nutrient loss are very high. For this study, the higher cumulative monetary values observed for the control plots during the study period (56.99, 57.10, 67.21 and 53.63 US$ ha^{-1} for sole soybean, maize and soybean intercropped, sole maize and sole cowpea, respectively) were related to the considerable amounts of soil and runoff losses under these treatments. Indeed, the lower economic loss observed on plots treated with inorganic fertilizers associated with biochar ranging from 30.62 to 46.75 US$ ha^{-1} against 53.62 to 57.10 US$ ha^{-1} observed under the control plots (without any soil management) was due to soil erosion reduction under the former. This shows the magnitude of the impact of soil erosion on nutrient loss on poorly managed soils. Moreover, the low values observed under NPK+BC accord the low rates of nutrient loss (Table 6.2) and ERs (Tables 6.2, 6.3 and 6.4) observed under this treatment.

The total amount of nutrients lost converted into economic value for the control plot was higher due to the magnitude of soil and runoff losses from these unmanaged plots. Moreover, the amounts of fertilizer applied were not high to increase soil nutrient entrainment into the sediment and runoff compared to the important amount of soil lost from these plots. Therefore, the total amount of nutrient lost due to erosion is mostly related to the soil loss rate than to the nutrient application. A study carried out by Quansah *et al*. (2000) showed that the economic value for NPK plots under maize was highly reduced compared to the plots without any amendments and the

bare plots.

The economic value of soil erosion was based on soil fertility erosion using the cost replacement method (Quansah *et al*., 2000). However, even though the method gives the magnitude of erosion on nutrient loss, it presents some limitations: soil erosion affects other nutrients and other forms of soil degradation which may require investments for restoration. Also, eroded nutrient forms and the nutrient forms in the fertilizers may be slightly different for accurate conversion. This notwithstanding, the method is still reliable to assess the economic value of soil loss under soil erosion constraints (Enters, 1998).

6.5 Conclusion

Soil erosion based on nutrients loss characteristics were influenced by cropping systems and soil amendments. Nutrient management practices showed positive effect on soil and nutrients loss reduction which was lower under sole inorganic fertilizers or in combination with biochar under different cropping systems, especially the sole cowpea system.

High ER values (>1) observed for all the soil nutrients assessed showed off-site nutrient accumulation due to erosion. Soil nutrients losses were important during the major seasons compared to the minor season where high values ER were observed. Fine soil particles (clay and silt) showed higher ERs throughout the study period while the sand particles had consistently ER values less than unity with the greatest values observed during the major seasons.

The monetary value of the nutrient loss was affected by the different management practices imposed. All the cropping systems without any amendment showed the highest monetary values due to nutrient loss. The external amendments, with the good impact on soil erosion and nutrient loss, were the least compared to the untreated plots. These findings give a new opportunity to highlight the importance of sustainable crop management to reduce nutrient losses on croplands in SSA.

CHAPTER SEVEN

7. EFFECT OF SOIL AMENDMENTS AND CROPPING SYSTEMS ON SOIL PROPERTIES

Abstract

Different strategies of soil and water conservation have been developed in SSA for the restoration of degraded soils. These practices which are fundamentally based on soil amendments and common cropping systems have not been widely studied in Ghana with respect to biochar. The current study was therefore conducted to assess the effect of different soil amendments including biochar on some soil physical and chemical properties under selected cropping systems. The study was a split- plot arranged in RCBD with three replications. The soil amendments (NPK fertilizer, NPK combined with biochar (NPK+BC), sole biochar (BC) and control) and the cropping systems (sole maize, sole soybean, sole cowpea and maize intercropped with soybean) were the two factors investigated in three consecutive cropping seasons. Results indicated that the soil physical properties, namely bulk density, volumetric moisture content and total soil porosity were significantly influenced by the treatments. The sole cowpea associated with the different soil amendments highly improved these properties while maize without any amendment increased soil degradation. The legume-based cropping systems associated with the inorganic inputs significantly ($P <$

0.05) improved total nitrogen, available phosphorus and exchangeable potassium. Despite the slight differences among the soil amendments with respect to soil pH, no significant effect ($P > 0.05$) was observed as also for the cropping systems. Among the different treatment, sole biochar or in combination with inorganic fertilizers improved better soil organic C, total N, and exchangeable K contents.

Keywords: biochar, cropping systems, nutrients management, soil, soil properties

7.1 Introduction

Soil degradation which characterizes smallholder farming systems in sub-Saharan Africa (SSA), requires specific and sustainable mitigation strategies to improve crop production. The actual magnitude of soil degradation experienced in this region, requires multipurpose and adaptive solutions, not only to increase crop yields, but also to enhance soil and water conservation and plant nutrients availability (Ngetich *et al*., 2014; Valley *et al*., 2017). Soil moisture availability is a key factor for plant nutrients use efficiency for sustainable crop production in smallholder farming systems. Cropping systems and nutrient management practices have thus been used as a mean to improve crop production and secure food supplies in developing countries (Adeli *et al*., 2017). Certainly, soil and water related constraints are counted amongst the most important agricultural threats which require lasting management practices (Amendola *et al*., 2017;

Pan *et al.*, 2017). In the study area, poor agricultural production is due to soil nutrient depletion coupled with climatic constraints on which less management options are available for small-scale farmers.

Several methods and strategies of water and soil conservation (SWC) have been widely developed to meet the demand of small-scale farming systems (Zougmoré *et al*., 2003; Guto *et al.,* 2011; Amegashie, 2014; Ngetich *et al*., 2015). The impact on soil chemical properties and yields were the most studied variables under these previous works (Quansah *et al.*, 2000; Zougmoré *et al*., 2003; Amegashie, 2014). The current study adds among the treatments, biochar, as a multipurpose soil amendment with expected positive effects on soil moisture storage and soil nutrients availability for increased crop productivity. As an option for soil carbon sequestration, agricultural value of biochar application is yet to receive the needed attention especially in the study area. The study aims to assess the effect of different soil amendments and cropping systems on soil chemical and physical properties.

7.2 Materials and methods

The research area, the experiment and the different soil and crop management options related to this Chapter have been described in sections 3.1 and 3.2 of Chapter three of general methodology. The methods and procedures used to measure the different soil properties as affected by the different interventions are described in the current section in line with the fourth objective of the overall study.

In order to assess the effect of the different soil amendments and cropping systems, from each plot, four soil samples were collected randomly from the 0-20 cm depth and bulked into a composite sample representative of each plot. These were then subjected to chemical analysis. For the physical parameters, an undisturbed soil sample was collected from each plot using the core sampler and the selected soil properties, namely bulk density, total porosity and volumetric moisture content determined as described under section 3.3.2 of Chapter three. For the chemical properties, the soil samples were air dried, crushed and sieved through a 2 mm mesh for analysis. The soil chemical properties considered in this study were soil pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P) and exchangeable potassium (K) and the specific methods of analyses are described under section 3.3.3 of Chapter three.

7.3 Results

7.3.1 Soil physical properties as affected by the soil amendments and cropping systems

Soil bulk density, volumetric water content and total porosity were influenced by the different soil amendments and cropping systems (Table 7.1). With regards to the cropping systems, the bulk densities ranged from 1.40 to 1.48 Mg m^{-3} under sole cowpea and sole maize, respectively whilst under amendments, between 1.39 to 1.58 Mg m^{-3}. The bulk density values under the amendments were in the order: Control > BC > NPK > NPK+BC. The interactions between the cropping systems and the soil amendments on bulk density were also significant ($P < 0.05$). It was observed that the cropping systems which received no amendment (control plots) had the highest BD compared to those treated with amendments.

The volumetric water content was significantly affected by the cropping systems. The lowest and highest values were recorded under sole maize and sole cowpea, respectively. All the legume-based systems were not significantly different each other. For the soil amendments, all the treated plots had similar values ($P > 0.05$) but which differed significantly from the control plot ($P < 0.05$). The interaction between the two factors showed significant differences wherein the highest values were observed on the amended plots for all cropping systems. The lowest moisture content (8. 88 %) was recorded under the maize + soybean intercrop which received no amendment while the highest value (27.20%) was observed under the sole cowpea treated with the combination of inorganic fertilizers and biochar.

Table 7.1. Effect of soil amendments, cropping systems and their interaction on selected soil physical properties at the end of the study

Treatments	Bulk density ($Mg\ m^{-3}$)	Volumetric water (%)
Cropping systems		
Cowpea (CW)	1.40	24.55
Maize (MZ)	1.48	15.48
Soybean (SB)	1.42	22.62
Maize+Soybean (MZ+SB)	1.44	20.81
CV (%)	6.60	9.40
LSD (5%)	0.03	5.18
Soil amendments		
Control	1.58	14.79
Biochar (BC)	1.40	22.49
Inorganic fertilizer (NPK)	1.38	23.03
NPK+BC	1.39	23.14
CV (%)	1.30	12.4
LSD (5%)	0.03	5.02
Cropping systems x Soil amendment s		
MZ x Control	1.59	42.14
MZ x BC	1.46	48.80
MZ x NPK	1.42	47.93
MZ x NPK+BC	1.38	48.53
M Z+SB x Control	1.57	41.98
MZ+SB x BC	1.42	49.27
M Z+SB x NPK	1.40	47.46
MZ+SB x NPK+BC	1.41	47.43
SB x control	1.52	42.02
SB x BC	1.36	48.63
SB x NPK	1.38	47.34
SB x NPK+BC	1.40	45.18
CW x Control	1.59	43.48
CW x BC	1.37	50.68

CW x NPK	1.33	48.53
CW x NPK+BC	1.35	47.79
CV (%)	3.00	4.20
LSD	0.05	3.13

7.3.2 Soil chemical properties under the soil amendments and cropping systems

Soil pH was not affected by the farming practices (i.e., amendments and cropping systems) ($p > 0.05$) (Table 7.2). However, there was an increase of 0.1 to 0.5 units under biochar amended plots compared to the control plots. There was a slight acidification of the soil in response to the treatments (about 0.16 - 0.7 units decrease of the initial values reported in the next chapter in Table 8.1).

Table 7.2. Effect of soil amendments, cropping system and their interaction on soil pH

Treatments	Soil pH		
	2016 –major	2016 –minor	2017 -major
	Cropping seasons		
Cropping systems (1)			
Cowpea (CW)	5.38	5.17	4.91
Maize (MZ)	5.34	5.25	5.04
Soybean (SB)	5.44	5.38	5.17
Maize+Soybean (MZ+SB)	5.48	5.50	5.32
CV (%)	2.8	1.2	1.00
LSD (5%)	NS	NS	NS
Soil amendments (2)			
Control	5.32	5.15	4.94
Biochar (BC)	5.42	5.46	5.48
Inorganic fertilizer (NPK)	5.34	5.32	5.14
NPK+BC	5.45	5.47	5.52
CV (%)	4.5	3.1	3.3

LSD (5%)	NS	NS	NS
Interaction (1) x (2)	NS	NS	NS

Soil organic carbon (SOC) was significantly influenced by the cropping systems and soil amendments (Table 7.3). The highest values were observed under the legumebased systems, wherein the values ranged from 1.46 to 1.84 % compared to the sole maize (1.33 to 1.44 %). The soil amendments were significantly different (P < 0.05) with respect to SOC; the lowest (1.08 %) and highest (2.4 %) SOC were observed under the control and NPK+BC treatments, respectively. Under sole biochar treatments, higher values were consistently observed compared to the sole NPK plots during the three consecutive cropping seasons. For the interaction effect, under each cropping system, the control plot had the least SOC compared to the treatments with the external amendments with values ranging from 1.09 and 2.15 %, respectively.

Table 7.3. Effect of soil amendments, cropping systems and their interaction on soil organic carbon

	Organic carbon **(%)**		
Treatments	2016-major	2016- minor	2017- major
Cropping seasons			
Cropping systems			
Cowpea (CW)	1.59	1.53	1.48
Maize (MZ)	1.44	1.35	1.33
Soybean (SB)	1.54	1.46	1.41
Maize+Soybean (MZ+SB)	1.84	1.62	1.61
CV (%)	15.7	6.1	3.6
LSD (5%)	0.79	0.57	0.55
Soil amendments			
Control	1.18	1.12	1.08
Biochar (BC)	1.75	1.77	1.51
Inorganic fertilizer (NPK)	1.28	1.52	1.50
NPK+BC	2.14	1.63	1.93
CV (%)	24.8	8.7	18.2
LSD (5%)	0.47	0.13	0.13
Soil amendments x C ropping systems			
MZ x Control	1.19	1.15	1.09
MZ x BC	1.39	1.33	1.42
MZ x NPK	1.29	1.15	1.13
MZ x NPK+BC	1.52	1.43	1.55
M Z+SB x Control	1.15	1.12	1.08
MZ+SB x BC	1.44	1.34	1.53
M Z+SB x NPK	1.76	1.21	1.17
MZ+SB x NPK+BC	1.71	1.46	1.46
SB x control	1.20	1.15	1.12
SB x BC	1.85	1.58	1.98
SB x NPK	1.31	1.21	1.21
SB x NPK+BC	2.15	1.94	2.11
CW x Control	1.25	1.20	1.19
CW x BC	1.86	1.90	2.01
CW x NPK	1.65	1.90	1.60
CW x NPK+BC	1.84	1.76	1.93
CV (%)	10.1	10.7	10.4

LSD (5%)	0.73	0.59	0.57

Significant differences (P < 0.05) were observed among cropping systems and soil amendments with respect to total N (Table 7.4). The legume-based cropping systems produced significantly higher N contents (P < 0.05) than the sole maize system. The soil amendments influenced soil total nitrogen, in that all the treatments with external amendments (BC, NPK and NPK+BC) were significantly different from the control under each cropping system.

