UNIVERSITY FOR DEVELOPMENT STUDIES

SIMULATION OF THE EFFECTS OF BIOCHAR AND INORGANIC FERTILIZER ON GROWTH AND YIELD OF UPLAND RICE-COWPEA INTERCROP AND SOIL PROPERTIES IN TOLON DISTRICT OF GHANA

BY

FRIMPONG-MANSO, JUDITH

(MPhil. SOIL AND WATER CONSERVATION AND MANAGEMENT)

(UDS/DSWC/0001/19)

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NOVEMBER, 2022

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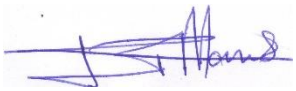
DECLARATION

I hereby declare that this Thesis is the result of my original work and that no part of it has been presented for a Degree in this University or elsewhere. The works of others, which served as sources of information for this study, have been duly acknowledged in the references.

(Student's Signature)  Date 25/10/2022

Frimpong-Manso Judith

UDS/DSWC/0001/19

I hereby declare that the preparation and the Dissertation/Thesis were supervised by the guidelines on supervision of thesis laid down by University for the Development Studies.

(Principal Supervisor's Signature) … Date 25/10/2022

Name: Ing. Prof. Abdul-Ganiyu Shaibu

(Co-Supervisor's Signature) ….. . Date 25/10/2022

Name: Dr. Joseph Xorse Kugbe

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ABSTRACT

A three-year short-term study (2017–2019) was conducted in the Guinea Savannah Zone of Ghana to evaluate changes in soil physical and chemical properties as well as productivity of rice-cowpea intercrop system attributable to biochar application under real field conditions. Nutrient leaching in the highly weathered Guinea Savanna soils is often considered a challenge for crop production. Three different sources of biochar were assessed for the rice-cowpea intercrop system's productivity, soil nutrient supply, and soil hydraulic properties at the field by integrating modeling with soil water content measurements in two cropping seasons. The effect of simulations of biochar on upland rice yield and nutrient leach was determined using the APSIM model. The treatments comprised No treatment (control) and 5 t ha^{-1} rates of high and low pyrolysis (400-700^{o}C) biochar. The three different sources of biochar materials (groundnut shells, poultry manure, and corn cobs) were incorporated into the soil at a depth of 0-30 cm. Biochar plus nitrogen (N), phosphorus (P), and Potassium (K) at rates (kg ha^{-1}) of 45N3030K, and 90N, 60P, 60K, and biochar alone were applied once in May. NPK fertilizer was applied throughout the planting periods. The randomized complete block design with 4 replicates was used. The Agricultural Production Systems Simulator (APSIM) models were calibrated and tested for rice growth and yield, soil water, soil N, surface organic matter, biochar, and soil temperature, and the assessment of model projection was done against independent data sets. The data were used to test the performance of the APSIM model in predicting the crop yield, available soil phase and soil organic carbon on P-deficient soil. The results show that additional amendments to input parameters for the P model, particularly concerning P amount and uptake for subterranean soil layers, may enhance the fit between experimental and model-predicted results. In a variation, APSIM predicted well the growth of cowpea that is well supplied with P, and the residual biochar and N benefits to a succeeding upland rice crop, including the response to additional inputs of N fertilizer. The bond between model predictions and measured data was acceptable for all three different sources of biochar. Biochar enhanced soil hydraulic properties. Leaching by saturated water flux was calculated using soil solution sampled with suction lysimeters and water flux estimates generated by the APSIM model. No significant difference ($p > 0.05$) was observed in surface saturated hydraulic conductivity or soil water retention, resulting in changes in water percolation for the three sources of biochar plus

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45N30P30K. However, due to differences in soil solution concentrations, leaching of inorganic NH_4^+, $N0_3^-$, P, and K measured in a depth of 70 cm increased ($p < 0.05$) in the 90N60P60K, whereas NH_4^+, $N0_3^-$, P, and K leaching decreased for the three sources of biochar plus 45N30P30K, and absolute control. Changes in leaching at 70 cm depth with the three sources of biochar plus 45N30P30K additions were about one order of magnitude lower than 90N60P60K. The findings show that biochar application increases soil solution concentrations and movement of nutrients in the root zone and decreases leaching of NH_4^+, $N0_3^-$, P, and K, possibly by a combination of retention and enhanced crop nutrient uptake. Rice farmers in Nyankpala-northern of Ghana can improve soil fertility and increase rice yield by applying 5t ha^{-1} biochar with a combination of cowpea intercrop, biochar, and inorganic fertilizer of N45P30K30.

Keywords: APSIM, leaching, nutrient, biochar, simulation, inorganic fertilizer, percolation

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DEDICATION

This dissertation is dedicated to my children Kofi Osafredu Asubonteng and Abena Osafredu Asubonteng, and all whose tireless efforts have brought me this far.

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Preliminary observations

This thesis is based on manuscripts that have been published, accepted, or are in the process of being published in peer-reviewed journals, and they are referred to in the text by their chapter Arabic numbers, as shown below.

Chapter 3: **Frimpong-Manso, J., and Abdul-Ganiyu, S., A. (2021).** Assessing upland rice, biochar and soil nutrient models in the Guinean savanna zone (Nyankpala) Ghana Proceedings of the International Conference on Agriculture, Vol.3, Issue 1, 2021, pp. 44-67 ISSN 2682-7018online DOI: https://doi.org/10.17501/26827018.2019.6104

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Chapter 6: **Frimpong-Manso J., Abdul-Ganiyu S., and Kugbe Xorse, J. (2022).** Influence of biochar and inorganic fertilizer on upland rice-cowpea intercrop competitive indices. Proceedings of the 6th International Conference on Climate Change 2022 (ICCC 2022) Vol.6, Issue 1, 2022, pp.31-55 ISSN 2513258X online DOI: https://doi.org/10.17501/2513258X.2022.6102

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CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background

Rice (*Oryza sativa* L.) cultivation was introduced in Ghana in 1960 from Asia (Nantui et al., 2012). It is a staple food for millions of people. After corn and wheat, it is currently the world's second-largest grain crop (Manu et al., 2018). Unlike other grains such as corn, millet, and sorghum which are depleted by human beings and livestock feed, rice remains the most favored human grain for use worldwide (Day, 2013). In total, annual production of paddy-milled rice currently stands at 963,000 metric tonnes from 2008 - 2019 equivalent to 665,000 tonnes (Amewu et al., 2021; Gyekye et al., 2020). The yearly rice production is increasing at the rate of (10%) per annum. This is due to gradual changes in feeding habits and their varied farm management practices (soil fertility approaches) (Amewu et al., 2021; Gyekye et al., 2020). A continuous increase in the global population has triggered a high demand for food tremendously in the recent past. Hence, rice in the economic development of Ghana cannot be underestimated. It is the second highest source of income for people in the northern regions, after maize, sorghum, millet, and peanuts. At present, rice is farmed in an area of 6000 hectares in the Northern Region of Ghana with a total annual output of 16,250 metric tonnes giving an average production of 4.9 tonnes per ha^{-1} (FAO and GIEWS, 2017). It is grown by small-scale farmers as both cash and food crops. Total cultivated farmlands for growing rice in northern Ghana are 4.52 ha or 56%, paddy irrigated land 0.19 ha, or 95%, upland crops land 3.19 ha, or 63%, and paddy rain-fed land 1.14 ha, or 41% (MOFA, 2008 JICA study team http://open_jicareport.jica.go.jp › pdf. This has necessitated the expansion of non-irrigated rice in Northern Ghana. New rice for Africa (NERICA) is a

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melodic line of hybrid rice that was originally produced by combining the hardiness of *Oryza glaberrima* (a resilient African rice species) with the high productivity of the Asian species (*Oryza sativa)* through interspecific breeding (Ndjiondjop et al., 2018; Tobita, 2004; Yelome et al., 2018) The variety performs well in conditions suited for grains and legumes. Grains such as rice, maize and legumes such as beans, and soybeans are used respectively. Therefore, there is the need to integrate NERICA rice into the current cropping system that is dominated by maize, sorghum and finger millet among other crops to sustain food production and cut poverty (Abdulsalam et al., 2021; Kassam et al., 2019; Saini et al., 2020; Tadele, 2017). Intercropping NERICA rice with cowpea is a potential area that is yet to be exploited in Ghana.

1.2 Intercropping systems

Intercropping is one of the important cropping systems in both sub-Saharan and tropical Africa that has become popular among small-scale farmers as it offers the possibility of yield advantage for both component crops, one of them as compared to monocropping through improved yield and stability of yield (Bhatti et al., 2008; Rabeya et al., 2018; Saleem et al., 2011). A cropping system involving cowpeas and cereals together in the same area for multiple food production has been and is still a popular practice among small-scale farmers in tropical countries (Abdulkadir et al., 2021; Layek et al., 2018; Matusso et al., 2014). Intercropping consists of growing two or more cultures in the vicinity (Kermah et al., 2017). Although the terminology differs from the literature as a whole, with terms such as "mixed crop" or "mixtures" being used, this study will refer to the cultivation practice as an intercropping crop. Intercropping is a prominent practice in low-input agricultural systems

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and has been used for centuries throughout the world up until the 20th century with the onset of agricultural intensification (Nelson, 2020). The increased use of mechanized practices, such as harvesting and fertilizing, has increased the efficiency of individual crop production (Lithourgidis et al., 2011; Madembo et al., 2020; Tan et al., 2020). However, such cropping strategies have not been without negative consequences for environmental health, which has increased interest in more sustainable systems where external resources are not available or are limited in certain circumstances (Albrecht et al., 2020; Reganold and Wachter, 2016; Tscharntke et al., 2012). While consumer choices, agricultural and trade policies are essential for multispecies systems to prosper, agricultural research has made constant efforts to appreciate the mechanisms behind them (Keating et al., 2003; Lefèvre et al., 2020; Nelson et al., 2018; Tsubo et al., 2005). The most significant benefits of intercropping are increased production per unit of land without additional inputs (such as mineral fertilizer) and increased buffering against constraint and plant production difficulties (Lienhard et al., 2020; Malézieux et al., 2009). (Ngwira et al., 2020; Rusinamhodzi et al., 2012) reported that in smallholder settings, intercropping maize and pea pigeons resulted in a financial gain of more than three times that of single maize in Mozambique. However, one of the major disadvantages is that the product is not ‘pure' but is blended, which may have a lower market value in some areas. Mixed crop management also presents challenges for existing mechanized systems, that is, product separation, which requires increased labour or special machines. Intercropping is traditionally used in smallholder systems with low inputs due to low plant populations, where farmers hope to capitalize on niches, i.e., the area between the initial plantings.

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This is called additive intercropping, where inter-row spacing is filled with intercropping (Carton et al., 2020; Haugaard-Nielsen et al., 2006; Layek et al., 2018). Another common system sees alternate rows of, for example, a sole cereal stand, replaced by companion crop rows (usually a legume), known as replacement intercropping, as seen in (Nelson et al., 2018). Intercropping systems do not only comprise row-based structures but are also cultivated as strips, whereby multiple rows, for example, of a cereal, are followed by multiple rows of a companion crop (Li et al., 2006; Streit et al., 2019). (Sun et al., 2018) also show a successful intercropping of legume alfalfa and maize, demonstrating that systems (grassland and arable in this case) can coexist.

This study deals with the intercropping of cereals and single-row legumes. The use of leguminous plant species as part of any intercrop system can be beneficial for low-input systems, due to the ability of legumes to fix nitrogen (Jensen et al., 2020; Xiao et al., 2004). The mechanisms by which positive mixing effects occur are highly hypothetical. The rhizobia symbiosis is particularly intriguing, as cereal-legume intercropping is viewed as particularly promising (Blum, 2009; Li et al., 2006; Nelson, 2020; Senbayram et al., 2008; Xiao et al., 2004). Scientific evidence and arguments that promote intercropping systems focus on numerous factors, such as increasing input costs, and a decrease in the availability of energy, nitrogen, phosphorous, and agrochemicals that can be connected to climate variability and environmental damage (Ali et al., 2021; Cavicchioli et al., 2019; Change, 2019; Newton, 2009; Randers, 2012; Tilman et al., 2002). The resource use efficiency of intercrop systems does not solely refer to nutrients but encapsulates factors such as water use, and space, be that above (light) or below ground (root) (Nelson, 2020; Chimonyo *et al.*, 2016; Keating *et al.*, 2003). Due to canopy covering and the benefits associated with greater

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biodiversity, intercropping is reported to better defend stands against weeds, plant diseases, and pests in low-input systems in particular (Finckh, 2008; Gronle and Böhm, 2012; Nelson, 2020).

A major challenge for agricultural production over the next few decades is to raise the productivity of existing production sites. To achieve this, resources such as light, water, nutrients, and labor must operate as efficiently as possible to develop environmentally efficient and resilient agricultural production systems (Finckh, 2008; Keating and Carberry, 2010; Stomph et al., 2020). In a recent study on accelerating genetic gains in legume crops, (Varshney et al., 2018) emphasize the importance of accuracy in the design of plant breeding programs and the importance of addressing agricultural challenges from a systemic perspective.

The development of successful intercrop systems is therefore likely to be achieved via a similar method, looking at specific conditions and certain crop combinations, planting diverse crop mixtures of various types with varying attributes (Lienhard et al., 2020; Malézieux et al., 2009). Indeed, Couëdel et al. (2018); Li et al. (2006); Ma et al. (2020) emphasize the importance of crop combinations for intercropping, as some may be more beneficial than others. The yield advantage gained via intercropping is referred to as the "mixing effect" (Bonke et al., 2021; Hof-Kautz and Rauber, 2003; Nelson et al., 2021), with land equivalent ratios (LER) higher than one indicating the superiority of inter-cropping over sole cropping (Bonke et al., 2021; Nelson et al., 2021; Pretzsch and Schütze, 2016). According to Bonke et al. (2021); Nelson et al. (2021); Hof-Kautz and Rauber (2003), land-equivalent ratios exceeded one case out of 60% of the 344 cases identified. Similarly, (Dowling et al., 2021; Paulsen et al., 2007; Paulsen, 2007) found the LER to be greater than

1 in 50 out of 76 arable land mixtures. On average, the mixing effects appear positive, with considerable variation from one case to another. This provides opportunities for exploiting favorable interactions between crops of specific components (Kremen and Miles, 2012; Layek et al., 2018; Lithourgidis et al., 2011; Songa, 2020).