Table 7.4. Effect of soil amendments, cropping system and their interaction on soil total nitrogen

Treatments	Total nitrogen (%)		
	Cropping seasons		
	2016-major	2016-minor	2017-major
Cropping system			
Cowpea (CW)	0.097	0.099	0.096
Maize (MZ)	0.065	0.620	0.063
Soybean (SB)	0.990	0.097	0.100
Maize+Soybean (MZ+SB)	0.104	0.091	0.094
CV (%)	1.800	2.900	3.000
LSD (5%)	0.015	0.035	0.031
Soil amendment			
Control	0.057	0.056	0.055
Biochar (BC)	0.100	0.095	0.092
Inorganic fertilizer (NPK)	0.113	0.104	0.099
NPK+BC	0.113	0.110	0.098
CV (%)	7.6	7.7	6.3
LSD (5%)	0.009	0.021	0.020
Soil amendment x Cropping system			
MZ x Control	0.053	0.051	0.050
MZ x BC	0.103	0.063	0.077
MZ x NPK	0.104	0.107	0.096
MZ x NPK+BC	0.107	0.101	0.107
M Z+SB x Control	0.051	0.050	0.067
MZ+SB x BC	0.095	0.099	0.104
M Z+SB x NPK	0.111	0.101	0.116
MZ+SB x NPK+BC	0.117	0.106	0.114
SB x control	0.065	0.057	0.054
SB x BC	0.108	0.099	0.097
SB x NPK	0.110	0.100	0.117
S x NPK+BC	0.110	0.097	0.087
CW x Control	0.057	0.058	0.064

CW x BC	0.108	0.099	0.091
CW x NPK	0.114	0.113	0.112
CW x NPK+BC	0.117	0.115	0.112
CV (%)	10.8	10.8	14.4
LSD (5%)	0.019	0.047	0.044

The various cropping systems did not differ significantly ($P > 0.05$) in the available phosphorus content (Table 7.5). However, there was a slight increase under the legume-based systems (ranging from 14.32 to 20.83 mg kg^{-1}) compared to the sole maize (12.21 to 13.56 mg kg^{-1}). On the other hand, significant differences were observed between the fertilized and the control plots under all the cropping systems. Application of amendments resulted in observable increases in available P content (18.50 to 22.49 mg kg^{-1}) compared to the initial soil content (15.67 mg kg^{-1}). There was, however, a decline in the control plots (Table 7.5).

Table 7.5. Effect of soil amendments, cropping system and their interaction available phosphorus

Treatments	Available phosphorus (mg kg^{-1}) Cropping seasons		
	2016-major	2016-minor	2017-major
Cropping systems			
Cowpea (CW)	17.81	14.32	16.60
Maize (MZ)	13.47	12.21	13.56
Soybean (SB)	20.83	18.40	16.77
Maize+Soybean (MZ+SB)	20.47	19.84	15.57
CV (%)	16.00	12.00	13.40
LSD (5%)	NS	NS	NS
Soil amendment			
Control	12.91	13.54	12.84
Biochar (BC)	19.32	18.50	19.11
Inorganic fertilizer (NPK)	22.49	21.52	20.84
NPK+BC	21.86	20.11	21.70
CV (%)	17.5	15.1	17.4
LSD (5%)	3.89	3.41	4.92
Soil amendment x Cropping system			
MZ x Control	10.53	10.71	10.09
MZ x BC	14.04	12.92	15.90
MZ x NPK	16.44	14.15	16.06
MZ x NPK+BC	17.84	16.17	17.55
M Z+SB x Control	12.64	11.74	11.09
MZ+SB x BC	21.87	20.32	18.37
M Z+SB x NPK	24.63	23.51	16.77
MZ+SB x NPK+BC	22.74	21.93	20.84
SB x Control	16.32	14.74	16.36
SB x BC	23.11	21.53	20.41
SB x NPK	20.98	21.92	22.56
SB x NPK+BC	22.91	25.31	22.93
CW x Control	12.16	13.51	11.38
CW x BC	17.25	17.76	17.93
CW x NPK	19.89	19.24	20.12
CW x NPK+BC	23.95	20.01	24.22

CV (%)	14.1	14.4	13.3
LSD (5%)	4.81	5.64	4.93

Exchangeable potassium was not significantly affected by the different cropping systems ($p > 0.05$) (Table 7.6). Conversely, the different amendments significantly influenced the exchangeable potassium ($P < 0.05$). The highest values were observed under inorganic fertilizer-treated plots with or without biochar, while the lowest values were recorded on the control plots. The interaction effects of the cropping systems and the soil amendments were significant. The sole legume plots amended with inorganic fertilizers with or without biochar had the highest values (0.43 to 0.54 $cmol_c$ kg^{-1}) while the lowest values (0.16 to 0.21 $cmol_c$ kg^{-1}) were observed on the sole maize control plots.

Table 7.6. Effect of soil amendments cropping systems and their interaction on exchangeable potassium

Treatments	Exchangeable potassium ($cmol_c\ kg^{-1}$)		
	2016 -major	2016-minor	2017-major
Cropping system	Cropping seasons		
Cowpea (CW)	0.42	0.41	0.40
Maize (MZ)	0.38	0.36	0.33
Soybean (SB)	0.42	0.31	0.29
Maize+Soybean (MZ+SB)	0.44	0.37	0.36
CV (%)	4.2	11.2	8.4
LSD (5%)	NS	NS	NS
Soil amendment			
Control	0.20	0.18	0.17
Biochar (BC)	0.38	0.35	0.32
Inorganic fertilizer (NPK)	0.51	0.43	0.38
NPK+BC	0.51	0.44	0.38
CV (%)	8.1	9.8	12.1
LSD (5%)	0.08	0.06	0.05
Soil amendment x Cropping system			
MZ x Control	0.17	0.15	0.14
MZ x BC	0.30	0.27	0.30
MZ x NPK	0.35	0.32	0.31
MZ x NPK+BC	0.34	0.29	0.28
M Z+SB x Control	0.21	0.18	0.17
MZ+SB x BC	0.34	0.36	0.37
M Z+SB x NPK	0.50	0.43	0.46
MZ+SB x NPK+BC	0.63	0.42	0.57
SB x control	0.21	0.21	0.19
SB x BC	0.40	0.39	0.32
SB x NPK	0.51	0.46	0.52
SB x NPK+BC	0.54	0.50	0.49
CW x Control	0.20	0.20	0.20

CW x BC	0.33	0.32	0.39
CW x NPK	0.50	0.46	0.53
CW x NPK+BC	0.46	0.43	0.49
CV (%)	14.6	10.6	17.4
LSD (5%)	0.08	0.23	0.22

7.4 Discussion

7.4.1. Soil physical properties as affected by soil amendments and cropping systems

Soil physical properties such as bulk density, moisture content, and total porosities are considered as soil quality indicators affecting soil structure under different management systems with implications for soil functioning and processes (Hu *et al.,* 2017). They influence soil productivity positively and negatively as they affect other soil parameters such as infiltration and permeability, root proliferation and depth, water storage and activity of microorganisms, all of which directly influence soil productivity (Lal, 2015; Hu *et al.,* 2017).

The relatively higher bulk density observed on the control plots of the different cropping systems was indicative of the degree of soil compaction, which is a major constraint to crop performance (Mahmood *et al.,* 2017). This explains the importance of soil amendments on soil physical properties as reported in earlier studies under different cropping systems (e.g. Jien and Wang, 2013; Ameloot *et al*., 2015; Peng *et al*., 2016; Lii *et al*., 2017). The lower SOC content of the control plot (Table 7.1) resulted in its higher bulk density. The relatively higher bulk density observed on the sole maize plot is also attributable to its relative lower SOC content (Table 7.3)

Under rainfed cropping systems, rainfall is the source of water for crop growth and yield. Most of the regions of SSA are characterized by erratic rainfall patterns with direct negative impacts on crop productivity (Lal, 2015). Adequate supply of water at each stage of crop growth is crucial for crop growth and yield. Under rainfed agriculture, adequate water storage within the root zone and reduced water loss are important factors to optimize nutrient use by crops. The dependence of plants on water stored in the soil root zone is due to the fact that plants store very little water compared to their daily requirements, which is about 40 to 100 m^3 ha^{-1} (Freschet *et al.*, 2013). Associating water storage techniques with conventional crop and soil nutrient management practices is one key step forward in a multipurpose approach to soil water and nutrients management.

The findings of this research have shown that cropping systems and soil amendments can be alternative options for improving soil water storage. The volumetric water content varied with the type of cropping systems evaluated (Table 7.1). Indeed, the low soil moisture observed under sole maize was possibly due to the low land cover by the sole maize compared to the intercropping system (maize and soybean), where the land surface was highly covered by both crops to reduce the impact of raindrops and water loss by evaporation. Under the sole cowpea and sole soybean systems, soil moisture contents were higher than the other systems (Table 7.1). This could be due to higher canopy cover by the cowpea and soybean, which reduced the kinetic energy of raindrops and their destructive impact on the surface soil (Vaezi *et al*., 2017). Apart from rainfall interception, the legumes produced large amount of litter seasonally, which contributed to the building up of soil organic matter content (Table 7.3) and soil physical properties (Foley *et al*., 2011). Thus, the production of biomass is an important component of soil moisture storage in cropping systems.

Improvement in soil moisture content was noticed on biochar treated plots, compared to the control plots (Table 7.1). Soil moisture storage characteristics defined by volumetric moisture content was low on the control plots. Application of sole biochar had significant effect on the water storage parameters due to its hydrological aptitude to improve soil properties and which has positive effect on soil water storage. This soil water characteristic improvement observed under biochar accords with several other findings with similar trends (e.g. Jien and Wang, 2013; Ojeda *et al.*, 2015; Amendola *et al.*, 2017).

7.4.2 Soil chemical properties

Application of biochar improved soil organic carbon status (Table 7.3) and this was in accordance with several other research findings where similar trends were observed (e.g. Jien and Wang, 2013; Gul *et al*, 2015; Partey *et al.*, 2016). Soil carbon sequestration and improvement in soil properties are the most important reasons for incorporation of biochar into soil management strategies (Rockström *et al.*, 2014). It was observed that SOC increased with biochar application during the different seasons (Table 7.3). Although biochar is not considered a common source of plant nutrients, compared to other available organic materials (Ajayi and Rainer, 2017), its associated effects on SOC and other soil properties impact positively on crop productivity (Jien and Wang, 2013). Therefore, biochar can be recommended as multipurpose soil management option.

Soil amendments and cropping systems affected soil total nitrogen content such that there were improvements under each treatment compared to the controls. In general, the initial soil total nitrogen content (0.09%) was increased under all the treatments with the application of the different amendments by 10 to 30 %, while the untreated plots showed a decrease of 26 to 44% of the initial level. The plots treated with inorganic fertilizers showed slight increases compared to those with biochar.

In all the unfertilized plots for both systems (maize and legumes), total nitrogen content was lower compared to the amended plots. Similar results were obtained by Logah *et al.* (2010) who observed higher soil N content of plots treated with poultry manure and nitrogen fertilizer than un-amended plots under maize-based cropping systems in Ghana. The low initial total nitrogen content (0.09%) of the study area describes the poor quality of the soil, which calls for the need of external nutrients application to improve soil quality. Application of soil amendments increased available phosphorus with respect to the initial values and the control plots. This is not surprising as the amendments are P containing materials. Due to its slow diffusion and immobilization attributes, the bulk of applied P remains in the soil (Prasad and Power, 1997).

Soil amendments improved the levels of exchangeable potassium (K) in all the three cropping seasons ($P < 0.05$). Although K deficiency is not common in tropical soils, external supply through inorganic or organic fertilizers, is still crucial to keep positive balance (VanderBom *et al.*, 2017). However, due to its high mobility, the application of high amount of mineral K can easily leach out of the soil profile.

7.5 Conclusion

Soil degradation under smallholder farming systems requires sustainable interventions. The findings of the current study showed the impact of soil management based on inorganic and organic amendments under different cropping systems. Soil physical properties were stabilized under the different practices with the least results under sole maize. Under each cropping system, biochar-based treatments improved physical properties more than the others. Soil nutrients were increased by the different soil amendments. In general, the legume-based systems had better influence on soil nutrients status than sole maize. Soil amendments and cropping systems can serve as good options for improving soil physico-chemical properties in small-scale cropping systems.

CHAPTER EIGHT

8. CROP PRODUCTIION UNDER DIFFERENT CROPPING SYSTEMS AND SOIL AMENDMENTS IN THE SEMI-DECIDUOUS FOREST ZONE OF GHANA

Abstract

Soil nutrients depletion is a major constraint to crop production in sub-Saharan Africa (SSA). In the era of climate change, integrated and a menu of climate-smart approaches have been proposed to enhance productivity of cropping systems in the sub-region. In this study, we evaluated crop grain and biomass yields, nutrients uptake and economic viabilities of integrated use of biochar (BC) under cereals and legumebased cropping systems in Ghana in three consecutive cropping seasons. The twofactor experiment comprised soil amendments (biochar, NPK fertilizers, biochar + NPK and control) and cropping systems (sole maize, maize intercropped with soybean, sole soybean and cowpea). Whereas sole application of mineral fertilizers generally resulted in significantly ($P < 0.05$) higher grain yields of maize and cowpea than the integrated application with biochar, differences in soybean grain yields under these treatments were generally similar ($P > 0.05$). With respect to biomass yields, integrated application of biochar and mineral fertilizers consistently outperformed the sole mineral fertilizer and biochar treatments under all cropping systems. Land equivalent ratios of maize was generally higher (> 1) under NPK + BC treatments than the sole applications and the control. Nutrients (N, P, K) uptake in maize was highest in sole NPK and NPK+ BC plots under sole cropping systems than the intercropping systems. Similarly, nutrients uptake and crop yields in sole biochar amended plots under all cropping systems were consistently higher than the non- amended plots. For example, grain and biomass nitrogen uptake were respectively 5468% and 54-90% higher in sole biochar plots than the non-amended plots. The value cost ratio (VCR) under NPK plots was consistently above the economic thresholds (>2.0) for all cropping systems evaluated. With respect to NPK +

BC, economic threshold was only exceeded under intercropping systems but not under sole cropping systems, indicating a considerable intercropping benefits in integrated nutrient management of biochar and mineral fertilizers.

Keywords: biochar, cropping systems, land equivalent ratio, nutrients depletion, yield

8.1 Introduction

Crop productivity in SSA is strongly affected by several constraints in small-scale farming systems. Several programs and technologies have been developed to reduce acute soil degradation characterizing cropping systems in SSA, but with low success

(eg., Bationo *et al*., 2003; Vanlauwe *et al.*, 2003; Sanginga and Woomer, 2009, etc). Different factors define the actual state of the degraded soils in this zone and which require more integrated and sustainable interventions. The amount of nutrients transported during plant harvest (yield and crop residues) coupled with nutrient loss through erosion (runoff and sediment) are important threats to soil nutrient depletion in the region.

Inorganic and organic fertilizers have been strongly recommended to increase agricultural productivity (Bationo *et al.,* 2003; Vanlauwe *et al.*, 2003; Vanlauwe and Giller, 2006). Whilst SSA is characterized by poor utilization of external fertilizers, natural and climate factors increase the risk of soil degradation through soil erosion.

Africa is characterized by the lowest rate of inorganic fertilizer use (8 kg ha^{-1})

(Bationo *et al*., 2011; Vanlauwe *et al*., 2011).
The major staple grain crops (maize and cowpea) of the semi-deciduous forest zone of Ghana, are generally poor yielding due to soil nutrients depletion coupled with climatic constraints. However, sustainable soil and crop management practices may increase soil

fertility and enhance nutrients use efficiency which are key drivers of crop production. Soybean, being progressively introduced into the common cropping systems of the zone, is constrained by soil degradation and water stress as most of the cultivated crops in the region.

Despite their abilities to fix nitrogen with rhizobia, soybean and cowpea require also external nutrients in the form of nitrogen fertilizers for good productivity. Several studies have shown the importance of starter N for improvement of legume production (e.g. Ankomah *et al.*, 1996; Revon *et al*, 2015; Dar *et al.*, 2016; etc). Enhancing sustainable soil management for maize, cowpea and soybean production, can boost the productivity of these crops, which are very important for food security in Africa. The cost effectiveness of the different interventions is, however, a determining factor for consideration to make agricultural activities more attractive and adoptable by the stakeholders. Biochar effects on crop productivity in the study area is limitedly studied. Therefore, the current study aims to improve crop productivity and profitability under different options of soil and crop management with good focus on biochar.

8.2 Materials and Methods

The research area, the experiment and the different soil and crop management practices for this study have been described in sections 3.1 and 3.2 of chapter three of general methodology. The specific methods and procedures used are described in this section.

8.2.1 Grain and straw/ haulm yields

For the maize, mature dried ears were handpicked from the plants within each net plot of 22 m² (the size of the entire plot was 12 m x 3 m). The grains removed from the ears, were weighted and a subsample taken for moisture content determination to adjust grain yield. Moisture content of 13 % was used for the grains yield correction (Mohseni *et al.*, 2014). After removal the ears from each net plot, the straws were cut from the surface soil and weighted. A subsample was taken to the laboratory for moisture content determination and adjustment after oven drying at 70 °C for 48 h to allow for biomass yield calculation.

For the legumes (cowpea and soybean), matured and dried pods were harvested from each plot and shelled. After weighing, the total grains and biomass from each net plot were subsampled and dried at 70 ° C for 48 h in the oven and the dry weights taken (Reddy, 2001).

8.2.2 Land equivalent ratios

The maize-soybean system was assessed using the land equivalent ratio (LER) which compares the yield obtained by intercropping two or more species together with yields obtained by growing the same crops as monocultures. The LER for the two intercrop species (maize and soybean) was calculated using equation 8.1 (Mead and Willey, 1980). Intercropped plots with LER greater than 1.0 shows a yield advantage while a value less than 1.0 shows a yield disadvantage in the intercropping system.

$$\text{LER} = \frac{\text{Yaa}}{\text{Yab}} + \frac{\text{Ybb}}{\text{Yba}} \quad (8.1)$$

where:

Yaa and Ybb are the yield of crops (a= maize and b = soybean) in sole cropping systems, Yab and Yba are respective yields of maize and soybean, in intercrop system.

8.2.3 Nutrient uptake

The subsamples of oven dried grains, straws and haulms were milled using Petern's laboratory mill 3310 and sieved through a 0.5 mm mesh. These plant materials were analyzed for nutrients content viz. total nitrogen, phosphorus and potassium as described in section 3.3.3 of chapter three.

8.2.4 The value cost ratio

The value cost ratio (VCR) determines the economic value of the different soil management options applied for crop yield increase. This is the ratio between the value of the additional crop yield obtained from input use (fertilizer and amendments) and the cost of inputs used. Therefore, the gross rate of returns from the applied inputs represented by VCR was calculated using the equation 8.3 (Mucheru-Muna *et al*., 2010)

$$\mathrm{VCR} = \frac{\mathrm{X-Y}}{\mathrm{Z}} \qquad (8.3)$$

where:

X = value of crop produced from plots with external amendments;

Y = value of crop produced from plots without any external soil amendment and

Z = cost of fertilizer or input

The prices of the different fertilizers did not vary during the three cropping seasons with values per kg of 1.9, 2.1 and 2.1 Ghana cedis for Urea, TSP and KCl, respectively.

The biochar was applied once during the study period at GH¢ 2.7 Ghana cedis per kg. The price of seed was also fixed during the three growing seasons at GH¢ 5, 8 and 10 per kg of maize, cowpea and soybean, respectively.

The crop yield values varied with the different cropping seasons. For 2016- major season, 1 kg of maize, soybean and cowpea was sold at GH¢ 1.2, 2.5 and 3, respectively. In 2016-minor season the prices per kg was GH¢ 1.4, 2.5 and 2.8 whilst in 2017-major season, the unit prices per kg were GH¢ 1.3, 2.5 and 3.2 respectively for maize, soybean and cowpea.

The exchange rates were GH¢ 4.0, 4.0 and 4.2 for 1 US$ in 2016-major, 2016-minor and 2017-major seasons, respectively.

8.3. Results

8.3.1 Biophysical characteristics of the study area

The initial soil properties (physical and chemical) of the experimental site are presented in Table 8.1. Soil pH (5.66) was moderately acidic. Soil organic carbon and total nitrogen contents were less than 1.5 % and 0.10 %, respectively. Available P was > 10 mg kg^{-1} and CEC was < 10 $cmol_c$ kg^{-1}.

8.3.2 Chemical characteristics of the rice husk biochar used for this study

The biochar used in the study was produced from rice husk pyrolyzed at 500-600 °C.

Its characteristics are presented in Table 8.2. The pH was alkaline (8.77) and total N, P and K contents were 0.56 %, 0.67 %and 0.52 % respectively. The C/N ratio was 68 whilst the ash content was 47.12 %.

8.3.3 Rainfall characteristics during the different cropping s seasons

The rainfall properties observed during the different cropping seasons are presented in Figs 8.1 and 8.2. The total rainfall amount was 387.3, 272 and 465.5 mm in 2016major, 2016-minor and 2017-major seasons, respectively. The storms were poorly distributed during the 2016-minor season compared to the two major seasons (Fig

8.2).

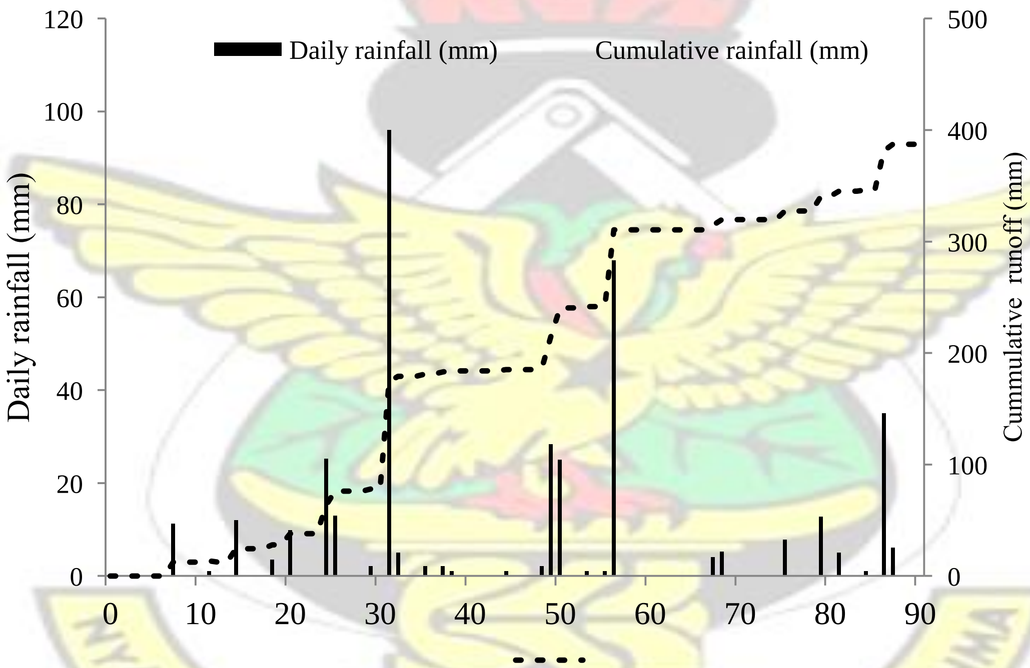
Table 8.1. Initial soil physico-chemical properties of the study area at 0-20 cm depth

Soil parameters	**Means**
Chemical properties	
pH (water 1 :1)	5.66 ± 0.013
Organic carbon (%)	1.20 ± 0.020
Total N (%)	0.09 ± 0.001
Available P (mg kg^{-1} of soil)	15.67 ± 0.083
Exchangeable cations ($cmol_c$ kg^{-1} of soil)	
Potassium	0.02 ± 0.001
Calcium	4.41 ±0.015
Magnesium	0.10 ± 0.001
Sodium	0.31 ± 0.001
Exchangeable acidity (Al^{+3} $+H^{+}$)	0.75 ± 0.011
ECEC ($cmol_c$ kg^{-1} of soil)	8.51 ± 0.040
Base saturation (%)	5.53 ± 0.025
Physical properties	
Sand (%)	79.60 ± 0.207
Silt (%)	7.88 ±0.015
Clay (%)	13.52 ± 0.070
Bulk density (Mg m^{-3})	1.48 ± 0.003
Texture	Sandy loam

Values after ± are standard deviation; n= 3

Table 8.2. Chemical characteristics of the organic material (biochar) used in the study

Parameters	Values
pH water (1 :1)	8.7 7
Organic Carbon (%)	38.12
Ash content (%)	47.12
Total nutrients (%)	
N	0.56
P	0.67
K	0.52
Ca	0.23
Mg	0.84
Na	0.25
C/N ratio	68.07



Days after sowing

Figure 8.1a. Cumulative and daily rainfall amounts during the 2016-major cropping season.