With the above examples in mind, while crop interactions have generally been positive, it is clear that some scenarios do not result in higher overall yields. Therefore, intercropping is not always considered a persuasive option for farmers. The processes that determine intercropping crop performance need to be much better understood before being considered a conceivable option. With a better understanding, specific crop combinations could be selected at the genotype level, as well as densities and other management options. Intercropping is a very sophisticated system and has the potential, with advanced understanding, to be managed accurately, much like many modern monoculture systems. While field experience can be expensive, it is crucial if we are to make progress. Linking crop simulation models (CSM) and field experiments presents itself as an effective method of dealing with the overwhelming variety of intercropping combinations to be tested and could help guide field-based research (Reynolds et al., 2018; Rötter et al., 2018).

1.3 Processed-based crop modeling

While a range of process-based crop models has been chosen for this study, the Agricultural Production Systems Simulator (APSIM) is widely used and has been chosen for this study. The model was and continues to be developed by the Australian Production Systems Research Unit (APSRU), which is a collaborative group made up of Commonwealth

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Scientific and Industrial Research Organization (CSIRO) and Queensland State Government agencies, having started in 1991. While different models vary in terms of the description of certain processes, they simulate plant growth, which is divided by the various organs, such as stem, leaves, and roots daily. Plant development is divided into growth phases, such as emergence, juveniles, flowering, grain filling, and maturity. A water balance of four and a nitrogen module allow APSIM (among other models) to evaluate these limitations. Crop model for APSIM, for example, cowpea (Chen et al., 2016; Chimonyo et al., 2016; Robertson et al., 2002), have been tested against field observations, which are documented, and can be found within the model and online. The upland rice-based cropping system is characterized by non-flooding during most of the growing period. Upland rice farming comprises about 4% of world rice production (htp/Erie.org/about-rice/rice). The current cropping system practiced by irrigated rice farmers in Ghana involves the rotation of cereals and or legumes with rice. This is because these crops can't grow in standing water. Initially, there were no rice varieties that could be grown under similar conditions to maize and sorghum. NERICA rice varieties perform in conditions similar to other cereals such as corn and sorghum. Hence, the need to integrate NERICA rice into the systems dominated by maize, sorghum, and finger millet to sustain food production and reduce poverty is considered a viable option. Moreover, during the off-season, the residues from these crops can help maintain animal health and milk production while also improving soil fertility (Selim, 2020; Wahla et al., 2009).

Rice, beans, and cowpeas are important crops that can provide more economic return to farmers (Ahmad et al., 2007; Iqbal et al., 2018). The areas under these crops cannot be

increased as they face substantial competition for space from traditionally well-known farmer's crops such as maize and sorghum.

1.4 Extent of rice cultivation and its contribution to food security in sub-Saharan Africa

Nearly one-sixth of the global population is malnourished. The problem is practically acute in tropical Africa, where constant or recurrent food shortages affect over 30 percent of the population (approx. 260 million people). Low levels of agricultural productivity are a key cause of hunger in this part of the world (Hall et al., 2017; Houlton et al., 2019; Sánchez, 2010). Projections of the United Nations Earth Project (2017) also indicate that the population of the Earth will surpass 9.2 billion people by 2050, up from the current 6.9 billion. The report further indicates that there is a rise in food prices since the 1990s while the amount of cultivated land per person declined in the same period (Alston et al., 2009; Fuglie, 2018). Researchers estimate that 30% of the rural populations of developing countries lack reliable access to food because of poverty. Meanwhile, models suggest that the climate is changing and could cause more droughts in key rain-fed agricultural areas of sub-Saharan Africa.

Rice is becoming progressively significant for food security in many low-income, food-deficient countries in Sub-Saharan Africa. The demand in Sub-Saharan Africa far surpasses production, which in the last 3 years has increased by 70 %, mainly because of the increased area planted for rice (Arouna et al., 2021; Arouna et al., 2017). Only 30 % of the growth can be ascribed to improved productivity (Fagade, 2000). West Africa's total upland rice accounts for 44 % of production. Over 75 % of the region's peasant farmers cultivate upland

and lowland rice as a subsistence crop (Al-Hassan, 2008). Presently, many smallholder farmers in Ghana are relocating to the inland valley bottom, which requires more moisture for rice culture of which low yields are currently reported. Slightly higher yields are attained in areas where soil, rainfall, and management conditions are favorable. These findings show unfavorable effects for areas already struggling with food shortages. An investigation of these findings has serious implications for the food security of the poorest rural population. In the environment of Nyankpala, in the Northern Region of Ghana, this is common in poor resource systems, although colimitation by some factors can occur in improved agricultural systems. If an improved cropping system increases the availability of a limiting resource, then yield should increase. These common limiting factors include such things as sunlight, water, oxygen (in waterlogged soils), temperature, and any one of 14 essential mineral elements. The essential minerals and the limiting factors are nitrogen (N), phosphorus (P), and water availability, whilst cropping season length is often restricted by daylight and temperature extremes. Crop production on 70 % of the world's agricultural land can be further restricted by the Phyto availability of iron (Fe), zinc (Zn), and copper (Cu) on alkaline and calcareous soils, or by aluminum (Al) or manganese (Mn) toxicities on acidic soils (Brooker et al., 2015; Shukla et al., 2018; White and Greenwood, 2013). Intercropping systems can increase Phyto availability and acquisition of limited resources, and management of root rhizosphere interactions can improve resource-use efficiency by crops (Dai et al., 2019; Ehrmann and Ritz, 2014; Shen et al., 2013; White et al., 2013; Yang et al., 2021; Zhang et al., 2010). This element in leguminous crops can improve land and increase crop yield.

Nyankpala, in the Northern Region of Ghana, where the study was conducted, soils are generally acidic and feature low-natural fertility with low-available N, P, K, and cation exchange capacity (CEC), and high-aluminum saturation (Compaoré, 2006; Kombiok et al., 2012; Scheiterle et al., 2019; Tetteh et al., 2016). Also, the Northern Region has a unimodal rainfall season and frequent dry periods occur during the cultivation period of rainfed rice. Upland rice production is seen as high-risk work in these circumstances. Increasing the amount of soil organic matter (SOM) enhances soil's chemical, physical, and biological properties, as well as nutrient cycling (Crusciol et al., 2015; Page et al., 2020; Petter et al., 2012). To raise SOM levels in the top soil layers, conventional and minimal tillage with monocropping systems are viable options. Biochar improves the chemical, physical, and biological properties of soil, as well as crop biomass and yield (Cooper et al., 2020; Glaser et al., 2002; Kookana et al., 2011). Rice is positively affected by eucalyptus charcoal add-on to the soil, according to (Miranda et al., 2017), based on research in upland rice. Upland rice showed a superior initial vigor and biomass increase, a more equal growth pattern, and a larger seed dry mass, according to these authors.

Biochar improves soil properties by lowering acidity and boosting P and K availability (Hafez et al., 2020; Naeem et al., 2021; Wang et al., 2020). The application of biochar (charcoal or biomass-derived black carbon (C) to soil is further proposed as a novel approach to establish a significant, long-term, sink for atmospheric carbon dioxide in terrestrial ecosystems (Guenet et al., 2021; Gupta et al., 2020; Panwar et al., 2019; Viswanathan et al., 2020). A key advantage of biochar compared to other amendments concerning soil ecosystem functions is that it is more efficient in improving soil fertility and nutrient

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retention than un-charred organic matter (Chathurika and Ronsse, 2019; Khan et al., 2020) (Hood-Nowotny et al., 2018; Lehmann et al., 2006).

1.5 Problem Statement and Justification

One important limitation facing the stability of crop production in Ghana is the declining soil productivity after a few years of cultivation (Williams et al., 2019). Nutrients are taken away from the soil through crop absorption, loss by leaching, erosion, and immobilization (Yang et al., 2021; Zhu et al., 2020). The nutrients so removed have to be replaced to ensure good crop performance. Nevertheless, these conditions are not suffered under the present land use systems in West Africa. Thus, food losses are manifested in a variety of food deficiencies. Therefore, fertilizers need to be supplied to provide the required nutrients (Bockman et al., 2015; Hussain et al., 2021; Vidyashree and Arthanari, 2021; Weeks and Hettiarachchi, 2019).

Most smallholder farmers have limited resources to buy fertilizers (Jayne et al., 2019; Mubanga and Umar, 2020). Hence, exploring management strategies to use low inorganic N combined with suitable grain legumes could sustain crop productivity. However, the potential contribution of grain legumes to crop production by subsistence farmers in Africa is largely becoming known (Adjei-Nsiah et al., 2018; Kermah et al., 2018; Vanlauwe et al., 2019). Nitrogen-fixing legumes have been shown to have a positive impact on soil fertility by enhancing nitrogen availability and therefore benefiting a cereal crop grown in the subsequent season (Adjei-Nsiah et al., 2018). In solving the multifaceted problem of food shortages, efforts have been made to develop crop varieties with higher yield potential. Rice is the second most widely consumed food crop worldwide, after wheat and corn. Low soil

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fertility has been cited by farmers and researchers as one of the constraints affecting cereal production in northern Ghana (Kombiok et al., 2012; RELC, 2005). Other problems limiting rice production include low adoption of high-yielding varieties hence low productivity, insect pests, and diseases (Tollens et al., 2013; Yuan et al., 2011). This is confirmed by the fact that low grain yield of cereals has been ranked first among the top constraints in almost all the districts of northern Ghana at the various regional planning sessions (Britwum and Akorsu, 2016; Britwum et al., 2019; Kombiok et al., 2012; Mbanya, 2011).

A decade has passed since NERICA (New Rice for Africa; *Oryza sativa x O. sativa x O. glaberrima*) was released from the Africa Rice Center (then West African Rice Development Association or WARDA, now Africa Rice). Because of its high-yielding potential, NERICA was expected to bring about a rice Green Revolution in sub-Saharan Africa (Arouna et al., 2017; Kijima, 2020; Nasrin et al., 2015). NERICA has attracted a lot of attention from researchers and policymakers, and some literature has been accumulated (Fujiie et al., 2010; Kijima, 2020; Kijima et al., 2011), including some recent literature that casts doubt over the potential of NERICA (Kijima et al., 2011). Information exists in the literature on the nutrient requirements of upland NERICA (Oikeh et al., 2009; Tollens et al., 2013). But, information on fertilizer recommendations for the NERICAs in rain-fed upland ecologies in the savannas is grossly lacking. Consequently, there is a need to harmonize the use of biochar in the rice-legume intercrop system for soil improvement to sustain yield over a long period to promote moisture and mineral elements in the soil, which have been found to be essential for growth enhancement and maximize yield production in crops (Aynehband et al., 2012).

The low soil fertility in this part of the country is attributed to the bushfires that occur annually during the dry season (October to April). This renders the soil bare, exposing it to

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both wind and water erosion and depleting the macro-nutrients, such as Nitrogen, Phosphorus, Potassium (NPK), and organic matter from the soil. Farmers used to replenish the soil with its nutrients by practicing shifting cultivation or land rotation. With the growth of the population and increased pressure on land, this practice is not being sustained and other measures are required to maintain soil fertility for sustainable crop production. Fractional use of inorganic fertilizers and low-input agriculture systems that alter soil organic matter have become common among crop growers in Ghana.

For this to succeed, proper use of land and soil management practices that emphasize the amendment and maintenance of soil organic matter would have effects on maintaining soil fertility levels and increasing crop productivity (Fageria, 2012; Loveland and Webb, 2003; Oldfield et al., 2019; Puget and Lal, 2005; Rao et al., 2017). Current improvements in organic agriculture involve intercropping with species of leguminous plants and biochar (Gujre et al., 2021; Jensen et al., 2020; Meena et al., 2018; Meena and Lal, 2018; Stavi and Lal, 2013), thus improving and sustaining soil fertility as an economic-benefit mechanism. Furthermore, nitrogen enrichment of soil can be achieved through biological nitrogen fixation, and the incorporation of legume biomass amendments plays a vital role in enhancing the recycling of plant nutrients, improving soil temperature, enhancing the structure of the soil and controlling erosion, stimulating high microbial activity, and conserving the high soil nutrient status (Agegnehu et al., 2017; Hendrix et al., 2020; Leogrande and Vitti, 2019; Li et al., 2018). According to Rawat et al. (2019) and (Oni et al. (2019), altering soils with biochar (a by-product of the pyrolysis of plant biomass in a limited oxygen ecosystem) decreases nutrient leaching and improves soil cation exchange capacity, soil organic matter, microbial biomass, pH, and soil moisture retention.

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In northern Ghana, rice-cowpea systems involving organic residue inputs are becoming common among smallholder farmers, but yield responses are often inhibited by the above-mentioned soil problems. The incorporation of biochar into these cropping systems is expected to enhance the beneficial effects of the intercrop systems in the long term by improving nutrient availability, N reclaims efficiency, and crop performance (Major et al., 2010; Steiner et al., 2008; Zhang et al., 2020). Biochar can be in the soil for several years without disintegrating; therefore, its incorporation could provide a long-term benefit for soil fertility improvement and crop production (Lehmann et al., 2006; Maroušek et al., 2019; Maroušek et al., 2017; Steiner et al., 2008). Presently, limited studies within the northern agroecosystems have investigated the suitability and sustainability of using biochar in rice-cowpea intercrop systems on upland rice, requiring further research in that area. This study will determine the residual effects of biochar use in the rice-cowpea intercrop on soil nutrient availability and agronomic activities and its performance in an upland rice system. Although considerable literature exists on upland rice-cowpea intercrops, knowledge on the effects of biochar use in a rice-cowpea intercrop system and also on the physicochemical properties of soils as well as on the growth and yield of rice in the Guinea Savannah agro-ecological zone of Ghana remains relatively unavailable. Little has been done in northern Ghana on the use of upland rice-cowpea intercrop system crop models (e.g., the APSIM model) to assess the impact of biochar application regimes on upland rice yield. Also, little is known about the impact (i.e., quantifying) of climate change on rice production by considering changes in temperature and carbon on soil, grain and biomass yields, harvest index, and soil water content using the APSIM model.