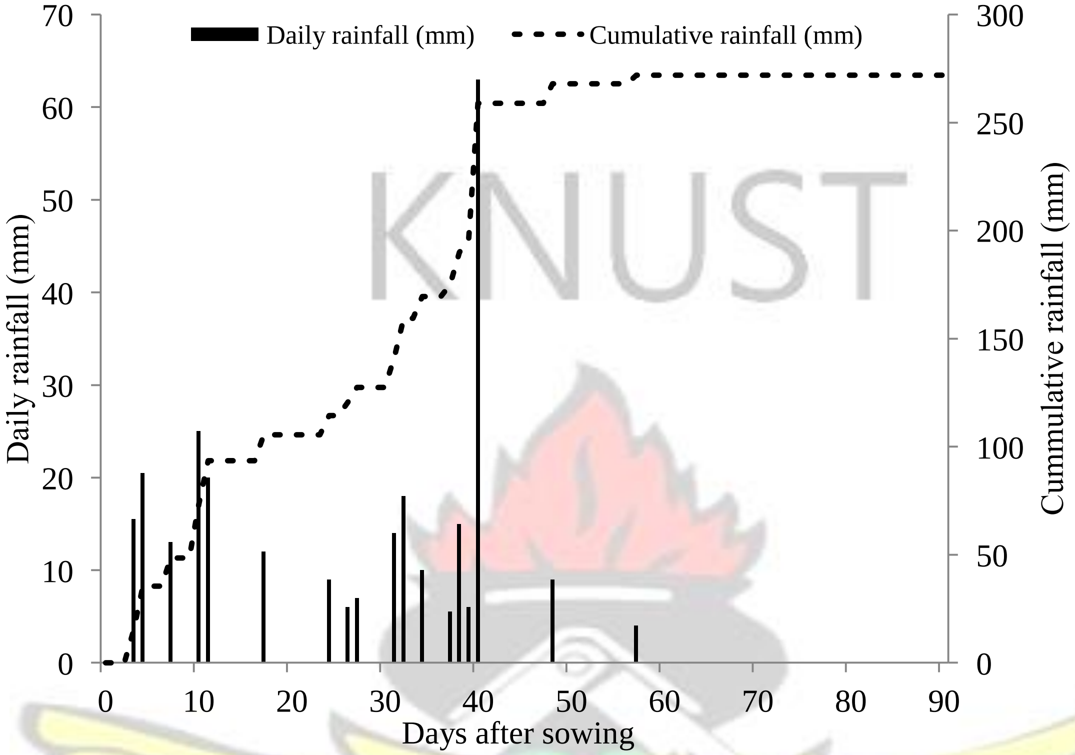


Figure 8.1 b. Cumulative and daily rainfall amounts during the 2016-minor cropping season.

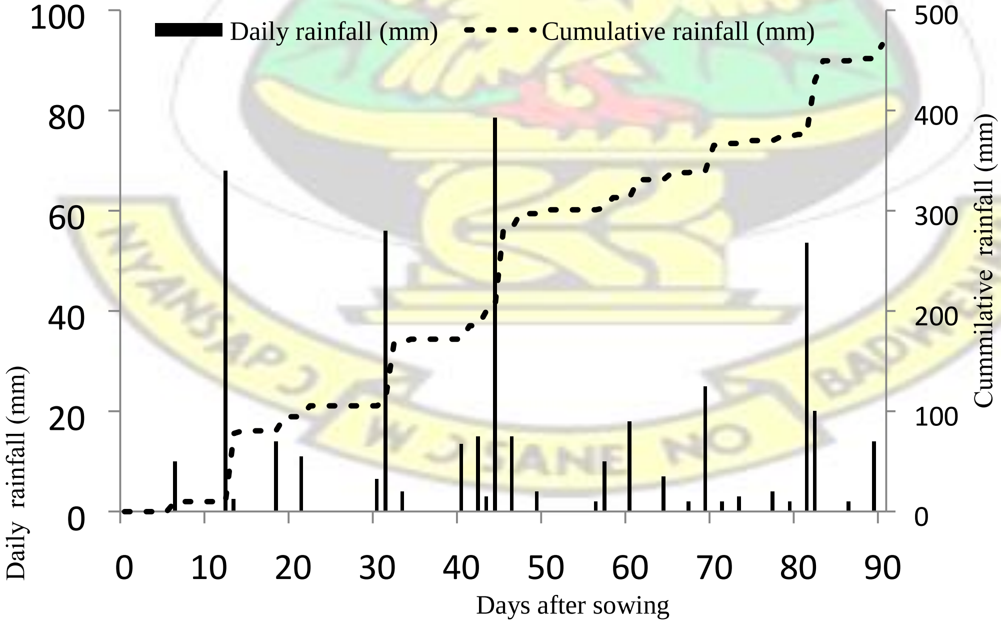


Figure 8.1 c. Cumulative and daily rainfall amounts during the 2017-major cropping season.

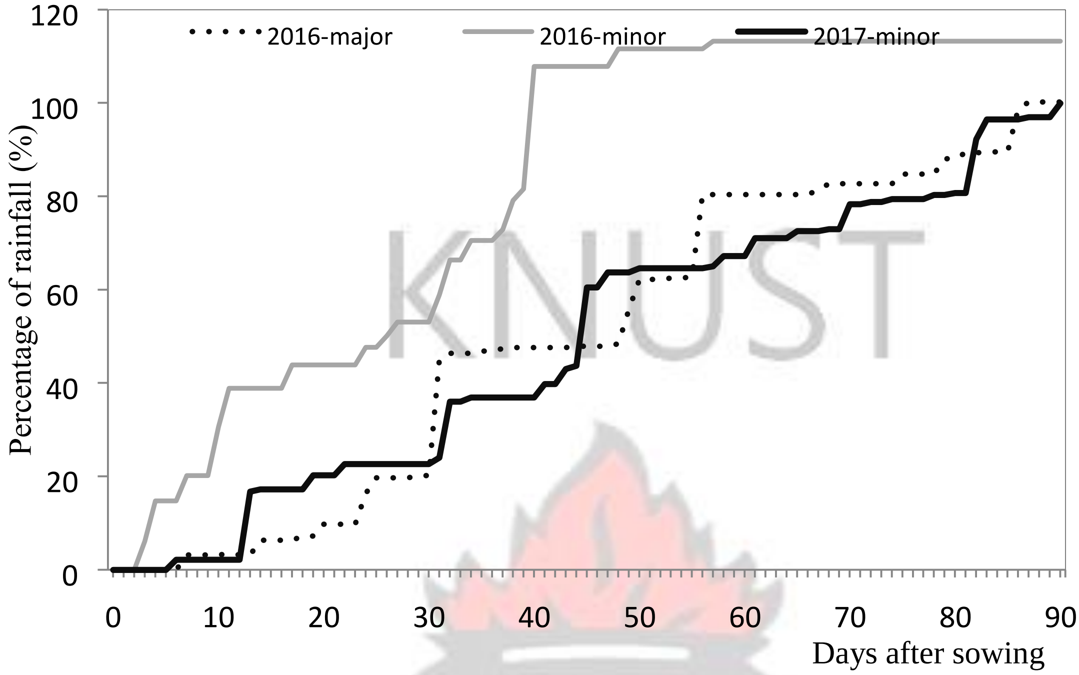


Figure 8.2. Seasonal rainfall distributions during the different cropping seasons

8.3.4. Effect of soil amendments and cropping systems on maize, soybean, and cowpea yields

The cropping systems differed significantly (P < 0.05) in maize grain and biomass yields during the different seasons (Tables 8. 3 and 8.6). Inorganic fertilizers with or without biochar increased significantly grain and biomass yields of all crops (Tables 8.3-8.8). Grains and biomass yields were lower under sole biochar (BC) application compared to the sole inorganic fertilizers for all three crops. However, sole biochar increased (P < 0.05) both biomass and grain yields of the different crops (maize, cowpea and soybean) than the control throughout the three consecutive cropping seasons.

The interaction effects between soil amendments and cropping systems were significant for both maize grain and biomass yields. During the 2016- major season, the interaction effect for grain yield ranged from 1.27 to 3.54 Mg ha^{-1} under intercrop x control and sole x NPK, respectively (Table 8. 3) whilst it ranged from 3.84 to 10.02 Mg ha^{-1} under intercrop x control and sole x NPK+ BC for, respectively for biomass yield (Table 8.6). During the 2016-minor season, maize grain yield varied from 0.91 to 2. 10 Mg ha^{-1} under the inter x control and sole x NPK, respectively (Table 8.3) whilst the biomass yield ranged from 2.30 to 4.43 Mg ha^{-1} for intercrop x control and sole x NPK+ BC, respectively (Table 8.6). In 2017-major season, the grain yield varied from 1.33 to 3.57 Mg ha^{-1} for sole x control and sole x NPK respectively. Biomass yield of the maize ranged from 3.20 to 6.86 Mg ha^{-1} under sole x control and sole x NPK+BC, respectively.

To assess the performance of intercropping maize with soybean, land use efficiency was determined based on Land Equivalent Ratio (LER). During the different cropping seasons, LER values for maize and soybean intercropped were greater than unity for all the treatments (Fig 8.3). All the treatments without external inputs had the least LERs compared to the amended plots. Moreover, amongst the soil amendments, the NPK+BC had the highest values ranging from 1.29 to 1.45 compared to the

treatments with sole biochar where the values ranged from 1.23 to 1.25.

Table 8.3. Maize grain yield under different cropping systems and soil amendments during three consecutive cropping seasons

Treatments	Maize grain yield (Mg ha^{-1})		
	2016 -major	2016 -minor	2017-major
Cropping systems	Cropping seasons		
Sole	2.53	1.81	2.88

Inter	2.08	1.50	2.37
CV (%)	4.10	6.50	3.40
LSD (5%)	0.32	0.16	0.37
Soil amendments			
Control	1.49	1.04	1.72
Biochar (BC)	2.02	1.50	2.32
Inorganic fertilizer (NPK)	3.18	1.97	3.37
NPK+BC	2.71	1.91	3.11
CV (%)	3.90	4.70	4.00
LSD (5%)	0.17	0.22	0.19
Soil amendments x C ropping syste ms			
Sole x Control	1.71	1.17	1.83
Sole x BC	2.31	1.55	2.43
Sole x NPK	3.54	2.02	3.57
Sole x NPK+BC	2.91	2.10	3.34
Inter x control	1.27	0.91	1.33
Inter x BC	1.72	1.45	1.98
Inter x NPK	2.81	1.91	3.17
Inter x NPK+BC	2.51	1.72	2.88
CV (%)	5.90	10.9	5.80
LSD (5%)	0.27	0.29	0.31

Inter= intercropping

Table 8.4. Soybean grain yield under different soil amendments during three consecutive cropping seasons

Treatments	Soybean grain yield (Mg ha^{-1})		
	Cropping seasons		
	2016-major	2016-minor	2017-major
Control	0.95	0.65	1.17
Biochar (BC)	1.02	0.80	1.25
Inorganic fertilizer (NPK)	1.54	1.19	1.77

NPK+BC	1.48	1.13	1.85
CV (%)	2.10	8.90	3.30
LSD (5%)	0.05	0.19	0.34

Table 8.5. Cowpea grain yield under different soil amendments during three consecutive cropping seasons

Treatments	Cowpea grain yield (Mg ha^{-1})		
	2016-major	2016-minor	2017-major
	Cropping seasons		
Control	0.88	1.06	0.81
Biochar (BC)	1.15	1.41	0.96
Inorganic fertilizer (NPK)	1.74	2.10	1.26
NPK+BC	1.77	1.85	1.28
CV (%)	12.4	2.10	2.5
LSD (5%)	0.05	0.12	0.07

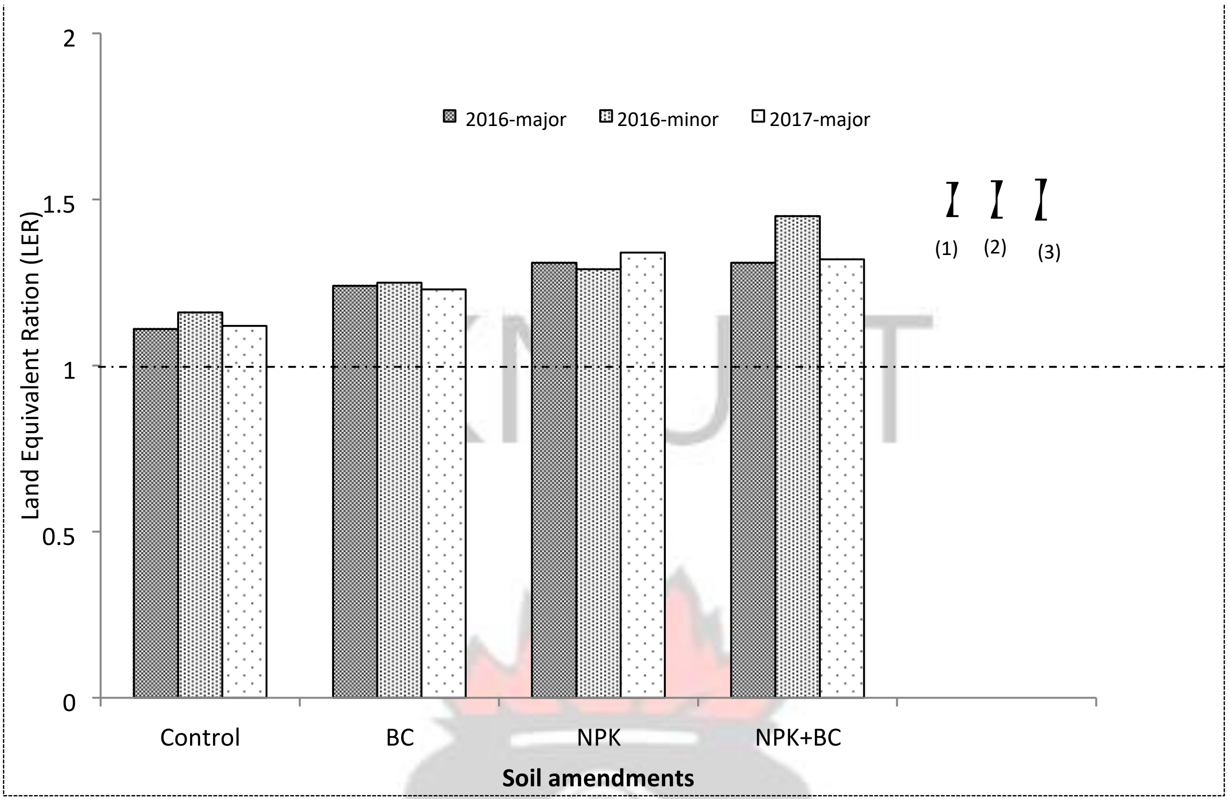


Figure 8.3. Land Equivalent Ratio (LER) under different soil amendments during the different cropping seasons. (1), (2) and (3) are the LSD (5%) for 2016major, 2016-minor and 2017-major, respectively