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1.6 Objectives

This study aims to determine/ascertain the effect of biochar and inorganic fertilizer on fertilizer application on upland rice-cowpea intercrop production and soil properties.

1.6.1 The specific objectives were to:

i. investigate the modeling dynamics and accumulation of N in the plant and the yield response to three different sources of biochar and fertilizer under rainfed conditions.

ii. validate the performance of the Agricultural Production Systems Simulator (APSIM) model to simulate parts of the experimental rice-cowpea intercrop responses to N and P inputs and the biochar benefits to a successful rice crop.

iii. determine the effect of soil biochar amendments on nutrient leaching after an inorganic fertilizer application in a typical Guinea savannah agricultural soil.

iv. determine the Influence of biochar and inorganic fertilizer on upland rice-cowpea intercrop competitive indices

v. and determine the effect of biochar on the hydrological properties of the soils using the Agricultural Production Systems Simulator (APSIM) model.

1.7 Research questions

1. Do biochar, soil water content, soil nutrient, and soil temperature significantly affect rice-cowpea growth parameters, above-ground biomass, and grain yield as compared to inorganic fertilizer?

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2. Does the impact of three different sources of biochar application on soils affect upland rice-cowpea yield, soil organic carbon, and NH_4^+, $N0_3^-$, P, pH, EC, and K leaching by saturated instability through a sandy soil over three cropping seasons?
3. Is the APSIM model capable of predicting the effects of biochar and mineral fertilizers on soil fertility indices, rice yield, and nutrient uptakes of upland rice-cowpea intercrop?
4. Is APSIM Model capable of simulating soil water content management practices in the study area?

1.7.1 Hypothesis

The symbols Ho and Ha represent the null hypothesis and alternative hypothesis, respectively.

H_o1: biochar, soil water, soil nutrient, and soil temperature significantly affect rice growth parameters, above-ground biomass, and grain yield as compared to inorganic fertilizer.

H_a1: biochar, soil water, soil nutrient, and soil temperature do not significantly affect rice growth parameters, above-ground biomass, and grain yield as compared to inorganic fertilizer.

H_o2: impacts of three different sources of biochar application on soils affect upland rice-cowpea yield, soil organic carbon, and NH_4^+, $N0_3^-$, P, pH, EC, and K leaching by saturated instability through a sandy soil over three cropping seasons?

H_a2: impacts of three different sources of biochar application on soils do not affect upland rice-cowpea yield, soil organic carbon and NH_4^+, $N0_3^-$, P, pH, EC, and K

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leaching by saturated instability through a sandy soil do not have an impact over the three cropping seasons.

H_o3: APSIM model is capable of predicting the effects of biochar and mineral fertilizers on soil fertility indices, rice yield, and nutrient uptakes of upland rice-cowpea intercrop.

H_a3: APSIM model is not capable of predicting the effects of biochar and mineral fertilizers on soil fertility indices, rice yield, and nutrient uptakes of upland rice-cowpea intercrop.

H_o4: APSIM Model is capable of simulating soil water content management practices in the study area.

H_a4: APSIM Model is not capable of simulating soil water content management practices in the study area.

1.8 Limitations of the research

The real effects of biochar, like organic material, manifest themselves, especially in soil fertility indicators, over time. Several uncontrolled factors, both biotic and abiotic, influence yield across Nyankpala. Bird damage, fast weed infestation, pests, and diseases are some of the most common biotic concerns. Unpredictable weather and rainfall patterns are examples of abiotic limits. Stress factors related to nutrients other than nitrogen, as well as the effects of pests and diseases, are all limitations of the APSIM model, despite the significant effort being made to mitigate these effects (Savary et al., 2018). Because the APSIM model is built on a modular architecture, it may be used for a variety of applications, including climate change assessments (Asseng et al., 2015) and plant breeding videotaping (He et al., 2018; Rötter et al., 2015).

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Models like APSIM's modular nature allow for the collection and integration of knowledge from various disciplines (Mao et al., 2015). The APSIM model is especially popular, owing to its user-friendly interface. Simulation experiments can be carried out without the assistance of a computer engineer, and they are frequently used in conjunction with field experiments. Due to, but not entirely, economic relevance and data availability, the scope of model development has primarily focused on monoculture cereals such as wheat, barley, maize, and rice. According to various scenarios, sustainable intensification strategies frequently favor legumes (Franke et al., 2018; Van Loon et al., 2018), as well as multi-species systems (Altieri and Nicholls, 2004; Masvaya et al., 2017). As a result, modeling groups have begun to investigate the integration of legumes into present systems, as well as niches (Sennhenn et al., 2017), yield gaps, and prospective improvement measures (Hajjarpoor et al., 2018). Intercropping is becoming more relevant as part of the global sustainability agenda and movements, even though research on separate legume systems is well established (Chimonyo et al., 2016; Mao et al., 2015). Studies that combine modeling with intercropping, on the other hand, are uncommon (Carberry et al., 1996), emphasizing the thesis's distinctive scientific contribution. With legume demand increasing to compliment cereal production (Varshney et al., 2018), intercropping presents itself as an obvious opportunity to exploit and play a key role in global legume integration programmes. The availability and competition for resources are important factors in determining the conditions in which optimal efficiency can be achieved (Sennhenn et al., 2017), especially in multi-species environments. Crop modeling has become an important technique for understanding the interaction between the environment, phenotype, and genotype in cropping systems, as such traits are sometimes difficult to quantify in the field alone (Hammer et al., 2010).

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1.9 Thesis conceptual framework

The thesis framework outlines the flow input, output, and flow of this research and thesis. This is divided into seven chapters comprised of two cropping season experiments, each of which answers five of the specific research objectives. Three different sources of biochar (groundnut shells, poultry manure, corn cobs), inorganic fertilizer recommended rate of 90N60P60K and a half rate of recommended rate of 45N30P30K, and rice-cowpea intercrop. The amendment enhances plant growth and yield, improves quality, and increases NUE and uptake. Nutrient increases availability, and reduce loss. Other reduce GHG emissions, C sequestration. Soil properties physical improve hydraulic characteristics aggregate stability and soil structure, increase porosity and reduce bulk density. It increases pH and CEC nutrient contents to reduce heavy metals. Biologically it favors microbial habitat and increases microbial population and activities. Below is the experimental flowchart of the work process (figure 1.1).

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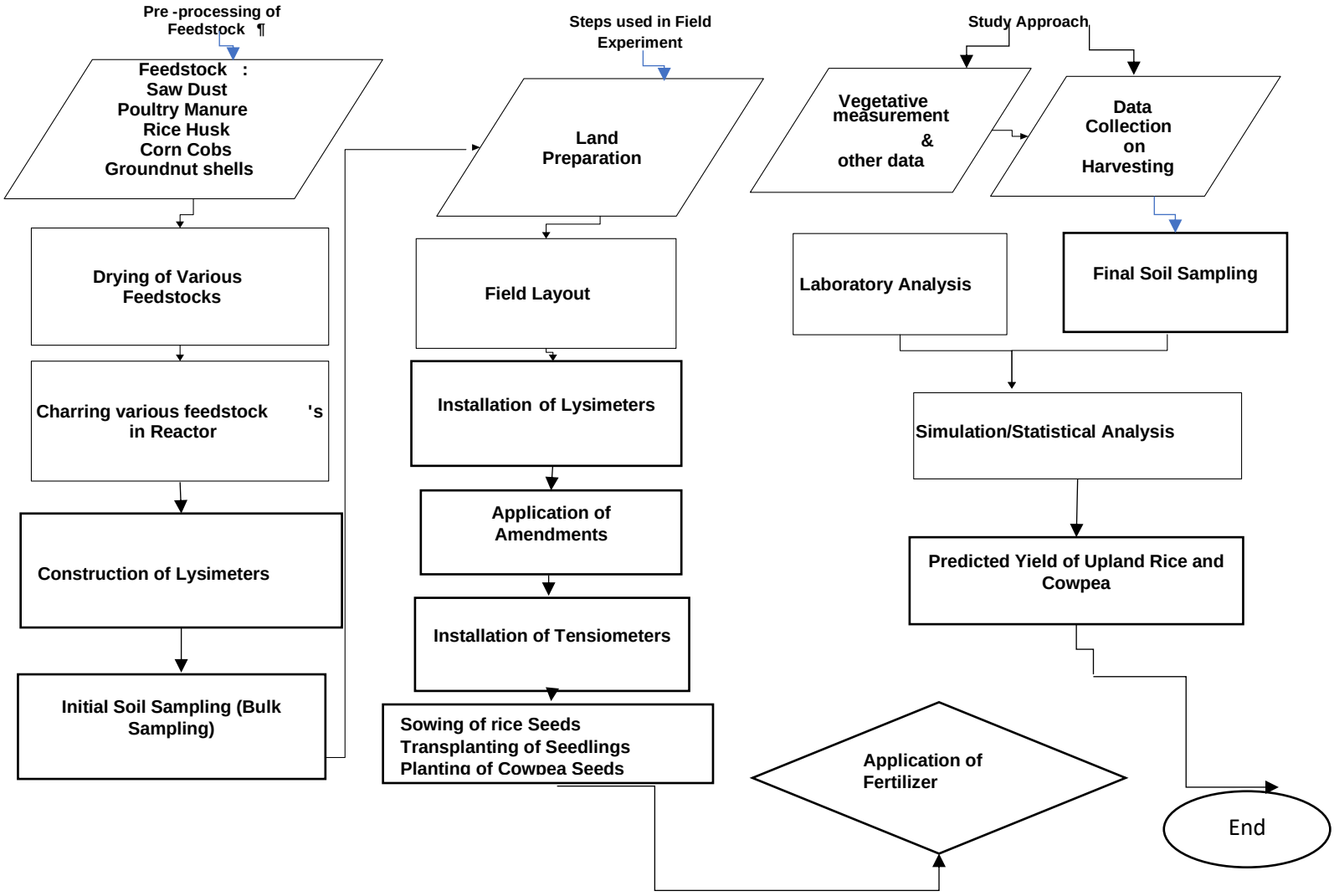

Figure 1.1: Experimental flowchart of the work process

1.10 General Methodology

1.10.1 Description of the study area

Nyankpala is located in the inner Guinea Savannah Agro-Ecological Zone, between latitude 9º 25'14" and longitude 0º 58'142", at an elevation of 183 m above sea level, with annual unimodal rainfall ranging from 800 to 1100 mm, beginning in April-May and ending in September-October (Kombiok et al., 2005). Grasses and a few shrubs make up the majority

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of the natural vegetation. Its average minimum and highest temperatures are 25 and 35 degrees Celsius, respectively. Its soil is made up of Voltaire sandstone and belongs to the Nyankpala series (ferric Luvisols and Plinthic Acrisol; (FAO, 1988). In the top 30 cm of arable soil, there is 66.7% sand, 27.3% silt, and 6% clay, with a pH of 4.4 (CaC_{l2}), 0.5 percent organic C, 0.3 percent total N, 18.3 mg kg^{-1} available P, 36.6 mg kg^{-1} available K, 158 mg kg^{-1} Ca, 18.4 mg kg^{-1} Mg, 3.8 cmol kg^{-1} CEC, and 26% base saturation. At a shallow depth of around 45 cm, ferric Luvisols have an iron pan that is impermeable to rainwater and can only be broken through. The texture of the surface soils ranges from sandy loam to loamy sand, but silty clay loams are widespread, with gravel percentages as high as 20% in some soils. Internal drainage issues plague the soils, which are classified as moderate to well-drained. When the impervious iron pan is removed, the top arable soil becomes well-aggregated and aerated (Fosu et al., 2004). According to Asamoah et al. (2013), crop performance is poor in northern Ghana. Ferric luvisol is responsible for marked seasonal hunger, low body weight, and systematic malnutrition in all sections of the population. In many of the low-density areas, shifting cultivation seemed to be dominating, but bush-fallow has recently taken its place. Millet, sorghum, pulses, cowpeas, maize, rice, groundnuts, and guinea yam

grow well on these soils. Small-scale farming of cassava, cocoyam, and sweet potatoes is common in riverine areas (Blench and Dendo).

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1.10.2 Nyankpala iron pan formation

The phrase "hardpan" refers to dense layers of soil that are typically found beneath the topsoil. Hardpan is classified into many categories based on soil structure, pH, and particle size, all of which are hard and water-resistant. The fusing and binding together of soil deposits ranging from dissolved silica to matrix made of iron oxides and calcium carbonate results in some hardpans. When it's made of iron oxides, it's called an iron pan. Others are generated by repetitive plowing, which causes man-made compaction. The soils of Nyankpala, such as those in the interior savannah and transitional zones, are formed atop shale rich in iron, which is responsible for the formation of iron pans in the subsoils (Asamoah et al., 2013). With hardpans, there are several challenges and routes to take. Hardpan obstructs water drainage, limiting the growth of plant roots. To allow water to drain, the hardpan is mechanically broken up by digging, ploughing, or soil amendments, especially at the commencement of development. Soil amendments are used to change the soil structure and avoid the formation of hard pans. Manure, compost, and peat amendments have been shown to improve soil organic matter, local drainage, and the number of earthworms that can break up hardpan over time. The pH of soils with problematic hardpans can be raised with lime and gypsum. The actions of hard salts of iron, calcium carbonate, and sodium, which enhance mobility through a higher pH while providing an adequate source of material exchange, can assist in removing clay particles from one another in a hardpan (the gypsum). Despite not being "soft," gypsum salts are permeable to water due to their bigger and more open structure. The process of breaking up a hardpan with soil amendment takes a long time and has few guarantees of success. The extent and intractability of the hardpan are critical to success (Grischow and Weiss, 2011; Malinda, 2002).

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1.11 Study area

1.11.1 Experimental design and field Layout

Two seasonal experiments were carried out on the Nyankpala series (Ferric Luvisol) (FAO, 1988) at Farming for the Future, U.D.S Nyankpala, near Tamale in the Northern Region of Ghana. It is located 600 km north of Accra (latitude 9.40750N and longitude 0.853330W) and climatic weather was observed in the study during the 2018 and 2019 cropping seasons (Figure 3.1). The treatment includes a control (no input), fertilizer, and cowpea intercrop, either applied alone or in combination with the three different sources of biochar. Biochar levels were 5 t ha^{-1} each and were incorporated into the soil at the same time. Inorganic fertilizer was applied at a rate of 90, 60, 60, and 45 kg ha^{-1} NPK as straight fertilizer and then top-dressed with nitrogen levels in the form of urea at a rate of 30 kg ha^{-1} N after eight (8) weeks of transplantation. Three cropping patterns and planting competitiveness indices (sole rice, sole cowpea, and rice + cowpea). A 57 m x 18 m (1026 m^2) plot was demarcated in the field (Figure 3.2). Four blocks were demarcated where plots were 12 m^2 (4 m x 3 m). The experimental design was randomized complete blocks (RCBD) with four replications (figure 1.3). Rice-cowpea intercrop plots were treated with Roundup (Glyphosate) of 300 ml per knapsack as pre-emergence and Gramoxone (paraquat) of 200 miles per knapsack post-emergence herbicides and hand weeded thrice during the season. The nursery seed bed was prepared to a finer tilth to allow uniform crop establishment. One fifty (150) seeds per square meter were drilled at a row spacing of 20 cm and sow seeds 2- 4 cm deep. Biochar that preceded the experiments was incorporated in early May 2017 for the nursery. The applied biochar was incorporated into the 20 cm surface soil layer. Short duration (85 days) upland rice (Nerica 14) (*Oryza sativa L.)* was transplanted by hand and erect cowpea (padituya) type (*Vigna unguiculata L. W*), respectively, was sown on the next day. Rice seedlings were

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transplanted at a spacing of 20 cm by 20 cm at the rate of 75 kg ha^{-1} in a sole crop, cowpea seeds were planted at the rate of 25 kg ha^{-1} at the spacing of 60 cm by 20 cm in pure stand. The space between any rice row and any of the cowpea rows was 60 cm apart. EmaStar 112 EC (Emamectin benzoate 48 g^{-1} + Acetamipride 64 $g^{-l)}$ 10 mls per knapsack was used to treat aphids and spittle bugs on the rice-cowpea intercrop plots. The cowpea was harvested at three months, while the rice was harvested at four months after planting.

The combination of the rice and cowpea was in a 3:1 ratio (half rice and half cowpea). Data on yield components were collected in the field, whereas yield was calculated using net plot area. Grain parts were analyzed for nutrient uptake and total nitrogen concentration using the micro Kjedahl method (Adjei-Nsiah et al., 2019; Emmanuel et al., 2020).

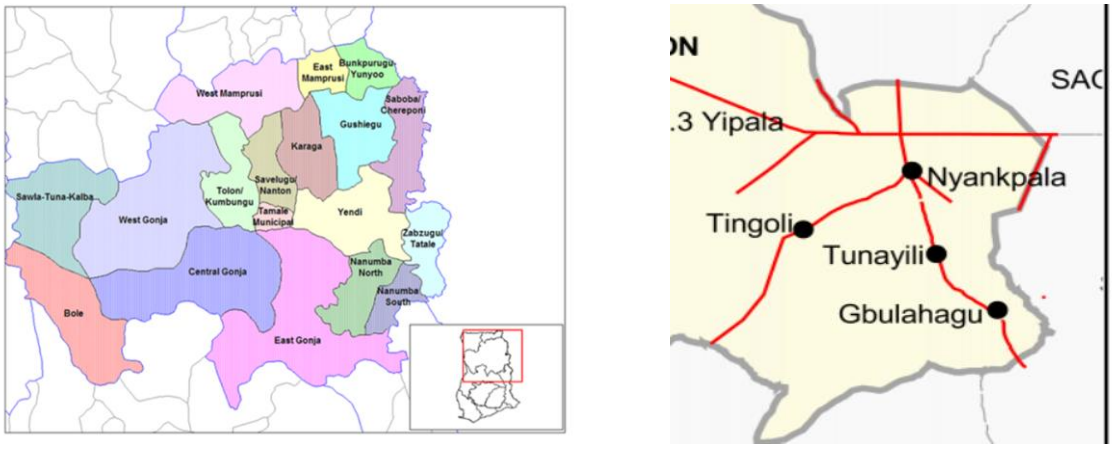

Figure 1.2. Farming for the Future, U.D.S Nyankpala near Tamale in the Northern Region of Ghana and soil type.

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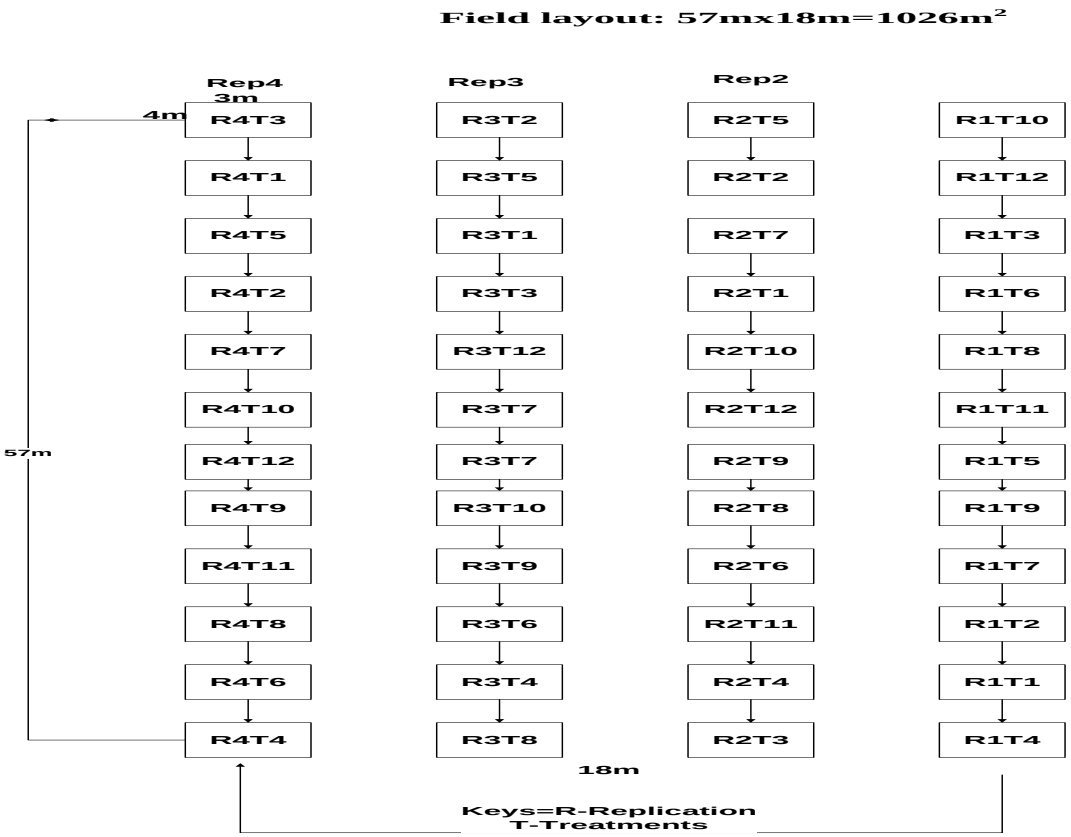

Figure 1.3: Experimental layout in randomized complete block design

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Table 1.1. Soil profile parameters used in this study

Soil Layer	**1**	**2**	**3**	**4**	**5**
Layer thickness (cm)	0-15	15-30	30-60	60-90	90-120
Soil water parameters					
BD ($g\ cm^{-3}$)	1.58	1.62	1.57	1.59	1.57
SAT (mm^{-1})	0.354	0.358	0.368	0.342	0.339
DUL (mm^{-1})	0.202	0.204	0.201	0.198	0.132
LL15 (mm^{-1})	0.050	0.106	0.153	0.128	0.198
Soil-C parameters					
OC (%)	0.47	0.41	0.33	0.38	0.33
pH (H_20)	4.66	4.66	4.66	4.56	4.56
finert[a]	0.36	0.36	0.70	0.90	0.90
fbiom[b]	0.016	0.02	0.02	0.01	0.01
Soil P parameter					
Labile P ($Mg\ kg^{-1}$)	11.6	5.8	5.0	2.0	1.0
P sorption ($mg\ kg^{-1}$)	60	80	150	180	200

Soil parameterization of ferric Luvisols at farming for the future, UDS experimental farm to specify APSIM simulations. LL, lower limit; DUL, drained upper limit; SAT, saturated volumetric water content; BD, bulk density; OC, organic carbon; Fbiom, a non-inert fraction of microbial C; and Finert, the inert fraction of organic C.

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Table 1.2: Studies used for model calibration and evaluation

References	Year/ soil series	Treatments	Crop/Cultivar	Measured
Frimpong-Manso 2018	2018 ferric Luvisol	Three different sources of biochar and inorganic fertilizer	Upland rice-Nerica 14 Cowpea-Padituya	LAI, crop biomass, straw, yield, plant uptake, soil moisture, nutrient use efficiency
Frimpong-Manso 2019	2019 ferric Luvisol	Three different sources of biochar and inorganic fertilizer	Upland rice-Nerica 14 Cowpea-Padituya	LAI, crop biomass, straw, yield, plant uptake, soil moisture, nutrient use efficiency
Frimpong-Manso 2019	2018 and 2019 ferric Luvisol	Five soil layers (depth)	Bare soil	Soil temperature

1.11.2 Climatic weather during the cropping Season 2018-2019

In the wet season of 2018–2019, Table 1.3 depicts the study area's seasonal water balance. In 2018–2019, the total rainfall was 133.29 mm, while the total evapotranspiration was 37.10 mm. The upland rice was planted in June of 2018 and 2019 and harvested in November of the same year. From July through October, 61.81 mm of rain fell, while 3.07 mm of evapotranspiration (Table 1.3). During the rice growth phase, from July to August, the table shows a favorable moisture balance. From July to August, rainfall increased and evapotranspiration decreased dramatically. However, because the September rainfall was lower, there was a slight water deficit after August. During the upland rice growing season, there was a drought. As a result, biochar amended had a higher yield than non-biochar amended. The significant drop in average temperatures during the upland rice plant's growth phase (Table 1.3) also contributed to a decrease in evapotranspiration, which favored the rice plant.

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Table 1.3 shows a summary of the climatic weather observed at the study site during the 2018–2019 cropping season.

MONTH	RAINFALL Mm	EVAPO RATION Mm	SOLAR RADIATION gm-cal / cm^2 /day	TEMPERATURE MIN ^0C	TEMPERATURE MAX ^0C	RELATIVE HUMIDITY MIN %	RELATIVE HUMIDITY MAX %
January	2.75	0.965	19.12	27.71	25.93	25.58	30.86
February	0	1.30	20.88	30.2	29.82	32.66	31.78
March	25.22	6.36	23.92	32.45	37.58	52.57	46.41
April	15.45	3.21	19.55	26.72	36.54	43.08	78.25
May	7.82	13.86	25.85	43.75	58.3	43.0	79.0
June	11.52	3.27	19.38	24.89	33.25	62.89	89.57
July	13.96	0	19.11	24.57	31.18	69.1	90.86
August	21.61	0	18.55	24.03	30.41	69.78	91.46
September	13.42	1.28	21.42	27.62	50.81	83.85	60.9
October	12.82	1.79	22.75	29.38	45.44	79.07	60.84
November	4.45	2.29	19.57	24.08	35.47	47.95	87.45
December	4.3	2.80	19.29	19.51	35.85	28.79	59.78
Total	133.32	37.13	249.39	334.91	450.58	638.32	807.16

(Frimpong-Manso, 2021)

1.11.3 Preparation of biochar

Three different sources of feedstocks were produced from slow and high pyrolysis of groundnut shells, corn cobs, and poultry manure at 400°C - 700°C with a dwelling time of 24 hours under oxygen-limited conditions in a reactor, followed by water and air cooling of charred feedstock to room temperature before grinding. Dry weights and chemical characteristics of the biochar applied are shown in Table 1.4.