Table 8.6. Maize biomass yield under different cropping systems and soil amendments during three consecutive cropping seasons

Treatments	Maize biomass yield (Mg ha^{-1})		
	Cropping seasons		
	2016 -major	2016 -minor	2017-major
Cropping systems			
Sole	6.97	3.94	6.39
Inter	5.97	2.96	4.87
CV (%)	8.2	11.1	3.3
LSD (5%)	0.75	0.53	1.08
Soil amendments			

Control	4.21	3.23	3.38
Biochar (BC)	6.73	3.75	4.59
Inorganic fertilizer (NPK)	6.62	4.36	5.98
NPK+BC	8.94	4.43	6.57
CV (%)	10.2	11.3	14.3
LSD (5%)	0.96	0.66	0.40
Soil amendments x cropping system	s		
Sole x Control	4.87	3.23	3.57
Sole x BC	6.87	3.75	4.85
Sole x NPK	7.88	4.36	6.27
Sole x NPK+BC	10.02	4.43	6.86
Inter x control	3.84	2.30	3.20
Inter x BC	6.59	3.60	4.32
Inter x NPK	5.24	3.86	5.69
Inter x NPK+BC	7.86	4.29	6.28
CV (%)	13.1	14.6	7.8
LSD (5%)	1.81	1.15	1.71

Inter= intercropping

Table 8.7. Cowpea haulm yield under different soil amendments during three consecutive cropping seasons

Treatments	Cowpea haulm yield (Mg ha^{-1})		
	2016-major	2016-minor	2017-major
	Cropping seasons		
Control	2.94	2.12	3.54
Biochar (BC)	3.46	2.69	3.98
Inorganic fertilizer (NPK)	5.56	4.13	6.12
NPK+BC	5.51	4.86	6.31
CV (%)	8.60	8.40	12.5
LSD (5%)	1.10	0.953	1.01

Table 8.8. Soybean haulm yield under different soil amendments during three consecutive cropping seasons

Treatments	Soybean haulm yield (Mg ha^{-1})		
	2016-major	2016-minor	2017-major
	Cropping seasons		
Control	2.35	1.88	2.57
Biochar (BC)	3.63	2.44	3.86
Inorganic fertilizer (NPK)	5.53	4.32	5.27
NPK+BC	5.85	3.04	5.86
CV (%)	12.2	4.8	6.5
LSD (5%)	1.055	1.376	0.85

8.3.5. Effect of soil amendments and cropping systems on crops nutrient uptake

Nutrients uptake of maize differed significantly among the cropping systems especially in the major seasons ($P < 0.05$) (Tables 8.9-8.11). The highest values were consistently recorded under the sole systems in grain and biomass during all the three growing seasons.

The soil amendments significantly influenced ($P < 0.05$) nutrients uptake in the maize, soybean and cowpea grains and biomass. The inorganic fertilizer treatments

(with and without biochar) produced the highest N, P and K uptake. Although slight variations were observed, no significant difference was realized in nutrients uptake between NPK and NPK+BC treatments during the three growing seasons (Tables 8.98.17). For the different amendments, biochar effect on nutrient uptake was generally significant compared to the control (Table 8.9-8.17). Significant interactive effect between the cropping systems and the soil amendments was observed for all the three plant nutrients (N, P and K). The least nutrients uptake in all seasons were observed under control x intercrop system.

Table 8.9. Nitrogen uptake in grain and biomass of maize under different cropping systems and soil amendments

Treatments	2016 –major		2016-minor		2017-major	
	NUG	NUB	NUG	NUB	NUG	NUB
	(kg ha^{-1})					
Cropping systems						
Sole	37.12	43.70	26.45	29.58	44.50	34.49
Inter	29.81	35.91	24.36	27.67	37.43	29.32
CV (%)	1.70	6.40	7 .00	14.60	4.40	2.20
LSD	5.84	5.23	NS	NS	1.83	3.73
Soil amendments						
Control	15.95	20.12	12.27	15.09	19.41	14.24
Biochar (BC)	24.51	38.21	21.00	23.22	32.70	22.64
IF (NPK)	50.81	45.34	34.96	32.62	57.34	41.47
NPK+BC	48.08	49.61	32.33	38.56	54.42	44.27
CV (%)	4.10	13.40	3.90	12.80	1.3	10.30
LSD (5%)	2.65	11.43	3.53	5.49	4.26	5.25
Soil amendments x Cropping systems						
Sole x control	17.99	21.32	13.96	16.20	21.90	14.95
Sole x BC	28.57	36.19	22.24	25.36	37.97	25.41
Sole x NPK	56.52	53.03	34.30	35.40	60.64	44.02
Sole x NPK+BC	48.08	54.61	35.31	30.90	57.49	53.57
Inter x control	13.91	19.23	10.29	13.98	16.91	13.53
Inter x BC	20.45	30.32	19.76	21.08	27.43	19.86
Inter x NPK	45.10	47.63	30.14	27.37	54.03	38.91
Inter x NPK+BC	39.76	44.62	29.35	26.23	51.36	44.96
CV (%)	6.20	4.20	3.30	4.10	8.30	13.10
LSD	4.16	17.22	4.59	9.70	5.26	9.24

NUG= Nitrogen Uptake in Grains; NUB= Nitrogen Uptake in Biomass; Inter= intercropping; IF= inorganic fertilizer

0. Phosphorus uptake in grain and biomass of maize under different cropping systems and soil amendments

Treatments	2016 – major		2016-minor		2017-major	
	PUG	PUB	PUG	PUB	PUG	PUB
	(kg ha^{-1})					
Cropping systems	Cropping seasons					
Sole	7.38	8.43	5.37	6.51	5.64	7.59
Inter	5.02	6.44	4.15	4.67	4.58	6.50
CV (%)	8.2	5.3	9.7	10.5	1.9	5.5
LSD	1.57	1.29	NS	NS	0.75	1.75
Soil amendments						
Control	4.91	4.84	1.48	3.05	1.97	2.33
Biochar (BC)	6.34	7.86	2.59	5.83	3.98	5.57
IF (NPK)	10.18	11.35	4.34	7.33	7.44	9.57
NPK+BC	9.38	12.00	4.28	8.17	7.05	10.73
CV (%)	1.03	13.50	2.20	14.3	4.20	15.10
LSD (5%)	1.83	1.11	0.88	1.19	1.14	1.40
Soil amendments x cropping systems						
Sole x control	5.11	4.19	1.94	3.34	2.22	2.52
Sole x BC	7.88	7.96	2.59	6.05	4.44	6.02
Sole x NPK	11.32	10.93	4.75	8.37	8.04	10.17
Sole x NPK+BC	10.23	11.35	4.72	8.29	7.87	11.66
Inter x control	4.11	3.49	1.21	2.76	1.73	2.15
Inter x BC	5.80	5.86	1.59	4.60	3.53	5.12
Inter x NPK	9.03	9.78	4.13	6.29	6.85	8.96
Inter x NPK+BC	8.54	10.64	3.78	5.04	6.22	9.79
CV (%)	1.43	12.7	12.2	13.9	17.8	15.80
LSD	1.23	2.11	1.08	1.35	1.43	2.88

PUG= Phosphorus Uptake in Grains; PUB= Phosphorus Uptake in Biomass; Inter= intercropping; IF= inorganic fertilizer

Table 8.1

Table 8.11. Potassium uptake in grain and biomass of maize under different cropping systems and soil amendments

Treatments	2016 _major		2016-minor		2017-major	
	KUG	KUB	KUG	KUB	KUG	KUB
	(kg ha^{-1}) Cropping seasons					
Cropping systems						
Sole	14.57	20.36	9.97	11.86	16.86	23.28
Inter	10.54	15.95	6.47	8.26	13.40	17.12
CV (%)	3.0	3.6	9.2	10.9	3.20	11.40
LSD	2.31	3.26	NS	NS	1.93	3.14
Soil amendments						
Control	6.01	6.90	3.47	4.44	5.13	7.12
Biochar (BC)	10.84	14.01	4.41	5.30	11.46	18.22
IF (NPK)	18.59	23.89	13.43	14.28	22.15	31.04
NPK+BC	17.75	21.98	12.57	15.32	20.78	27.07
CV (%)	6.9	10.7	2.3	12.7	3.6	10.2
LSD (5%)	0.95	2.87	1.26	2.05	2.49	4.21
Soil amendments x cropping sy	stems					
Sole x control	8.44	9.80	4.25	4.80	6.34	10.32
Sole x BC	12.57	13.91	8.09	9.68	13.86	16.92
Sole x NPK	20.42	36.36	14.71	16.54	24.49	40.11
Sole x NPK+BC	17.84	33.42	13.84	15.70	22.76	37.39
Inter x control	7.61	8.00	2.69	4.16	3.91	11.53
Inter x BC	10.12	11.22	6.73	7.92	9.07	12.34
Inter x NPK	16.77	25.22	11.15	12.00	21.82	32.11

Inter x NPK+BC	14.66	26.40	10.30	11.86	18.79	34.61
CV (%)	7.90	11.90	10.9	10.2	13.1	12.00
LSD	1.80	2.62	1.57	2.88	3.16	4.43

KUG= Potassium Uptake in Grains; PUB= Potassium Uptake in Biomass; Inter= intercropping; IF= inorganic fertilizer

2. Nitrogen uptake in grains and haulm of cowpea under different soil amendments

Treatments	Cropping seasons					
	2016 –major		2016-minor		2017-major	
	NUG	NUB	NUG	NUB	NUG	NUB
	($kg\ ha^{-1}$)					
Control	34.38	28.12	13.71	9.52	28.53	29.53
Biochar (BC)	53.89	39.83	22.73	16.81	42.75	43.31
IF (NPK)	82.55	87.32	50.21	48.63	84.60	101.32
NPK+BC	79.66	85.12	54.12	46.24	82.26	103.41
CV (%)	3.5	8.8	15.3	2.9	3.7	12.3
LSD (5%)	6.33	8.96	6.25	5.82	12.25	17.11

NUG= Nitrogen Uptake in Grains; NUB= Nitrogen Uptake in Biomass; IF= inorganic fertilizer

Table 8.13. Phosphorus uptake in grains and haulm of cowpea under different soil amendments

Treatments	Cropping seasons					
	2016 –major		2016-minor		2017-major	
	PUG	PUB	PUG	PUB	PUG	PUB
	($kg\ ha^{-1}$)					

Table 8.1

Control	3.60	3.25	3.06	2.39	4.89	2.79
Biochar (BC)	5.22	4.34	4.88	2.84	9.54	4.86
IF (NPK)	13.00	10.80	10.96	6.14	16.30	10.70
NPK+BC	14.25	10.86	10.07	4.90	18.26	11.24
CV (%)	14.1	10.7	0.2	4.7	11.8	13.41
LSD (5%)	2.43	3.12	1.78	1.55	3.87	1.93

PUG= Phosphorus Uptake in Grains; PUB= Phosphorus Uptake in Biomass; IF= inorganic fertilizer

Table 8.1
4. Potassium uptake in grains and haulm of cowpea under different soil amendments

Treatments	2016 –major		2016-minor		2017-major	
	KUG	KUB	KUG	KUB	KUG	KUB
	(kg ha^{-1})					
	Cropping seasons					
Control	10.72	27.82	6.82	9.62	12.12	24.81
Biochar (BC)	15.47	36.73	9.84	13.24	14.53	38.11
IF (NPK)	25.49	74.78	18.80	27.7	33.37	72.74
NPK+BC	22.68	74.46	19.47	24.3	30.55	69.53
CV (%)	1.44	1.84	13.5	1.12	1.55	4.3
LSD (5%)	3.4	7.8	2.16	3.76	10.52	4.12