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Table 1.4: Basic biochar properties used for simulations

Feedstock	Pyrolysis Temperature oC	pH 1:5	C.E.C me/100g	N %	P %	K %	C/N ratio (-)	Fraction C (0-1)
Biochar Corn cobs	High	6.67	118.26	0.95	0.21	0.45	11.0	0.129
Biochar Poultry manure	high	9.29	125.63	2.19	0.5	0.47	10.5	0.324
Biochar Groundnut shells	Low	11.13	85.52	1.34	0.13	0.74	12.3	0.243

CEC-cation exchange capacity, N-nitrogen, P- phosphorus, K-potassium, C-carbon

1.12 Methods APSIM and biochar model

The APSIM cropping systems model is made up of sub-models (models), each of which may independently simulate various soil, crop, and management processes. This model can simulate soil processes such as water dynamics, soil temperature, and nutrient cycling (nitrogen and phosphorus cycle and availability in soils), as well as their interaction with different crops and management practices (fertilization and amendment) (Ahmed et al., 2019; Nezomba et al., 2018). The APSIM framework's adaptable design allows sophisticated simulations and new modules to be developed. The biochar module is a sub-model developed in the APSIM framework (Dokoohaki et al., 2018) to provide a dynamic, processed-based simulation of the effects of biochar on soil and crop operations. This module was adopted by the APSIM committee and integrated into the official APSIM 7. The biochar module uses a two-pool exponential decay function model to estimate daily carbon degradation as a result of microbial activity. The labile pool reflects the more susceptible proportion of total carbon in biochar to mineralize, whereas the recalcitrant pool is made up of more recalcitrant carbon (Archontoulis et al., 2016). Water, nitrogen, and temperature amendments are also used to arbitrate biochar decomposition under limiting conditions. To directly limit biochar decomposition, APSIM's water and temperature amendments on the rate of soil organic carbon decomposition were employed, while a new function was

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constructed to account for the influence of nitrogen (N) limitation on biochar decomposition rate (Archontoulis et al., 2016). In this module, the net nitrogen mineralization and immobilization were estimated by making comparisons between the total amount of N required for biochar decomposition and the amount of N released during biochar decomposition, and both quantities were estimated as a function of the C: N of different soils and biochar pools. The main idea behind estimating changes in soil CEC is that, given the biochar mass fraction, this variable may be approximated using a weighted average of biochar and soil CEC. Soil CEC can also be estimated based on the percentage of clay in the soil, SOC, and soil order. A user-defined liming value for biochar, as well as the soil CEC, were used to determine the soil's buffering capacity and change in pH.

1.13 Soil sampling and preparation

Samples were collected to a depth of 30 cm over the experimental area and then bulked for laboratory examination to characterize the soil. The soil samples were air-dried, then pulverized with a wooden mortar and pestle in the laboratory before being sieved through a 2 mm mesh. The sieved samples were taken to the Soil Research Institute in Kwadaso-Kumasi and preserved in polythene bags for laboratory chemical and physical analyses.

1.14 Soil chemical analysis

1.14.1 Soil pH

A Cyberscan pH meter with glass electrodes (H19017 Microprocessor) was utilized to monitor soil pH with a soil-to-water ratio of 1:2.5, according to the methods described by IITA (1979).

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1.14.2 Organic carbon in soil

Nelson and Sommers (1983) reported on the modified Walkley-Black method for determining soil organic carbon.

Calculation:

Soil organic carbon content was calculated as:

$$\% \text{ O.C} = \frac{M\ X\ 0.39\ Xmcf\ x(v1-v2)}{s} \qquad 3.1$$

where

M=molarity of ferrous sulphate solution

V_1=ml of ferrous sulphate solution required for blank

V2=ml of ferrous sulphate solution required for sample

S=weight of air-dry sample in grams

Mcf= moisture correcting factor $\frac{(100+\%\ moisture)}{100}$

0.39 =3x0.001x100 % x 1.3(3=equivalent weight of carbon)

1.3 = a compensation factor for the incomplete combustion of the organic carbon.

1.14.3 Total nitrogen

Total nitrogen was determined by the Macro-Kjeldahl method (Bremner, 1965). Calculation:

The nitrogen proportion in the sample was articulated as:

$$\% N = \frac{(M\ X(a-b)\ x\ 1.4\ x\ mcf}{S} \qquad 3.2$$

Where

M = concentration of hydrochloric acid used in titration

A= volume of hydrochloric acid used in the sample titration

b=volume of hydrochloric acid used in the blank titration

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s= weight of air-dry sample in grams

mfc= moisture correction factor $\frac{100+\%\ moisture}{100}$

1.14.4 Bray's No. 1 phosphorus (available phosphorus)

The readily acid-soluble forms of phosphorus were extracted using an HCl: NH_4F mixture known as Bray's no.1 extract, as described by (Bray and Kurtz, 1945) and (Olsen, 1982).

Calculation:

$$P(mg\ kg^{-1}) = \frac{(a-b)x\ 35\ x\ 15\ x\ mcf}{S} \qquad 3.3$$

Where

a = mg 1^{-1} Pin sample extract

b = mg1^{-1} P in blank

s = weight of air-dry sample in grams

mcf = moisture correcting factor $\frac{100+\%\ moisture}{100}$

35 = volume of extracting solution

15= final volumes of sample solution

1.14.5 Determination of available potassium

The Gallenkamp flame analyzer was used to assess the amount of potassium that was extracted using Bray's no. 1 solution.

Calculation:

$$K\ (mg\ kg^{-1}) = \frac{(a-b)x\ 35\ x\ mcf}{S} \qquad 3.4$$

a= ųgK ml^{-1} in samples

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b = ųgK ml^{-1} in blank

s = weight of air-dry sample in grams

mcf = moisture correcting factor $\frac{100+\%\, moisture}{100}$

1.14.6 Exchangeable cations

In a 1.0N ammonium acetate (NH_4OAc) extract, exchangeable bases (calcium, magnesium, potassium, and sodium) in the soil were measured.

1.14.7 Extraction of the exchangeable bases

A 5 g soil sample was placed in a leaching tube and leached with 100 ml of buffered 1.0N ammonium acetate (NH_4OAc) solution at pH 7 for 30 minutes.

1.14.8 Determination of calcium

An Erlenmeyer flask was used to transfer a 25 ml quantity of the extract. The following ingredients were added: hydroxylamine hydrochloride (1.0 ml), potassium cyanide (1.0 ml of 2% solution), and potassium ferrocyanide (1.0 ml of 2% solution). 4 ml of 8M potassium hydroxide and a spatula of murexide indicator were added after a few minutes. To get a purely blue color, the solution was titrated with 0.01N EDTA solution. The value of the titer was recorded once more.

1.14.9 Determination of calcium and magnesium

Exchangeable Ca and Mg were determined by inductively coupled plasma atomic emission spectroscopy (Shimadzu ICPS 2000).

Calculation:

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Exchangeable Calcium (cmol of Ca (+) kg^{-1} soil) =

$\frac{V1-V1}{V3}$ x V4 x N x $\frac{100}{W}$ x mfc 3.5

V_1 = volume of EDTA required for sample aliquot titration, ml

V_2 = volume of EDATA required for blank titration, ml

V_3 = volume of aliquot taken, ml

V_4 = total volume of original NH_4 OAc extracts, ml

N = normality of EDTA

W = weight of sample taken in g

mcf = moisture correcting factor $\frac{100+\%\, moisture}{100}$

Exchangeable Calcium + magnesium (cmol of Ca (+) kg^{-1} soil) =

$\frac{V5-V6}{V7}$ x V4 x N x $\frac{100}{W}$ x mfc 3.6

V_1 = volume of EDTA required for sample aliquot titration, ml

V_2 = volume of EDATA required for blank titration, ml

V_3 = volume of aliquot taken, ml

V_4 = total volume of original NH_4 OAc extracts, ml

N = normality of EDTA

W = weight of sample taken in g

mcf = moisture correcting factor $\frac{100+\%\, moisture}{100}$

1ml 0.01 N EDTA =0.2004 mg Ca^{2+}= 0.1216 Mg^{2+}

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1.14.10 Exchangeable potassium and sodium determination

Sodium and potassium in the extract were determined by atomic absorption spectrophotometry as described by (Schueler and Thomas, 1933).

Calculations:

Exchangeable K (cmo1kg^{-1}soil) = $\frac{(a-b)x\ 250\ x\ mcf}{10\ x\ 39.1\ x\ s}$ 3.7

Exchangeable K (cmo1kg^{-1}soil) = $\frac{(a-b)x\ 250\ x\ mcf}{10\ x\ 23\ x\ s}$

Where

a = mg l^{-1} K or Na in the diluted sample percolate

b = mg 1^{-1} K or Na in the diluted blank percolate

s = weight of air-dry sample in grams

mcf = moisture correcting factor $\frac{100+\%\ moisture}{100}$

1.14.11 Exchangeable acidity

Exchangeable acidity was determined by first extracting with potassium chloride (1 m KCL) and titrating the extract with sodium hydroxide as described by (McLean, 1965). The total of Al^{+} H was used to calculate exchangeable acidity in a 1.0M KCl extract, as reported by (Thomas and Page, 1982).

Calculation:

Exchangeable acidity (cmo1kg^{-1} soil) = $\frac{(a-b)XM\ X\ 2\ X100\ X\ mcf}{S}$ 3.8

Where

A = ml NaOH used to titrate a sample

b = ml NaOH used to titrate blank

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M = molarity of NaOH solution

s = weight of air-dry sample in gram

2 = 50/25 (filtrate/ pipetted volume)

mcf = moisture correcting factor $\frac{100+\%\, moisture}{100}$

1.14.12 Effective cation exchange capacity (ECEC)

Effective cation exchange capacity (ECEC) was calculated as the sum of the exchangeable cations (K, Ca, Mg, Na) and the exchangeable acidity. Particle size analysis was conducted by the pipette method as described by Gee and Bander (1986); Heneberg, 2004; Klute, 1986).

1.15 Soil physical analysis

1.15.1 Soil texture

The hydrometer method was used to determine the soil texture. A total of 40 g of soil was weighed into a 250 ml beaker and oven-dried overnight at 105 ^{O}C. The proportions of coarse silt, medium silt, fine silt, and clay were then graphically estimated. The texture was determined using the textural triangle and the various components were expressed in percentages.

1.15.2 Bulk density

The core method developed by (Blake and Hartge, 1986) was used to assess bulk density in the field at depths of 0–15 cm and 15–30 cm. Undisturbed soil was sampled using a cylindrical metal sampler with a diameter of 5 cm and a length of 15 cm. The soil sample was carefully retrieved from the core after it was driven to the specified depth (0 –30 cm).

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The soil was then weighed, dried for two days at 105 degrees Celsius, and reweighed. The bulk density was calculated as follows:

$$P_b = \frac{Ms}{Vt} \quad 3.9$$

Where

Pb = soil bulk density (gcm^{-3})

Ms. = mass of the oven-dry soil (g)

Vt = total volume of soil (cm^3)

1.16 Characterization of soil and organic materials used in the experiments

1.17 Chemical analysis

The pH, organic carbon, N, P, and K of the soil and organic materials utilized in the experiment were determined using the protocols outlined in sections 1.7 to 1.7.12.

1.17.1 Plant analysis

1.17.2 Plant sampling and preparation

Rice grain and straw samples were collected at harvest and stored in paper envelopes before being oven dried at 60 °C for 48 hours and milled to pass through 20 mesh sieves.

1.17.3 Total nitrogen

The Kjeldahl method, which involves digesting plant material with concentrated sulphuric acid and hydrogen peroxide using selenium as a catalyst, was used to quantify total H_4^+ formed from the organic nitrogen that was present (Baker and Thompson, 1992).

Calculation:

$$\%\ N\ D\ M^{-1} = \frac{(a-b)x\ M\ x\ 1.4\ x\ mcf}{S} \quad 3.10$$

where

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a = volume of 0.1 M HCI used for sample titration

b = volume of 0.1 M HCI used for the blank titration

M = molarity of HCI

1.4 = 14 X 0.001 X 100 % (14 = atomic weight of N)

s = weight of sample in gram

The dichromate-acid oxidation method was used to determine the organic carbon content of organic materials. In an Erlenmeyer flask, 10 ml concentrated sulphuric acid, 10 ml 0.1667 M $K_2Cr_2O_7$, and 10 ml concentrated orthophosphoric acid was added to 0.5 g of organic material. After adding water, the solution was allowed to rest for 30 minutes before being titrated with 1.0 M $FeSO_4$ solutions using diphenylamine as a diphenylamine indicator. The following equation was used to compute the organic carbon content:

$$\% C = \frac{M\ X\ 0.39\ X\ 10{-}3\ X\ (a{-}b)}{s} \qquad 3.11$$

Where

M = Molarity of $FeSO_4$

a = volume of $FeSO_4$ solution required for blank titrated

b = volume of $FeSO_4$ solution required for sample titration

s = weight of oven–dried sample in grams

0.39 = 3 x 0.001 x 100 % x 1.3 (3 = equivalent weight of carbon)

1.3 = compensation factor allowing for incomplete combustion

1.17.5 Determination of phosphorus and potassium

Plant N content was analyzed by distilling the NH3 from the digested material (Thomas et al., 1967). Plant P and K concentrations were quantified by the molybdenum blue color method and flame photometry, respectively.

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1.18 Agronomic data collected and method of data collection

A. Crop growth

Height of the plants (cm) at 21, 42, and 63 (maturity) days intervals. The number of tillers hill^{-1} at 21, 42, and 63-day intervals, Leaf area index at maximum tiller Canopy cover at maximum tiller Time of flowering and maturity.

i. For both rice and cowpea, plant height was measured in centimeters (cm) from ground level to the tip of the awn from five randomly selected plants.
ii. By counting the number of headed tillers per stand apart from the parent plant, the number of effective/productive tillers was obtained from five randomly selected plants.
iii. Using the meter rule, the length of the spikelets was measured from the base of the panicle to the tip.
iv. Counting the number of spikelets per spikelet of five randomly selected plants was done.
v. Five plants were selected at random and the number of seeds per spikelet was counted.
vi. From ten (10) randomly selected cowpea plants, the number of pods per plant, pod length (cm), and the number of seeds per pod were also obtained.
vii. The harvested plot was also used to calculate aboveground biomass yield (t ha^{-1}), grain yield (t ha^{-1}), and thousand-grain weight (g). When the leaves turned yellowish-brown and the pods started to dry up at the tip, cowpea grains were considered

mature.

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Viii. To count and evaluate nodules, the cowpea was exposed to destructive sampling. The crop biomass and grains were sun-dried and threshed before data collection on cowpea and rice grain yields. Before weighing the grains, the moisture content was corrected to 13 percent.

B. Yield and yield components length of panicle (cm)

Number of fertile spikelets panicle^{-1}

Number of sterile spikelets panicle^{-1}

Mass of 1000-grains (g)

Grain yield (t ha^{-1})

Straw yield (t ha^{-1})

Biological yield (t ha^{-1})

Harvest index (%).

1.19 Procedures for documenting data in detail

During the study, the following data recording procedures were used:

A. Crop growth characters

i. Height of the plant (cm)

At 21, 42, and 63 (maturity) days after transplanting (DAT), as well as at maturity, plant height was assessed. The distance between the soil surface and the tip of the leaf height before heading and the tip of the panicle after heading were used to determine the plant's height.

ii. A number of tillers hill^{-1} (no.)

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At 21, 42, and 63 DAT, the number of tillers hill^{-1} was counted and expressed as the number of hill^{-1} from 10 randomly selected hills for the experiment.

iii. Leaf area index (LAI) and canopy.

The ACCUPAR model LP-80 is a light, portable linear photosynthetically active radiation (PAR) sensor that measures canopy PAR interception and computes leaf area index (LAI) at any point inside a plant canopy.

$$CC=1-exp^{(-kxLAI)} \quad 3.12$$

Where

CC is canopy cover, K is extinction coefficient and LAI is leaf area index. The values of the extinction coefficient for rice are between 0.4 to 0.7 (Hay and Walker, 1989).

iv. Time of flowering

When 50% of the blooms in a plot emerged, the time of flowering (days) was recorded.

B. Yield and yield components

i. Panicle length (cm)

The length of each panicle was measured from the rachis's basal node to the apex. An average of 5 panicles were selected for each observation.

ii. Fertile spikelets panicle^{-1} (%)

If a spikelet had a kernel, it was deemed fruitful. The total number of fertile spikelets present on five panicles was counted and averaged.

iii. Sterile spikelets panicle^{-1} (%)

Sterile spikelet refers to the absence of any kernel inside, and such spikelets were counted and averaged on each of the ten panicles.

iv. Mass of 1000-grains (g)

A total of 1,000 cleaned dried seeds were counted arbitrarily from each sample using a seed counter and weighed with a digital electric balance at the stage when the grain retained 14 percent moisture and the mean mass was calculated in grams. The moisture content of the harvested grains was measured using a moisture meter called PM 600. However, the moisture content of the paddy or the grain was first monitored on the field using a digital 95 moisture measuring meter called SATAKE at the laboratory.

v. Grain yield (t ha^{-1})

Grain yield refers to the mass of cleaned and dried grains harvested from a unit area. For rice, grain yield is usually expressed either in kilograms per hectare (kg ha^{-1}) or in metric tonnes per hectare (t ha^{-1}) at 14 % moisture (Gomez and Gomez, 1984). Grain yield was determined from the 1 m^2 plots and expressed as t ha^{-1} and adjusted to 14 % moisture basis. Rice was regarded mature when the spikelets turned straw-colored and 80 percent of the grains were in the hard dough stage. Grain moisture content was measured by using a digital moisture meter (PM 600). Adjustment of grain mass to 14 % moisture was calculated using the formula:

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Adjusted grain mass=A x W 3.13

Where

A is the adjustment coefficient and W, the mass of the harvested grains. The coefficient, A can be computed using the formula (Gomez and Gomez, 1984):

A=100-M/86

Where M is the moisture content (%) of the grains.

vi. Straw yield (t ha^{-1})

The straw yield was determined from the 1 m^2 areas of each plot. After separating grains, the sub-samples were oven dried to a constant mass and finally converted to t ha^{-1}.

vii. Biological yield (t ha^{-1})

Grain yield and straw yield were together regarded as biological yield. The biological yield was calculated with the following formula and expressed as %:

Biological yield (t ha^{-1}) = Grain yield (t ha^{-1}) + Straw yield (t ha^{-1})

viii. Harvest index (%)

It denotes the ratio of economic yield (grain yield) to biological yield and is calculated with the following formula (Gardner et al., 2017, 1985):

Harvest index (%) = Grain yield/Biological yield x100

1.19.1 Legume nodulation

At 20 and 50 days after sowing (DAS), the roots of ten (10) randomly selected plants from each plot were examined for nodulation (Chapagain and Riseman, 2014; Etany et al., 2016; Toukabri et al., 2021). The earliness, total number, color, and distribution of the root nodules

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were all measured. Nodulation was visually evaluated as indicated. According to Birnbaum et al. (2017), scores ranging from 0 to 5 were assigned based on nodule number, size, color, and distribution. The mean nodule score per treatment was then calculated by averaging.

1.19.2 Competition indices

To determine the advantages of intercropping and the impact of interspecific competition among intercropped species, the land equivalent ratio (LER), Land Equivalent Coefficient (LEC), and relative crowding coefficient (K) were calculated. This was computed based on the rice grain yield and the component crops cultivated under the three different biochar sources and inorganic fertilizers. In intercropping trials, these mathematical indices can be used to summarize and analyze the inter-plant competition.

1.19.3 Land equivalent ratio

The first criterion was LER, which was used to demonstrate the advantages of single and mixed cropping over the others among the various species (Donyavian et al., 2018; Tang et al., 2021). In comparison to monocropping, it is used to demonstrate the effectiveness of intercropping in resource consumption in the environment (Glaze-Corcoran et al., 2020). In other words, LER can be utilized to identify intercrop complementarities between species (Li et al., 2020; Tang et al., 2021). A unitary value serves as the LER reference value. Intercropping is better than sole cropping in terms of growth and yield of both species if the LER value is greater than one. An LER value of less than one implies that the interaction has a

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negative effect on the species in the mixture (Li et al., 2020; Tang et al., 2021; Yu et al., 2016). LER was estimated using (Willey and Osiru, 1972; Yu et al., 2016),

as; LER = LER rice (A) + LER cowpea (B);

where, LER rice = $(\frac{Y\,A\,I}{Y\,A\,S})$and LER cowpea = $(\frac{Y\,B\,I}{Y\,B\,S})$ 3.14

Where YAI and YBI are yields of rice and cowpea in the intercrop respectively while YAS and YBS are the sole crop yields of rice and cowpea respectively.

1.19.4 Land equivalent coefficient (LEC)

A measure of interaction concerned with the strength of a relationship in terms of mixture productivity is the land equivalent coefficient (LEC). Because LEC, also known as productivity coefficient (PC), is a superior index for evaluating crop mixture performance, it was chosen. The minimum predicted productivity coefficient (PC) for a dual-crop mixture is 25%, implying that a yield advantage is realized if the LEC value surpasses 0.25.

It was calculated as,

LEC = La x Lb 3.15

Where, La = LER of main crop and Lb = LER of intercrop (Adetiloye and Adekunle, 1989; Raza et al., 2019; Tesfahun, 2020).

1.19.5 Crowding coefficient (K)

Furthermore, the relative crowding coefficient was one of the indices used to calculate the intercropping competition effect. In multiple cropping, the crowding coefficient is used to determine the relative dominance of one species over another (Layek et al., 2018;

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Neamatollahi et al., 2013; Tesfahun, 2020). When the value of K is more than 1, there is a yield advantage, when K is equal to 1, there is no yield benefit, and when K is less than one, there is an intercropping disadvantage. The relative crowding coefficient K was established using species "a" and "b" for legumes and grains, respectively, intercropped in a 1:1 ratio as follows (de Wit et al., 1960; Layek et al., 2018)

Kab = $\frac{Yab}{Yaa-Yab}$ and Kba = $\frac{Yba}{Ybb-Yba}$ 3.16

where K = relative crowding coefficient

Kab = relative crowding effect of the rice-cowpea intercropping

Kba = relative crowding effect of the cowpea-rice intercropping

Yab = yield of rice intercropped with the cowpea

Yba = yield of cowpea intercropped with rice

Yaa = yield of the rice in monocropping

Ybb = yield of the cowpea in monocropping

1.19.6 Economic benefits of intercropping

The economic advantage of the intercropping system was assessed using the monetary advantage index (MAI) to provide information on the economic benefits of intercropping. Because the LER only shows the yield advantage of intercropping over sole cropping, it does not allow for a comparison of the system's economic benefits. The cropping systems' economic advantages were compared as follows: The monetary advantage index (MAI) was computed using the following formula:

MAI = (value of combined intercrops) x (LER - 1) / LER**.** 3.17

The higher the MAI number, the more profitable the cropping system (Sarwar et al., 2008; Tesfahun, 2020; Yaqub et al., 2010).

1.19.7 Nutrient use efficiency (NUE) and their application

The difference in the nutrient of interest between the fertilized and control plots was used to calculate nutrient use efficiency (NUE). The NUE was calculated using physiological efficiency (PE), agronomic efficiency (AE), and crop recovery efficiency (RE). The PE, defined as grain yield per unit of nutrient uptake, refers to a plant's ability to convert a given amount of an acquired nutrient into grain yield. The AE refers to the increase in crop yield per unit of applied nutrients. The RE, on the other hand, describes the increase in nutrient uptake by plants per applied unit of nutrient. The following formula was used to determine these nutrient use efficiencies for various N, P, and K treatments: Daradjat et al. (1991). As the example of N

$$PE_N = \frac{grain\ yield}{N\ uptake}\ (kg\ kg^{-1})$$

$$AE_N = \frac{\text{grain yield Ndose} - \text{grain yield at N0}}{\text{applied N dose}}\ (kg\ kg^{-1}) \qquad 3.18$$

$$RE_N = \frac{\text{N uptake at applied Ndose} - \text{N uptake at N 0}}{\text{applied N dose}}\ (\%)$$

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In the above equation expressions, the uptake of a nutrient means its uptake in the above-ground biomass and was expressed in kilogram per hectare; the applied dose of a nutrient means its rate of application and was also expressed in kilogram per hectare; and N0, P0, and K0 imply the omission of the respective nutrients.

1.20. Statistical analysis

All collected data were analyzed following the analysis of variance (ANOVA) technique using STATISTIC 10.

1.21 Overview of the thesis

The study contains ten chapters. Chapter one gives the general introduction, including a description of the APSIM Model, problem statement and justification, research objectives, questions, and hypotheses as well as the limitation of the research. Chapter two is all about previous works and findings in line with this study on rice-cowpea plant growth, development, and yield, biochar on soil characteristics, Intercropping's benefits, Inorganic nitrogen fertilization, Leaching losses, crop modeling of rice and soil nitrogen module. Chapter three, however, contains the study of subheadings including, the introduction, materials, and methods for data collection as well as the description of the study areas; results and discussions, and conclusion. Chapter four is a write-up titled “Assessing APSIM upland rice, biochar, and soil nutrient model in the Guinean savanna zone (Nyankpala), Ghana’’. Chapter five contains a study on simulating plant growth response to biochar applications on upland rice-cowpea intercrop and inorganic nitrogen and phosphorus on a ferric Lixisol soil in Ghana. Following this, chapter six is on the effect of biochar on water retention

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and leaching of nutrients in sandy loam soil. Chapter seven is on, “Influence of biochar and inorganic fertilizer on upland rice-cowpea intercrop competitive indices”. Chapter eight “effect of biochar used in a rice-cowpea intercrop system on soil hydrological properties. chapter nine- the impact of biochar on soil water retention, growth and yield of upland rice-cowpea intercrop”. The last chapter (nine) contains the general discussion, conclusions, and recommendations for all the sub-topics studied.

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CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 The effect of biochar on the properties of soil

The physicochemical, hydrological, and biological properties of the soil, as well as their responses to agricultural production inputs and harsh weather conditions, are indices of soil health and fertility. Soil chemical properties such as pH, CEC, base saturation percentage, plant nutrient availability, and soil organic matter all play a role in soil fertility and crop development. Biochar has a high potential to neutralize with acidic soils because it is alkaline (Atkinson et al., 2010; Castaldi et al., 2011; Jien and Wang, 2013; Van Zwieten et al., 2010), for example, established a pH change from 5.2 to 6.7 in the soil, seeded with maize throughout two growing seasons, with further biochar changes of 3 and 6 kg. The oxidation of aromatic carbon and the formation of carboxyl groups on the biochar surface may raise the CEC of the altered soil (Buss et al., 2012; Haider, 2016) and other studies; (Laird et al., 2010) found a 20 percent rise in CEC and a 69 percent rise in soil organic carbon 500 days after biochar accumulation in a clay loam soil. Water infiltration, aeration capacity, and root development are all influenced by the bulk density of the soil. Biochar is porous by nature (Atkinson et al., 2010; Chia et al., 2015; Joseph et al., 2009; Sohi et al., 2010; Verheijen et al., 2010) and has a large surface area, which can help reduce soil bulk density after soil alteration (Laird et al., 2010; Oguntunde et al., 2008). Soil aeration and porosity may be improved as a result of biochar modification, increasing soil water holding capacity (Busscher et al., 2010; Githinji, 2014). During the first and second years of the following biochar addition, (Tammeorg et al., 2014) discovered increased plant-accessible water content in the topsoil (20 cm) and decreased soil bulk density. Using *Leucaena leucocephala*

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(Lam.) biochar at 0 and 5 percent in acidic Ultisol, (Tsai and Chang (2020); Jien and Wang, 2013) found a significant reduction in soil bulk density from 1.4 to 1.1 Mg m^{-3}, saturated hydraulic conductivity, and soil aggregation. Soil stability and aggregation can be improved by using biochar (Heikkinen et al., 2019; Wang et al., 2017; Yoo et al., 2020).