KUG= Potassium Uptake in Grains; PUB= Potassium Uptake in Biomass; IF= inorganic fertilizer

Table 8.15. Nitrogen uptake in grains and haulm of soybean under different soil amendments

Treatments	2016 –major		2016-minor		2017-major	
	NUG	NUB	NUG	NUB	NUG	NUB
	(kg ha^{-1})					
	Cropping seasons					
Control	47.28	18.43	27.41	13.83	53.68	34.91
Biochar (BC)	64.64	38.63	33.61	28.53	63.80	64.33
IF (NPK)	101.18	85.28	59.18	52.62	99.52	119.62
NPK+BC	91.09	88.21	58.08	43.21	105.24	126.83
CV (%)	2.2	18.18	7.61	4.600	4.20	16.10
LSD (5%)	12.76	13.90	11.74	12.31	6.77	29.63

NUG= Nitrogen Uptake in Grains; NUB= Nitrogen Uptake in Biomass; IF= inorganic fertilizer

Table 8.1 6. Phosphorus uptake in grains and haulm of soybean under different soil amendments

Treatments	2016 _major		2016-minor		2017-major	
	Cropping seasons					
	PUG	PUB	PUG	PUB	PUG	PUB
	(kg ha^{-1})					
Control	5.02	3.62	1.31	1.68	2.59	3.08
Biochar (BC)	6.97	6.62	2.21	2.70	4.19	6.07
IF (NPK)	13.64	18.10	5.42	8.38	9.11	16.26
NPK+BC	11.72	17.22	5.03	7.37	9.13	15.78
CV (%)	9.31	11.12	12.21	3.2	6.21	4.7
LSD (5%)	3.25	3.17	0.97	1.52	0.77	1.20

PUG= Phosphorus Uptake in Grains; PUB= Phosphorus Uptake in Biomass; IF= inorganic fertilizer

Table 8.17. Potassium uptake in grains and haulm of soybean under different soil amendments

Treatments	2016 _major		2016-minor		2017-major	
	Cropping seasons					
	KUG	KUB	KUG	KUB	KUG	KUB
	(kg ha^{-1})					
Control	11.69	28.50	5.74	15.82	11.29	28.87
Biochar (BC)	17.26	49.92	8.60	26.33	16.31	58.62
IF (NPK)	27.66	76.89	18.57	49.82	31.25	115.73
NPK+BC	25.33	82.12	16.30	45.2	31.29	131.73
CV (%)	3.9	6.56	13.51	7.00	3.26	14.5
LSD (5%)	4.62	11.28	1.51	7.70	7.20	9.9

KUG= Potassium Uptake in Grains; PUB= Potassium Uptake in Biomass; IF= inorganic fertilizer

8.3.6 Cost effectiveness of the different soil amendments options under the cropping systems

Value cost ratios with respect to the different cropping systems and soil amendments are presented in Fig 8.4. All treatments with biochar (sole or combined with inorganic fertilizers) were not consistently economically viable except NPK+BC under maize intercropped with soybean, and sole biochar within the intercrop system in 2017major season. Although there was improvement in soil properties with biochar supply, the yield increase did not express any economic gain, except in the few cases stated above.

It was observed that, for all the sole NPK treatments, the VCR values were above the economic threshold (2.0) for each cropping system throughout the three consecutive growing seasons. The highest VCRs were recorded under sole soybean with sole NPK and which were 3.89, 3.02 and 4.28 during the 2016-major, 2016-minor and 2017major seasons, respectively. The cumulative ranking for all the treatments, based on the VCR followed the order: NPK>NPK+BC>BC for all the cropping systems and during each growing season.

Table 8.1

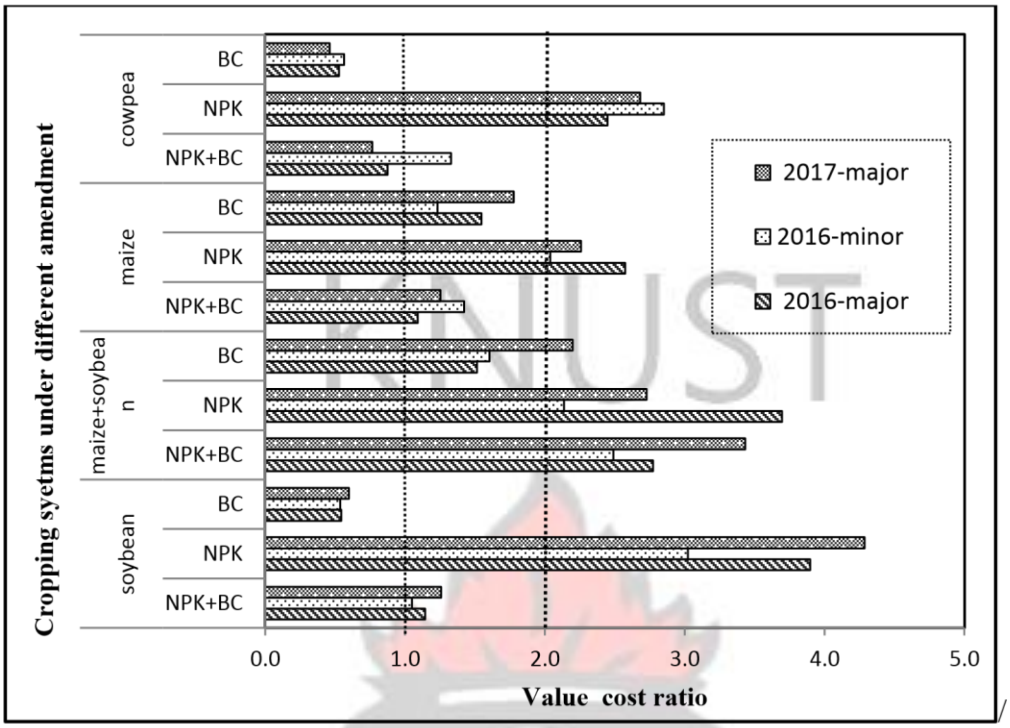


Figure 8.4. Value of cost ratio for the different cropping systems and soil amendments

8.4. Discussion

8.4.1 Effect of soil amendments and cropping systems on maize, soybean and cowpea productivity

The good response of all the three crops to the different soil management options confirmed the low soil nutrients status of the study area. Therefore, appropriate soil management technologies are required to increase and sustain crop production in the area.

The grain yield of all the three crops increased (Tables 8.3-8.5) under nutrient management practices. Moreover, not only the external soil amendments (inorganic fertilizers and biochar) could improve maize grain yield under the intercropping systems, as the soybean intercropped with maize might have also improved soil fertility via biological nitrogen fixation (Mathu *et al.*, 2010; Mucheru-Muna *et al.*, 2010). However, Sanginga *et al*. (1996) and Matusso *et al.* (2014) reported that the nitrogen fixed is available in small portion for the associated crops during the cropping season and more effects are expected under rotation systems during subsequent growing seasons.

Although soybean and cowpea are nitrogen fixing crops, there was good response of inorganic fertilizers when starter nitrogen was applied. Starter N has been confirmed to improve legumes' productivity despite their biological nitrogen fixation abilities (e.g. Sadeghipo and Abbasi 2012; Janagard and Ebadi-Segherloo, 2016). Nitrogen fixation starts 3 to 5 weeks after sowing whereas the plants need nitrogen at early growth stage prior to commencement of biological nitrogen fixation (BNF) (Moawad *et al*., 2004; Li *et al*., 2015). Moreover, the fixed nitrogen does not totally satisfy the

N need of the crops, not only due to the small amount fixed but also because a portion will be used by the plant during its growth stage for its metabolisms (Janagard and Ebadi-Segherloo, 2016). In addition, grain legumes may not fix N on a given land due to constraints such as soil degradation, low population of endogenous bacteria which requires bio-augmentation through inoculation (Gil-Quintana *et al.*, 2013).

With the good impact of biochar on soil properties as reported by several studies (e.g. Nelson *et al*., 2011; Jien and Wang, 2013; Gul *et al*., 2015, etc), its effect on crops production relative to the control, was observed during the three cropping seasons (Tables 8.3-8.4). Despite the low mineralization rate of biochar and its poor nutrients content relative to the other classic organic amendments, there was yield improvement with biochar application (but with low magnitude when compared to inorganic fertilizers). As a soil amendment, biochar increased the yields (grains and biomass) of maize, soybean and cowpea (Tables 8.3-8.8).

The findings of this study showed that the sole cropping systems gave the best maize grain and biomass yields than the intercropping systems (Tables 8. 3 and 8.6). The yields improvement under the sole systems was probably due to the absence of competition as observed also by Mucheru-Muna *et al.* (2010) and Aguyoh *et al*. (2016). However, the total production value from the intercropping showed the advantage of the crops' association compared to the sole systems when the intercropping performance were assessed using the LER approach (Fig. 8.3). One of the reasons for intercropping is to obtain improved yield per unit area, diversity of products and also improve soil properties as well as minimizing risk against total crop failures (Matusso *et al.*, 2014; Regehr *et al*., 2015; Aguyoh *et al*., 2016). For an area where cropland availability is an important constraint, sustainable intercropping systems are recommended (Thierfelder *et al.*, 2013). This emphasizes that intercropping maize and soybean is more beneficial than the sole systems.

As a multipurpose approach, intercropping is an important system in SSA to minimize the major constraints to food security and increase agricultural food diversity. Additionally, the agronomic importance of the intercropping (diseases and pests control, soil properties improvement) and social values (land availability) give more reasons to improve and sustain the system under small-scale farming systems.

Different intercropping systems are available in small-scale farming systems based on spatial crops arrangement. Indeed, the system "MBILI", which was adopted in the current study, and where between two rows of maize, two rows of legume were planted (Tungani *et al.*, 2002) without changing the plant population of maize, has more legume production potential compared to the conventional system of 1:1 as showed by Mucheru-Muna *et al.* (2010). Consequently, the agricultural value of maize and soybean intercropped was better than the individual production value of each crop planted on the same land size and this was confirmed by Aguyoh *et al.* (2016). The results agree with other several studies (e.g. Rusinamhodzi *et al*., 2012; Matusso *et al.*, 2014 Aguyoh *et al*., 2016, etc) where the beneficial effect of the intercropping compared to the sole systems were observed.

Thus, sustainable cropping systems are required for increased agricultural production in smallholder farming systems of SSA.

8.4.2 Effect of soil amendments and cropping systems on crops nutrient uptake

With regard to the two maize based cropping systems, there were significant differences between the sole and the intercrop systems ($P < 0.05$) during the two major seasons in N, P and K uptake (Tables 8.9-8.11). This is attributable to competition within the intercropping system which reduced crop grain and biomass

yield.
The soil nutrient management options increased nutrient uptake for all the three crops (maize, cowpea and soybean) more than the control due to the external nutrients supplied (Tables 8.9-8-11). As reported by Agegnehu *et al.* (2016), soil nutrient management through organic and inorganic materials enhances nutrients

accumulation in plants. On the control plots, where there was no soil amendment, the least nutrient uptake was observed. Biochar applied alone improved nutrient uptake compared to the control due to its improvement of soil properties (Al-Wabel *et al*., 2015) which increased soil nutrients availability (Tables 7.4-7.6) for sustainable plant growth. Despite its lower nutrients content (Table 8.2), biochar is an alternative soil amendment which can improve soil nutrient status when applied especially with other nutrient sources (Siddiqui *et al*., 2016) .

When inorganic amendments were applied with organic matter (poultry manure), Abera (2017), observed significant increase in NPK uptake of maize compared to the sole inorganic and organic materials. However, in the current study, there was no difference in uptake between the sole inorganic fertilizers and the combination of biochar and inorganic fertilizers for all the nutrients assessed under the different cropping systems. Indeed, this could be due to the probable partial immobilization of nutrients by biochar (Ameloot *et al.*, 2015).

8.4.3 Cost effectiveness based on the value cost ratio (vcr) of the different soil management options associated with the cropping systems

The economic viabilities of the soil amendments under the cropping systems were assessed based on VCR approach. Values greater than 2 implies the likelihood of the treatment adoption by the stakeholders (Vanlauwe and Giller, 2006). The higher

VCRs observed under sole NPK under the different cropping systems (Fig 8.4) is explained by the good improvement in yields of the different crops which received this treatment.

Although there was increase in yields under NPK+BC and BC under the sole cropping systems, the low VCR observed (VCR < 2) was mostly due to the high cost of biochar as soil amendment. However, the good economic thresholds (VCR > 2) recorded under NPK+BC with respect to the intercropping systems (Fig 8.4) could be due to intercropping effect associated with integrated nutrient management. The same reason of intercropping effect perhaps accounted for the good VCR under BC with respect to the intercropping system. Sole biochar was profitable only during the last growing season under the intercrop system, due to its longer-term effect on crop yield improvement (Gul *et al*., 2015) and the intercropping effect as expressed by LER. Thus, maize intercropped with soybean produced viable VCR for all the treatments where inorganic fertilizers were applied (with or without biochar) throughout the three cropping seasons. Though the yield of each crop (maize and soybean) in the intercropping system decreased compared to the sole systems (Table 8. 3), the economic returns were better in the former. These findings agreed with other several studies where the intercropping of maize and soybean showed more cost effectiveness (e.g. Mateus *et al.*, 2010; Mucheru-muna *et al.*, 2010; Seran Thayamin, 2010). For the rest of the cropping systems, where biochar was applied, no economic viability was observed.