2.2 Effects of biochar on soil hydrology

Soil biochar modification can affect soil hydrology, leading to significant changes in soil-plant-water supply and ecosystem processes (Ahmed et al., 2019; Haider, 2016; Walters and White, 2018; Yoo et al., 2020). Mechanical alterations to soil quality Compaction, soil infiltration, and drainage all have an impact on soil structure (Basso et al., 2013), it increases the soil water content and water holding capacity improve water use efficiency in agricultural soils (Basso et al., 2013; Jeffery et al., 2011), the available water content of plants and the amount of water retained in soil between field capacity and permanent wilting point plays a significant role in soil water retention curve (Cornelissen et al., 2013; Haider et al., 2015; Laird et al., 2010; Mulcahy et al., 2013); (Basso et al., 2013; Cheng et al., 2008; Joseph et al., 2010). The effects of biochar on soil infiltration and drainage may vary depending on the pore size distribution of biochar and differences in biochar pore size after oxidation, familiarity with field conditions, or field maturation (Brewer et al., 2014; Sorrenti et al., 2016), as well as soil porosity, varying in texture from clear sand to clayey, biochar pores may become clogged (Brewer et al., 2014; Masiello et al., 2015; Sorrenti et al., 2016). The potential of biochar to hold up to tenfold more water content than its weight, depending on its feedstock and production method, is regarded as the most essential benefit of biochar application for rainfed agriculture (Brockhoff et al., 2010; Jeffery et al., 2011; Kinney et al., 2012; Sorrenti et al., 2016). However, sawdust biochar has been shown to have a water

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retention capacity of 1-3 times its weight, which is still significantly higher than sandy soils. Wood biochar has a high water-holding capacity. It is important to evaluate the water-holding capacity of soil-desirable biochar blends rather than just raw biochar (Masiello et al., 2015). As a result, the potential for increased water-holding capacity in various soils after the accumulation of specific biochar is determined by both biochar and soil parameters. Additionally, not all biochar modifications may result in increased water-holding capacity (Haider et al., 2015; Major et al., 2009; Rex et al., 2015; Verheijen et al., 2019) or plant-available water content (Haider et al., 2015; Major et al., 2009; Rex et al., 2015). Atkinson et al. (2010), expect that biochar changes in sandy soil could increase the available water content. According to (Kameyama et al., 2012; Sun and Lu, 2014) biochar change in soils improved the plant's available water content in several tests. The hydrophobic properties of biochar may have a direct impact on soil water holding capacity or plant available water content (Gray et al., 2014; Verheijen et al., 2019). Additional treatments to oxidize tars and other hydrophobic chemicals may be required for some biochars, particularly low-temperature biochars (Rios et al., 2018). According to Verheijen et al., 2019, there was no increase in plant-available water content, which they attributed to the hydrophobicity of biochar. To review, biochar effects on soil moisture cannot be generalized because different biochars have different effects on the hydrology of different soils in terms of infiltration and drainage, water holding capacity, plant available water content, and soils with low water affinity. Plant growth in biochar-changed soil under situations of water scarcity is the final test, and other factors such as fertilizer application can be ruled out.

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2.3 Effects of biochar on nitrogen dynamics in the soil

Nitrogen is the most constraining nutrient in crop yield (Li et al., 2021; O'Neill et al., 2021; Prommer et al., 2014). The four primary patterns in the soil are soil organic matter (humus and plant material), soil microbes and other creatures, ammonium ions held by soil organic matter and clay minerals, freely available NO_3^- and NH_4^+, and (low) nitrite (NO_3^-) concentrations in the soil solution (Clough and Condron, 2010; Pan et al., 2013). (Prayogo et al., 2014) Willow (*Salix viminalis*) biochar (470 °C) prevented N mineralization in clay loam soil by containing 2.87 and 0.24 percent C and N, respectively. Plant residue decomposition was reduced in loamy soil after a change in wood biochar (oak, 400 °C) (Awad et al., 2017; Dempster, Gleeson, et al., 2012; Dempster, Jones, et al., 2012) reported decreased soil organic matter breakdown and N mineralization following the application of Jarrah (*Eucalyptus marginata*) biochar in a coarse-textured soil under incubation conditions in another study. However, the poultry litter biochar significantly increased N mineralization in two soils with higher soil organic matter (9 and 16 g C kg^{-1}, respectively) (Ameloot et al., 2015).

Adding pine chip biochar to both soils resulted in significantly increased N immobilization, according to the same study. Furthermore, the amount of N immobilized increased as the pyrolysis temperature increased (Ameloot et al., 2015). The impacts of biochar on soil organic matter turnover may be highly dependent on the organic material, circumstances of pyrolysis, and physical-chemical characteristics of biochar and the soil being studied (Stewart et al., 2013). Biochar's highly porous structure, which includes micropores, allows it to retain a significant amount of water as compared to sandy soil (especially when created at a higher temperature). It may provide labile organic carbon as a microbial feeding substrate following soil modifications (Liang et al., 2010), leading to an increase in microbial

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populations (Lehmann et al., 2003; Xu et al., 2014). Rice straw biochar (500 °C) had a significant impact on soil microbes in a greenhouse study (as evidenced by increased bacterial diversity and relative tax shifts), most likely due to changes in soil chemical properties influencing soil nitrogen cycling (C and N). Another study found that adding woody biochar (Oak, 0.5, 1, and 2%) to degraded red soil increased microbial biomass and enzyme activity (Demisie et al., 2014). Following 31 months of application in permanent grassland, Miscanthus straw biochar (550-600°C, 9.3 Mg ha^{-1}) increased almost 50% of total soil microbial biomass (Rex et al., 2015). In a broader and more long-term (6-year) field research, however, biochar alteration had no effect on the soil microbial population.

The soil microbial community structure was substantially altered when the same biochar alteration was combined with NPK fertilizers (Tian et al., 2016). Biochar's bioavailability of organic nutrient absorptions cannot be accurately predicted because feedstocks and pyrolysis conditions have a significant impact on the final biochar characteristics (Ippolito et al., 2020; Kloss et al., 2012). Plant- and manure-based (pine chip and poultry dung) biochars, according to (Ippolito et al., 2020), only preserved 27.4% and 89.6% of total feedstock nitrogen, respectively. As a result, the final N content of biochars is determined by the feedstock and pyrolysis temperature, which is not always available to plants (Ippolito et al., 2015). The sorption of nitrate has been observed in a range of biochars synthesized under varied experimental settings (Dempster, Jones, et al., 2012; Haider et al., 2015; Jassal et al., 2015; Kameyama et al., 2012; Kammann and Graber, 2015; Mishra and Patel, 2009; Mizuta et al., 2004; Yao et al., 2012). However, several research show that biochar modification has no effect on NO_3 retention. (Gai et al., 2014), for example, found no NO_3 adsorption after alteration with organic material derived biochar (400-700 °C, peanut shell, wheat, and

maize straw). Although several studies have reported reduced NH_4^+ leaching following a type of biochar alterations in field conditions (Güereña et al., 2013; Solaiman et al., 2020; Yuan et al., 2016), there have also been reports of no sorption retention following biochar alterations in field conditions (Güereña et al., 2013; Haider et al., 2015; Han et al., 2016; Solaiman et al., 2020; Yuan et al., 2016).

2.4 Effects of biochar on crop production

Increased crop yield is one of the most important and desirable outcomes of using biochar in agricultural soils (Harpole and Biederman, 2014; Holatko et al., 2020; Maroušek et al., 2019) However because claimed outcomes to date vary substantially under particular settings, there are still some questions about biochar's effects on crop yield. Biochar amendment in greenhouses, for example, has been shown to improve biomass and grain output in a variety of crops (Chew et al., 2020; Haider et al., 2015; Kammann et al., 2011; Liu et al., 2021; Wang et al., 2012; X. Zhao et al., 2014), or field conditions (Cornelissen et al., 2013; Genesio et al., 2015; Glaser et al., 2002; Glaser et al., 2015; Kimetu et al., 2008; Zhang et al., 2016). Biochar addition (30-60 Mg ha^{-1}) improved wheat biomass (30%) and grain yield in a silty loam under field conditions, with no difference in biochar addition rates (Vaccari et al., 2011). In temperate soils, beech wood biochar (550 °C, 24 and 72 Mg ha^{-1}) enhanced barley grain yield by 10% over the control (Karer *et al.*, 2013). Increases in biomass and grain production in various crops cultivated in various soil and environmental conditions were reported as improved water retention capacity and nutrient availability. Several studies have concluded that adding biochar to agricultural production has little effect. Biochar made from eucalyptus or maize stalks (550°C, 10 Mg ha^{-1}) had little influence

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on corn yield in fine sandy loam soil (Free et al., 2010). In a fertile sandy clay loam soil with wheat, faba bean (*Vicia faba*), or turnip rape (*Brassica rapa*) under field conditions, (Tammeorg et al., 2014) found no yield benefit from the later charcoal application. As a result, the consequences of applying raw biochar to enrich soil are unknown, while biochar's favorable impacts are mostly associated with extensively worn and sandy soils (Jien and Wang, 2013). Furthermore, biochar modification may harm crop development and yield (Asai et al., 2009; Lehmann and Joseph, 2015a). Rice grain yield was lowered by 27–35 percent in sandy soil after adding rice straw biochar (450 °C, 5 Mg ha^{-1}) (Ly et al., 2015).

Scientists discovered variable outcomes in another investigation using two distinct biochars (peanut hull and pine chip biomass, pyrolysis at 400 °C) applied at 0, 11, and 22 Mg ha^{-1} with or without nitrogen fertilizer. For example, even with nitrogen fertilization, peanut shell biochar lowered maize output at higher rates, whereas pine chip biochar linearly decreased maize yield only after the first year of application (Gaskin et al., 2010). Biochar has also been shown to have complex effects on crop productivity in several studies. For instance, (i) increasing biochar use resulted in lower crop yields (Asai et al., 2009); (ii) later in the first year of additional, adverse effects were observed (Borchard et al., 2014); (iii) after the first year of addition, the unfavorable effects faded and disappeared (Gaskin et al., 2010; Haider et al., 2017; Schulz and Glaser, 2012) and (iv) reduced biochar adding rates resulted in lower and higher rates of the same biochar (Chan et al., 2007). As a result, biochar modifications can have a variety of effects, which are mostly linked to its impact on soil, plant nutrients, and water relations, which can result in diverse outcomes depending on the circumstances.

2.5 Plant nutrition with biochar

Biochar can affect plant nutrition for a variety of reasons. P, K, Ca, Mg, and Na contents in biochar produced from *Lantana camara L.* at 300 °C, for example, were 0.64, 711, 5880, 1010, and 1145 mg kg^{-1}, respectively (Masto et al., 2013). Fresh biochar can also emit 23-635 mg kg^{-1} N and 46-1664 mg kg^{-1} P (Mukherjee and Zimmerman, 2013). However, the entire nutrient concentration in biochar may not be plant-available, and biochar nutrient contents are also influenced by variations in production temperature. This is especially true when it comes to the nutrient "nitrogen." While studying the effect of pyrolysis temperature (100–1100 °C) on the retention behavior of carbon, hydrogen, oxygen, and nitrogen, (Ding et al., 2016; Wang et al., 2020) reported that a drop-in biochar material began at 400 °C, leading to a 50 % loss at 750 °C of four herbaceous and three wood-based biochar. The conversion of biochar into heterocyclic N as the pyrolysis temperature rises causes a drop-in biochar N concentration and availability (Liu et al., 2022; Wang et al., 2020). Hence, biochar made from various feedstocks may contain variable nutrient concentrations, which fluctuate depending on pyrolysis conditions, resulting in varying plant availability. Biochar's physical and chemical properties are important in defining soil properties and hence enhancing soil fertility. The porous structure of biochar, according to evidence, enables more water retention, therefore boosting the most essential factor of water holding capacity, which is crop productivity (Lal, 2008; Lehmann and Joseph, 2015a, 2015b; Sohi et al., 2010). Biochar can significantly modify soil pH (Laird et al., 2010), resulting in changes in soil nutrient patterns (Ding et al., 2016), so boosting or decreasing nutrient availability. In volcanic ash soil, for example, biochar lowered soybean and maize yields significantly, with the yield drop attributable to biochar-induced changes in soil pH, which resulted in reduced micronutrient availability. Biochar modification improves the extractability of nutritional

elements such as Ca, Mg, Na, and K via increasing CEC (Ding et al., 2016; Laird et al., 2010). However, not all biochars improve soil physical and chemical properties, resulting in increased soil fertility and plant nourishment (Ding et al., 2016). Additionally, Biochar can reduce nutrient leaching (N, P, Mg, and Si) (Laird et al., 2010), N in the form of nitrate is especially important (Haider, 2016; Mandal et al., 2016), hence, plants have better access to nitrogen. For example, biochar modification increased the availability and uptake of P, K, Ca, Cu, and Zn by plants (DeLuca et al., 2015); (Lehmann et al., 2003; Major, Lehmann, et al., 2010; Major, Rondon, et al., 2010). Moreover, in acidic soils, biochar modification can neutralize pH, boosting P and decreasing aluminum (Al) availability (respective toxicity) to plants (Hammes and Schmidt, 2009). Recent research on biochar-compost mixes or the usage of biochar-compost found that biochar worked as a nutrient transporter after co-composting, and that using it in conjunction with organic fertilizers increased plant productivity (Glaser et al., 2015; Kammann and Graber, 2015). Numerous investigations have found that biochar modification improves N retention or reduces N availability, as well as limits absorption or immobilization (Dong et al., 2015; Güereña et al., 2013; Guo et al., 2014; Haider et al., 2015; Knowles et al., 2011; Lehmann et al., 2003; Major et al., 2009). The use of high-temperature wood biochar (> 600 °C) for N immobilization or NO_3^- sorption capture is the most common use. Biochar utilization has yet to yield a complete image of nitrogen cycle and soil nitrogen changes.