Under soybean-sorghum based systems, Egbe (2010) observed good economic performance of the intercrop system compared to the sole systems. He realized that the yield decreased for both crops in the association systems but the net revenue of the intercrop showed more benefits than in the sole systems. Under long-term study involving millet-groundnut based systems carried out in Niger, Bationo *et al.* (2011) observed higher returns for all intercropped treatments compared to the sole systems.

The high cost of biochar production mostly accounted for its low VCR throughout the study periods, which were generally below the economic thresholds. The 5000 kg ha^{-1} of biochar, applied in this study, was more expensive than using the recommended rate of NPK fertilizers for each crop. For example, the cost of the recommended rate used in this study (5 t ha^{-1}) is the equivalent of 162% of cost of inorganic fertilizers (NPK) at a recommended rate of 90-60-60 for maize production.

In smallholder farming systems, any cropping technologies that do not give returns on investment expressed by increased yield are scarcely adopted. For the small-scale farmers, increasing crop yields supersedes social and environmental effect of their practices (Okpara and Igwe, 2014). Furthermore, the amount of organic matter required to produce the biochar is highly important. Including the labour cost, biochar is not economically viable to the smallholder farmers. However, its environmental value (Pereira *et al*., 2015), gives an opportunity of associating biochar in the soil management practices rather than for direct economic value improvement (Uzoma *et al.*, 2011; Lone *et al*., 2015). This multipurpose effect of biochar is considered as an advantage for agricultural production as well as environmental protection through stabilization of soil organic carbon. However, any effort by policy makers to subsidize biochar production through implementation of locally less expensive biochar production options/equipments to farmers can reverse this observation.

8.5 Conclusion

Soil degradation in SSA requires specific and sustainable management options for agricultural production through soil improvement. The soil at the study site was characterized by poor nutrients status and poor rainfall patterns were observed.

Application of the different amendments led to an increase in biomass and grain yields of maize, cowpea and soybean. Despite its low nutrients status, yields produced under biochar were higher than the control. Thus, the multipurpose function of biochar is an opportunity to promote its integration into soil management components. The intercropping of maize and soybean showed positive effect (based on LER) despite the slight maize yield reduction due to competition effect. Nutrients uptake was strongly influenced by the soil amendments for all three crops throughout the study periods. The sole systems associated with the different amendments improved nutrient uptake than the intercrop system in both maize grains and biomass.

The different cropping systems influenced differently net economic returns. For all the three crops under the different soil amendments, sole inorganic fertilizers performed better in economic returns during the three cropping seasons All biochar treated plants were not viable (VCR<2) except NPK+BC (throughout the three growing seasons) and BC (during the last growing season) under the intercropping system. Sole soybean and sole cowpea fertilized with NPK had more economic advantage than sole maize under the same treatment (NPK); but all had good economic thresholds (VCR > 2).

CHAPTER NINE

9. GENERAL DISCUSSION

Soil erosion is considered an important agricultural and environmental threat (Pimentel and Burgess, 2013), especially under small-scale farming systems due to limited resources for its sustainable management. Sub-Saharan Africa is prone to such menace due to harsh climate factors and poor soil management practices (Sanginga and Woomer, 2009). Assessing soil erosion under field conditions is a way forward to improving crop productivity through identification of the magnitude of the constraints (soil loss, nutrients loss, soil structure destruction) and suggestion of sustainable management practices (soil nutrient improvement, soil erosion control). Therefore, soil nutrient depletion under tropical cropping systems needs multipurpose approaches to prevent further decline. Besides nutrient uptake and the inherent poor soil characteristics, soil erosion influences largely the soil nutrient balance in the region. Adoption of all the suggested methods of soil and crop management options is based on economic profitability which is a key factor for technology dissemination to agricultural stakeholders. Market oriented agriculture is an important factor of crop production intensification where both input and output markets should be developed to complete the agricultural value chain. Thus, soil and crop management practices aimed at improving crop yields should also be cost effective to attract farmers and other farming stakeholders (Sanginga and Woomer, 2009; Vanlauwe *et al.*, 2013; Alemu and Kidane, 2014; Kihara *et al.*, 2016).

Soil erosion as a multi-factor-agricultural constraint, requires integrated and sustainable approaches for its quantification and control to improve productivity of cropping systems.

9.1 New method for soil runoff measurement characterization

Soil erosion characterization based on direct and indirect methods has been recommended by different researchers (e.g. Wischmeier and Smith, 1978; Enters 1998; Yang *et al.*, 2016; Vaezi *et al.*, 2017). Each of these earlier developed methods has its specific advantages and limitations. The adaptability of each method to several conditions as well as the accuracy is important. Ngetich *et al.* (2014) analyzed runoff using big tanks fixed at the end of each runoff plots to assess the effect of different tillage systems on soil and water conservation. Guto *et al.* (2011) also collected the eroded sediments into the channels dug at the end of each runoff plots in their runoff study in Kenya. Amegashie (2014) by using the tipping bucket method, quantified soil and runoff under different soil amendments and tillage systems. All these methods which are based on direct measurements of soil loss and runoff are constrained by quantity of sediments and runoff to harvest, loss of runoff through infiltration before sampling and the tiring nature of the experiments. From the first equation of Wischmeier for soil erosion prediction, several other models have been suggested, derived either from the first proposal (e.g.Vaezi *et al*., 2010 ; Senti *et al.*, 2014) or using newly developed empirical, conceptual or physical equations (e.g. Onori *et al*., 2006; López-vicente *et al*., 2013; Tamene and Le, 2015; Pandey *et al.*, 2016, etc). All these studies have contributed largely to the progress of research in soil and water conservation but yet need some improvement for wider applications.

As observed in the current study, the developed model provided accurate parameters for its assessment. This can be an alternative to soil erosion characterization under diverse conditions of soil and crop management. The harvested runoff can help quantify also soil and nutrient losses under erosive systems based on representative elementary volume (REV) approach. Furthermore, soil and nutrient management will be based on the method to sustain crop productivity and to compensate the loss due to erosion.

It was observed during the study that, the prediction was still acute ($R^2 > 0.8$ and $p < 0.001$) under different slope classes and this confirmed the applicability of the method for different landscapes. As defined by Moriasi *et al*. (2007), low RSR (<0.5) determines the applicability of water erosion models to different conditions of landscape. The RSR ranged between 0.38 and 0.46, satisfying the suggestion of Pandey *et al.* (2016) which defines the adaptability of models to different conditions and environments for acceptability and goodness. Most of the previous specific and site-based methods, despite their accuracies, are mostly applied to specified ecosystems and are less open to different environments.

For the sensitivity of the model, it was observed that, there was high variability of the prediction based on the land cover factor. The bare plots showed less accuracy due to high rate of generated runoff as there was overflow prior to sampling. Therefore, establishment of runoff plots should be based on the expected maximum individual rainfall amounts of the study area. This will help decide the different dimension characteristics of N, n and v and invariance under scaling and distance (ISD) principle. Thus, the characteristics of the method as shown for bare and cropped plots emphasized the importance of land cover under improved soil management on the magnitude of soil runoff. The generated runoff (runoff coefficient) is a result of both surface soil cover and soil properties under specific rainfall regimes. Thus, the observed model characteristics are strongly related to the rainfall parameters as well as soil and crop management practices.

The developed model is a new option to assess the magnitude of soil erosion under field conditions to enhance sustainability of crop and soil management systems.

9.2 Soil erosion characteristics under different soil and crop management systems

Besides climatic factors, soil erosion is strongly related to soil and crop management practices. Different methods have been developed and suggested to reduce soil erosion on farms (e.g. Zougmore *et al.*, 2000; Guto *et al* 2012; etc) but with some limitations and constraints which increase soil nutrient depletion and reduction in cropland availability (Pan *et al.*, 2017). The current study has shown the importance of sustainably managing cropping systems to reduce soil erosion related degradations.

Indeed, the bare soil had 2 to 15 times soil loss compared to the cropped plots under different soil and crop management practices. Thus, the rate of soil loss on the bare land was beyond the tolerable limit and emphasized the constraints to soil productivity under poor land cover. Seasonally, the amount of soil lost was 8.18, 6.57 and 9.35 Mg ha^{-1} in 2016-major; 2016-minor and 2017-major seasons, respectively on the uncropped land. For the plots under different amendments and cropping systems, the annual cumulative soil loss (2016) was below the threshold of tolerable soil loss while for the control plots, nearly 7 Mg ha^{-1} yr^{-1} was lost. This was due to better soil cover in the former. For the different soil nutrient management options, the inorganic based treatments gave lower rates of soil loss and runoff coefficient than the sole biochar which was lower than the control. This confirms the recommendations of Vanlauwe *et al*. (2013) to integrate soil nutrient management practices into the components of soil conservation. Govers *et al.* (2016) also confirmed the need for crop intensification based on integrated nutrient management to improve soil and water conservation. Therefore, soil nutrient management practices for direct plant nutrition can also be useful for soil erosion control in small-scale farming systems.

With respect to the cropping systems, sole cowpea was more suitable for erosion control because the amount of biomass produced was higher for effective soil cover than the other cropping systems. Generally, the legume-based systems were stable and decreased soil loss and runoff compared to the sole maize which poorly covered the soil. The seasonal leaf decay might have impacted on soil biology as well as soil structure which is positively correlated with soil erosion as reported by Govaerts *et al.* (2009). The other soil erosion parameters such as soil depth reduction and runoff coefficient followed the same trend of soil loss under the soil and crop management practices. Higher values were observed under the poorly adapted systems which was a result of low rate of crops peroformance. Soil depth reduction due to soil erosion is an improtant factor infleuencing water holding capacity. However, under natural process of pedo-genesis, the rate of seasonal soil loss on degraded soil will require decades to replenish. The findings of this study showed the importance of cropping systems with specific soil amendments on soil erosion reduction.

9.3 Soil nutrients loss via erosion under different cropping systems and soil amendments

Soil nutrient loss characteristics based on total crop nutrients loss, enrichment ratio and the monetary value of the those nutrients were strongly influenced by the different inteventions. The amount of soil nutrient loss was mostly related to the sensivity of the soil to erosion and not the type and rate of nutriennts applied through the different fertlizers. Thus, the bare plot (without any crop or nutrient management) suffered the highest rates of nutrient loss compared to other cropped plots. The treatments without any amendment (control plots) under each cropping system suffered the greatest nutrient loss. This emphasizes the adverse effect of soil erosion on soil nutrients, especially where soil cover is poor under rainfed cropping systems; a similar result was reported by McHugh *et al*. (2007). The low rates of N, P and K loss observed under inorganic fertilizers (with or without biochar) application, were due to the small soil losses and runoffs arising from good crop development and growth, hence adequate soil cover. Zougmore *et al.* (2009) observed similar tends in Burkina Fasso where sorghum treated with urea gave low rate of nutrients loss compared to the control plots. In their study, Jien and Wang (2013) observed lower rates of nutrients loss under sole biochar due to its effects on crop performance as well as its impact on soil physical properties. Lii *et al.* (2017) observed the same trends where application of biochar reduced the rate of nutrients (N and P) loss.

The low amount of nutrients loss on inorganic treated plots was proportional to the volume of soil eroded. Thus, off-site effect of soil erosion, assessed using the ER showed that soil nutrients were highly concentrated in the sediments and runoff under the managed plots, irrespective of the rate of nutrients loss. All the cropped plots had ER values greater than unity, confirming the accumulation of soil nutrients outside the eroded area with possible contamination of rivers and water bodies. The high values of ER (> 1) explained the nutritional value of the eroded surface soil which affects strongly soil nutrients status in small-scale farming systems (Garcia-Diaz *et al.*, 2017). The plots treated with inorganic fertilizers recorded higher ERs than the control and the amended plots.

Due to the selectivity of the ersion process (Pan *et al*., 2016), the clay and silt particles had ERs greater than unity unlike the sand particles. Although the ERs of the sand particles were less than one, values observed in the major seasons were higher than that of the minor season due probably to more eroeive rainfall

characteristics in the former.

The magnitude of soil erosion was economically assessed by evaluating the monetary value of nutrients lost. Besides other cost related to physical and mechanical soil rehabilitation due to erosion, Govers *et al.* (2016) have showm that the N and P fertilizers lost into sediment and runoff represent aproximatively 1 to 2% of global agricultural food production. Therefore, soil erosion is an important threat to global economic development. During the study period, inorganic treatments (with or without biochar) had economic nutrients loss ranging from US$ 30.65 to 48.29 ha^{-1} while the (control) had figures varying from US$ 53.62 to 57.10 ha^{-1}. This is explained by the effect of each treatment on soil nutrient loss through erosion. The most stable treatments for soil erosion reduction (low rates of runoff and sediments) had low monetary values of soil nutrient loss.

9.4 Effects of soil amendment and cropping system on soil characteristics and crop production

The experimental site was characterized by low soil nutrients status as is the case for most SSA regions (Sanginga and Woomer, 2009). Such soils require integrated nutrients management to improve crop yield. The rainfall was poorly distributed, especially during the minor seasons and the amount was low to meet crop water requirement. Thus, soil and crop management options based on soil moisture conservation are very essential for such agro-ecosystem.

Soil chemical and physical properties were influenced by the different cropping systems and soil amendments. The inorganic inputs had good effect on both physical and chemical properties viz. soil bulk density, soil moisture content,, soil nutrients and soil organic carbon as observed also by Ameloot *et al*. (2015) and Peng *et al*. (2016). Despite the improvement in soil nutrients due to the amendments, the levels were still below the thresholds (Landon, 2014) for sustainable crop production. Thus, there is a need for seasonal nutrient supply for soil and crop yield improvements. Soil pH was not affected by the different practices except biochar related treatments where a slight increase was observed. Such liming characteristics of biochar were also reported by Ebeheakey (2014) and Ameloot *et al*. (2015).

The positive effect of biochar on soil chemical properties was also observed but with a smaller magnitude than the inorganic treatments. This organic material is important for soil moisture improvement (Jien and Wang, 2013; Ojeda *et al*., 2015) as well as soil chemical property amelioration due to its nutrient supplying ability on soil (DeLuca, 2009; Lone *et al.*, 2015; Amendola *et al.*, 2017). It was observed that the legume-based cropping systems had more positive impact on the assessed soil properties, probably due to the litter which impacted positively on soil physicochemical parameters (Foley *et al*., 2011). There was increase in grain and biomass yields under the different soil amendments. However, the yields were below the potential yield of each crop.

The study showed also positive impact of biochar on yield for all the crops compared to the control plots due to its positive impact on soil physico-chemical properties (Jien and Wang 2013). Despite its low nutrients content, biochar supplied soil nutrients and improved soil physical properties for increased crop production, a phenomenon observed in several other studies (e.g. Jien and Wang 2013; Gul *et al*., 2015; etc).

Intercropping effect was assessed using LER and values greater than unity were observed for all the treatments. The intercropping system used was the MBILI, which based on productivity, is more suitable than the traditional systems of 1:1 as explained by Tungani *et al.* (2002) and Mucheru-Muna *et al.* (2010). Due to its multipurpose effect, it is sustainable for smallholder farming systems where a diversity of agricultural products is required amidst different threats (e.g. pest and diseases, soil degradation, etc). However, for the intercrop, maize yield slightly decreased compared to the sole crops probably due to competition between crops. The highest yield decrease was observed on the control plot, especially due to low nutrients status characteristic of natural and untreated soils. Despite the negative effect of the intercropping on maize yield, the overall agricultural value was more beneficial for both crops with respect to their individual sole yields.

With respect to cost effectiveness, the findings of the study showed that, under each cropping system, sole NPK had VCR greater than 2 (the acceptable threshold). The cost of the fertilizers and the magnitude of yield improvement accounted for the good values under these treatments. For all the sole cropping systems, biochar based treatments (BC and NPK+BC) had VCRs below 2. Despite improvement in yields, the application of biochar did not show any economic advantage for all the sole systems. Due to intercropping advantage as observed also by Mucheru-Muna *et al.* (2010) and the long-term effect of biochar (Gul *et al*., 2015), sole biochar produced a VCR of 2.19 under intercrop system during the third season while during the same season, lower values were observed for the sole systems. Under the intercrop system, NPK+BC had values of 2.77, 2.49 and 3.43 in 2016-major, 2016-minor and 2017major seasons, respectively and this was the only biochar based treatment with VCR greater than two; probably due to the intercropping and integrated nutrient management effects (Mucheru-Muna *et al*., 2010; Vanlauwe *et al*., 2010). The low

VCR under treatments with biochar, especially the sole systems, was due to the high cost of this organic material as soil amendment and the observed small magnitude of yield improvement compared to the treatments with inorganic fertilizers. However, due to its multipurpose effect (Uzoma *et al*., 2011; Lone *et al.*, 2015), biochar as soil amendment has more advantage beyond the economic value expressed by yield increase. Therefore, its use as soil amendment will also be more profitable for soil carbon sequestration (Woolf, 2008; Lone *et al*., 2015; Ojeda *et al*., 2015); and this environmental importance can orient biochar based studies in science and crop production. The climate factor had an impact on productivity as evidenced by the low VCRs during the minor season where there was water stress which generally reduced yields.

CHAPTER TEN

10. GENERAL CONCLUSIONS AND RECOMMENDATIONS

10.1 General conclusions

Based on the different objectives of the study, the following conclusions are drawn:

All the five factors used (p-value, R^2, RMSE, NSE and RSR) gave promising results that the developed model is good for soil erosion characterization. This method is applicable to the quantification of runoff in individual erosive storms and can remain stable and accurate under different slope classes. Clearly, the study has contributed to knowledge through the development of a model which can reduce the limitations associated with direct runoff quantification under field conditions.

Soil nutrients management reduced soil erosion under specific cropping systems showing decrease in soil loss, runoff coefficient and soil depth reduction. The maizebased cropping system was more vulnerable to soil erosion than the legume-based ones and among them, sole cowpea with good biomass production and good ground cover was the most efficient. Good land cover by crop biomass improved soil properties and reduced soil erosion. This study has provided useful information on the magnitude of soil loss under different soil and crop management options towards suitable production.

Soil nutrient loss was influenced by the different soil amendments and cropping systems. The bare plots had the highest rate of nutrients loss whilst the least was recorded on the fertilized plots. The study has shown off-site effect of soil erosion to be characterized by higher enrichment ratios for soil nutrients and fine soil particles.

The heavy soil particles (sand) had ER less than unity throughout the study period. The systems without external nutrient supply had the highest rates of economic losses based on erosion replenishment method.

The physico-chemical soil characteristics were improved under the different interventions studied such that the legume-based cropping systems were the most efficient. Inorganic fertilizers did not only improve soil nutrients status but also physical parameters by increasing biomass production which reduced rainwater impact on some soil physical degradation through interception. Sole biochar slightly decreased soil acidity compared to the other soil amendments which had greater effect on soil nutrients improvement than on soil pH. Biochar treatments had greater positive effect on soil physical properties than the inorganic based treatments.

Crop yield improvement as well as soil nutrients uptake was more pronounced under inorganic amendments. In all cases the biochar and inorganic fertilizer-based treatments increased crop productivity over the control but the magnitude was higher under the latter than the former. For income improvement, sole inorganic treatments were the most important based on the value cost ratio (VCR). Generally, the biocharbased soil management options were not economically viable, except for intercropping systems during 2017 major season under sole biochar and during the three growing seasons under biochar combined with inorganic fertilizers.

Intercropping system was more profitable than all sole cropping systems.

10.2 Recommendations

The new model developed is accurate and recommended for runoff estimation under different soil and crop management options. However, despite the accuracy of the model, further investigations based on different soil types and ecosystems are recommended for wider applicability and precision.

Under soil degradation (erosion and nutrient depletion), farmers should target soil cover improvement with cowpea to increase soil stability and crop yield.

In small-scale farming systems, improving legume-cereal cropping systems through integrated nutrients management is recommended for higher economic returns and diversity.

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APPENDIX : PROFILE DESCRIPTION

The soil profile characteristics of the site as reported by Amegashie (2014) are presented below.

1. Characterization of Soil and horizon description

The physiographic position of the profile pit was the upper slope. The soil was formed in in-situ parent material derived from weathering products of granite. The soil was identified as Kotei Series (Ghana classification) and Plinthic Vetic Lixisol (Profondic, Chromic) (Amegashie, 2014). Eight horizons were obtained from the profile pit (Appendix 1).

Appendix 1. Description of soil profile at experimental site

Horizon №	Horizon Depth (cm)	Horizon Profil	Description
1	0-25 cm	Ap	Dark brown (7.5YR 4/2), moist, dark greyish brown (10YR 4/2), dry; sandy loam; moderate fine granular; slightly hard, friable, slightly sticky slightly plastic; few (3 %) quartz gravels and stones; many fine interstitial pores, few medium channels; many very fine roots; abrupt smooth boundary

2	25-37	BA	Brown (7.5YR 4/3), moist; sandy clay loam; moderate medium subangular blocky; hard, friable, sticky plastic; few fine (5 %) quartz gravels and stones; very few iron and manganese nodules; many fine interstitial pores, few medium channels; very few roots; gradual smooth boundary
3	37-48	Bt1	Reddish Reddish brown (5YR 4/4), moist; sandy clay; moderate medium subangular blocky; firm, sticky plastic; common (10 %) quartz gravels and stones; very few (<1 %) iron nodules; many fine interstitial pores, few medium channels; very few, very fine roots; diffuse smooth boundary
4	48-67	Bt2	Red (2.5YR 4.5/6), moist; sandy clay; moderate medium subangular blocky; firm, sticky plastic; common (10 %) fine, few (3 %) coarse quartz gravels; very few (<1 %) iron nodules; many fine interstitial pores, few medium channels; very few, very fine roots; diffuse smooth boundary

5	67-83	Bt3	Red (2.5YR 4.5/6), moist; sandy clay; moderate medium subangular blocky; firm, sticky plastic; common (10 %) fine, few (3 %) coarse quartz gravels; very few (<1 %) iron nodules; many fine interstitial pores, few medium channels; very few, very fine roots; diffuse smooth boundary
6	83-108	Btv1	Red (2.5YR 4.5/6), moist, common distinct medium red (10R 4/6), moist, and brownish yellow (10YR6/8), moist, mottles; sandy clay loam; moderate medium subangular blocky; sticky plastic; very few (<1 %) quartz gravels; common (15 %) soft iron nodules; many fine interstitial pores, few medium channels; few (4 %) flakes of muscovite; very few, very fine roots; gradual smooth boundary
7	108-130	Btv2	Red (2.5YR 5/7), moist; sandy loam;, weak medium subangular blocky; slightly sticky slightly plastic; abundant (50 %) soft iron nodules, many fine interstitial pores, few medium channels; common flakes of muscovite; very few and very fine roots; gradual smooth boundary

8 130-170 Btv3 Red (2.5YR 5/7), moist; sandy loam; weak

medium subangular blocky; slightly sticky slightly plastic; abundant (50 %) soft iron nodules, many fine interstitial pores, few

medium channels; common flakes of muscovite; very few and very fine roots; gradual smooth boundary.

2. Chemical properties of soil profile

The pH of the soil profile was acidic with an average value of 4.37 (Appendix 2). The organic carbon and the total nitrogen contents of the profile were generally very low with averages of 0.37 and 0.06 % respectively and generally decreased with depth. The average concentration of the available phosphorus for the profile was low (3.85 mg/kg) and also in most instances decreased with depth. However, some layers (0-10 and 20-30 cm) had a marginal concentration of available phosphorus (P > 5 mg/kg). Adequate amount of available phosphorus was observed in the 10-20 cm and 110- 120 cm layers.

Appendix 2. Chemical properties of soil profile at the study site

Depth (c m)	pH (Water) (1: 2.5)	Total N (%)	Available P (mg/kg)	Organic C (%)	Exchangeable Cations cmol(+)/kg Na	K	Ca	Mg
0-10	5.11	0.11	8.05	0.94	0.12	0.20	2.60	1.40
10-20	5.27	0.11	15.57	0.82	0.10	0.14	2.60	1.80
20-30	5.11	0.09	6.48	0.62	0.11	0.21	2.40	1.20
30-40	4.96	0.07	1.24	0.50	0.14	0.17	3.00	1.00
40-50	4.83	0.07	1.96	0.40	0.12	0.22	3.00	1.60
50-60	4.92	0.07	1.96	0.38	0.09	0.07	2.80	1.20
60-70	4.67	0.07	1.24	0.34	0.09	0.06	2.60	1.60
70-80	4.52	0.06	1.24	0.36	0.08	0.04	2.60	0.80
80-90	4.37	0.06	1.96	0.38	0.07	0.05	2.00	1.20
90-100	4.17	0.05	1.24	0.34	0.08	0.05	2.00	1.20
100-110	4.14	0.05	1.24	0.10	0.08	0.06	1.80	0.80
110-120	3.85	0.04	12.97	0.06	0.08	0.07	1.60	0.80
120-130	3.65	0.04	1.96	0.08	0.08	0.07	1.40	0.80
130-140	3.53	0.04	1.96	0.12	0.08	0.05	1.00	1.60
140-150	3.43	0.04	1.24	0.18	0.12	0.17	1.00	1.20
150-160	3.39	0.03	1.24	0.34	0.06	0.04	0.80	120
Mean	**4.37**	**0.06**	**3.85**	**0.37**	**0.09**	**0.10**	**2.08**	**1.21**

Source: Amegashie (2014)