2.6 Ecophysiology of plants and biochar

The effect of biochar alternation on plant ecophysiological parameters has been assessed in a few types of research, according to (Kammann and Graber, 2015). Most investigations

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utilizing biochar changes focused on crop plant agronomic yields or soil parameters analytical of soil fertility. Nonetheless, this is a human-centered perspective, as increasing yield may be attractive to humans but not to plants in terms of long-term survival in their environment (Kammann and Graber, 2015). Following biochar change in Thale cress (*Arabidopsis thaliana* (L.) and lettuce (*Lactuca sativa L.*), higher biomass yield was achieved at the expense of decreased defense (Haider, 2016; Polzella et al., 2019; Simiele et al., 2021).

Understanding the impacts of biochar at the soil-plant interface may be aided by investigating plant ecophysiological solutions. Borah et al. (2020); Haider et al. (2015) are two of the few studies that have looked at the impact of biochar alone or loaded with highly alkaline and porous (HAP) on maize photosynthetic, water, and osmotic interactions under controlled settings. With biochar modification, significant improvements in plant ecophysiological parameters were found, resulting in higher biomass yield. The beneficial production gains and ecological physiological impacts of biochar are assumed to be mostly due to its water-saving properties (Haider et al., 2015; Singh et al., 2022). In another study, (Akhtar et al., 2014) discovered that under deficit irrigation, tomato physiology, yield, and quality improved, with more pronounced impacts in particular under partial root-zone drying irrigation in biochar-enriched soil under controlled settings. Under high day and night temperature treatments, rice husk biochar (900-1100 °C) amendment in combination with P in a silty loam soil increased rice photosynthetic efficiency and water use efficiency above the control (Fahad et al., 2016). Changes in biochar can affect plant physiology not just through interactions with soil-plant-water relationships, but also through nutrition. Wheat Na absorption, for example, was reduced as a result of adsorption onto the biochar surface,

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reducing salt stress in the crop (Akhtar et al., 2015). Biochar amendment may not necessarily have the same beneficial benefits on all species' physiology. Despite adequate salt sorption, altering Fagus grandifolia sawdust biochar (378 °C) did not increase water use efficiency, photosynthetic carbon gain, or chlorophyll fluorescence in two broadleaf herbaceous plants, *Abutilon theophrastus* and *Prunella vulgaris* (Al-Wabel et al., 2019; Thomas et al., 2013). Biochar was discovered in another study to lower phenolic acid concentrations in replanted soils (Chen et al., 2021; R. Wang et al., 2014), as well as enhance plant photosynthesis, height, and fresh biomass (Chen et al., 2021; R. Wang et al., 2014). In the same study, adding biochar to seedlings increased antioxidant activity (peroxidase, catalase, superoxide dismutase, and ascorbate peroxidase (Chen et al., 2021; Wang et al., 2014). Thus, depending on the biochar used, plant species, soil nutritional state, soil moisture, microbial population, and other ecological factors, the biochar amendment in distinct soils may generate different physiological effects.

2.7 Effects of biochar on carbon sequestration and emissions of greenhouse gases

Anthropogenic GHG emissions are the primary source of global climate change in 2014, due to fossil fuel use and land use change, as well as rising economic and population growth IPCC, 2014 (Pachauri and Meyer, 2014; Waheed et al., 2018). According to historical records, agriculture may have been the first man-made source of increasing GHG emissions (Crucifix et al., 2005; De Sy et al., 2019). Agriculture is responsible for 14 % of global GHG emissions in IPCC, 2014 (Pachauri and Meyer, 2014; Waheed et al., 2018). CO_2 emissions rank highest in terms of radioactive forcing and last in terms of global warming potential among GHGs (GWP). One kilogram of CO_2 has a GWP of one, but methane (CH4)

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and nitric oxide (N_2O) have GWPs of 25 and 298 times that of CO_2 after 100 years, respectively (Harwatt, 2019; Li et al., 2022). In the fast-reacting terrestrial global C cycle, the soil organic carbon pool is the most important reservoir (otherwise, the largest fast-responding pool is the CO_2 dissolved in seawater). As a result of its magnitude and rapid interactions with the environment, soil organic carbon might be a significant source or sink of GHGs (Lal, 2004; Muneesa et al., 2019). The transition from natural to managed ecosystems on arable farmed lands is a major source of CO_2 emissions from the soil's organic carbon store. Arable lands, on the other hand, can serve as C sinks if managed properly. Many solutions for enhancing soil fertility and crop performance, such as crop rotation, reduced tillage, cover crops, mulching, of late biochar modification to sequester C, have been proposed and tested (Adeyemi and Idowu, 2017; Lal, 2008; Paustian et al., 2019; Sainju, 2016; Xu et al., 2019). As a result of its resistance and good potential for sequestering carbon in soil and lowering other GHG emissions, biochar has been promoted as a promising strategy for climate change mitigation (Wang et al., 2016).

2.8 Sequestration of carbon

Carbon can be taken out of the atmosphere (vegetation) or abstracted from emission and deposited in geologic establishments, and terrestrial environments such as soils, deposits, plants, and the oceans. Soils have the largest terrestrial C pool after oceans, with between 1500 and 2400 Gt C (1 Gt (Gigaton) = 1 billion tons) at depths of 1-2 m (Zinn et al., 2018). On a global scale, this soil organic carbon pool is three times the current atmospheric CO_2 (830 Gt C) and 240 times the CO_2 emissions from yearly fossil fuel consumption (10 Gt) (Ciais et al., 2014; Scharlemann et al., 2014). As a result, even a small increase in soil carbon

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storage could result in a significant carbon sink (Paustian et al., 2019). A 10 percent shift (rise or reduction) in the soil organic carbon pool, for example, is comparable to 30 years of anthropogenic emissions and might have a significant impact on atmospheric CO_2 levels (Follett, 2001; Ramesh et al., 2019; Zhang et al., 2015). There are two strategies to increase the soil carbon sink's potential. For example, increasing organic matter inputs and reducing their decomposition rate can help increase soil carbon and decrease atmospheric carbon stocks (Paustian et al., 2019). Nevertheless, renewed organic elements (composts and slush) degrade quickly, and the inclusion of these materials does not immediately result in larger soil C stores (Bot and Benites, 2005; Rahardjo et al., 2021), because they are a living organic component that helps the soil biota. Soil organic carbon pools in general may benefit from a global decline in average yearly temperature (Chen *et al.*, 2020; Janzen *et al.*, 2018). However, at the moment, the exact opposite is taking place.

Biochar modification in carbon-deficient soils has emerged as a potential approach for carbon sequestration due to its resilience to microbial degradation and gaseous emissions (Kamau et al., 2019; Knoblauch et al., 2021). Although at least 50% of biomass C is considered resistant to degradation, roughly 40 % of biomass C is lost during pyrolysis, and around 10 % is lost during the first years after soil alteration due to the first mineralization of biochar (Han et al., 2020; Wiesmeier et al., 2018). For instance, different biochars have varied feedstocks and pyrolysis temperatures, therefore Pine biochar is a good example. The percent carbon loss of several biochars was researched, and it was determined that Cedar biochar (400 °C) lost the least amount of carbon (7 percent) and Eastern Gamma grass biochar (400 °C) lost the largest amount of carbon (100 %) (27 percent). At 650 °C, both biochars (Cedar and Eastern Gamma grass) lost 3 and 37 percent of their carbon after 100

years, respectively (Zimmerman, 2010). Some research, suggests that biochar modification to soils has essentially little effect on C loss. In a wheat field soil, wood biochar modification (30 and 60 Mg ha^{-1}) after 420 days, there were no substantial effects on carbon loss via CO_2 emission (Castaldi et al., 2011). Several studies have demonstrated that biochar is extremely resistant to weathering in soils (Lehmann and Joseph, 2015a, 2015b; Schneider et al., 2011).

Soil organic modifications (for example, adding biochar) can have priming or perceived priming effects on native soil organic carbon, which can be seen using spectroscopy (Wardle et al., 2008a, 2008b). These include both direct and indirect impacts on soil organic carbon mineralization increases and decreases after biochar alteration (Whitman et al., 2015). Biochar, for example, may have high-energy, high-density carbon, degradable organic compounds that, when added to the soil, might promote enhanced soil microbial proliferation and enzyme activity, resulting in the mineralization of a wide range of native organic matter (Luo et al., 2017; Whitman et al., 2015). Altering the pH of the soil with biochar may have an indirect effect on SOC mineralization. Luo et al. (2017), impose nutrient constraints (e.g., N, P) (Mukherjee and Zimmerman, 2013; Smebye et al., 2016; Sun et al., 2014; Zimmerman and Gao, 2013). significant changes in the fauna and microbiological habitat of the soil (Domene et al., 2015). Biochar, on the other hand, may cause changes in the substrate, resulting in a reduction in SOC mineralization (Chen et al., 2014). Due to its unique features and impacts on the altered soil, biochar modification may also reduce SOC mineralization indirectly. (1) Sorption of labile native SOC on the surface of biochar or within biochar pores, lowering the amount of time it takes for microbes to break it down (Heitkötter and Marschner, 2015; Prayogo et al., 2014); (2) SOC mineralization is influenced by sorption to biochar, which influences enzyme activity (Ladygina and Rineau, 2013; Zimmerman and

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Gao, 2013), (3) Organo-mineral interactions are influenced by ligand exchange, resulting in prolonged soil agglomeration and less SOC accessible for microbial decomposition (Kästner and Miltner, 2018; Kögel-Knabner and Amelung, 2021; Wang et al., 2022) and (4) if nutrient availability is restricted, microbial activity may be lowered. There are numerous potentials for increasing or decreasing soil organic carbon with biochar alteration, depending on the biochar, soils, and environmental circumstances. Research is required to determine the appropriate coupon for specific soils in order to raise soil organic carbon without preventing priming. Over the span of a few months to a few years, this part examined how soil organic carbon stocks responded to biochar alteration. Biochars, on the other hand, have been shown to contain refractory carbon that can be sequestered for up to 100 years in the soil (Kätterer et al., 2019; Leng et al., 2019; Xu et al., 2019; Zhang et al., 2018).

2.9 Advantages of Intercropping

The increase in yield per area of land is one of the key advantages of intercropping. In most tropical mixed cropping studies, more than one acre of the pure stand was required to achieve the yield of one acre of mixed crop, and there was no benefit to be gained by replacing the customary practice of mixed cropping for small-scale farmers in the tropics (Iderawumi, 2014; Iderawumi et al., 2018). Intercropping maize is one of the most widely used mixed cropping combinations in rain-fed agriculture in the tropics, according to reports. As a result, maize cultivation in combination with other crops is common in northern Ghana, particularly in the Northern Region. Intercropping legumes, okra, melon, pepper, and cassava with maize is rather widespread. When compared to maize as a single crop, systems that intercrop maize with cowpea can lower the number of nutrients extracted from the soil. Odhiambo and Ariga,

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2001, 2002 found that production increased due to reduced rivalry between species compared to competition within species when maize and beans were intercropped in varying ratios. Intercropping is also thought to be a cost-effective way to increase output while using fewer external inputs (Assefa et al., 2021; Bedoussac and Justes, 2010a, 2010b). This improved efficiency is critical, particularly for small-scale farmers and in places with short growing seasons. Higher Bedoussac and Justes, 2010a, 2010b; Gu et al., 2021; Yu et al., 2020; Hoffland et al 2020; Kuyper et al., 2020, Zhang et al., 2020; Samarappuli and Berti, 2018) growth rates, fewer weeds, fewer pests and diseases, and more efficient resource usage due to variances in resource use are all factors that contribute to producing more in intercropping (Eskandari, 2012a, 2012b; Eskandari and Ghanbari, 2009). Furthermore, if the intercropped components have "complementary effects," production will increase as the competition among them decreases (Nandhini and Somasundaram, 2020).

In an intercropping system, increased diversity in the physical structure of plants, such as leaves and roots, has several advantages. Once the crops are established, increased leaf cover in intercropping systems aids in weed control (Yasodha et al., 2021). Water loss is reduced, water intake is increased, and transpiration is increased by having a diverse root system in the soil. Increased transpiration may help to cool the soil and reduce evaporation by making the microclimate cooler (Gebregergis, 2016). Intercropped plants use a greater percentage of available water from the field than mono-cropped plants, which is significant during times of drought or water stress (Glaze-Corcoran et al., 2020). According to Seran and Brintha, 2010, rows of maize in a field with a shorter crop reduce wind speed above the shorter crops, reducing desiccation. By providing additional habitat for predatory insects and increasing

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the distance between plants of the same crop in intercropped fields, increased plant diversity may lessen the impact of pest and disease outbreaks. Intercropping has environmental benefits such as using less acreage for crop production, reducing inorganic fertilizer consumption, pesticide and herbicide use, and soil erosion (Tidåker et al., 2021).

Intercropping has many advantages for farmers, including lower farm input costs, the addition of cash crops, diet diversification, greater labor usage efficiency, and a lower risk of crop failure owing to weather uncertainty. The amount of time required to plant the various kind of seeds would be minimized, resulting in improved labor usage efficiency. When two or more crops are harvested at separate periods, peak labor requirements are spread out, allowing the smallholder to finish the harvest with family help (Bedoussac et al., 2015; Hong et al., 2019; Lulie, 2017; Snapp et al., 2019). For smallholders in northern Ghana, intercropping offers a significant amount of risk reduction. The farmer can still harvest the other crop in the field if the one is destroyed by pests or drought. Planting numerous varieties of the same crop in an intercropped field gives the farmer a higher chance that some crops will survive the unpredictable rainy season and the variable water requirements of each crop (Krah et al., 2019). Intercropping can reduce insect and disease damage, which is a significant advantage (Daryanto et al., 2020; Dwivedi et al., 2015; Frimpong et al., 2020; Mousavi and Eskandari, 2011). In general, according to Matusso et al.(2014), there are three kinds of solutions for reducing insect infestation and damage in intercropping. The first is the delimiter crop hypothesis, which states that the second specie weakens a pest's ability to attack its host and is more commonly found with proprietary pests. The second theory is the trap crop theory, in which the second species attracts a pest or pathogen that ordinarily harms the main species, and is more commonly utilized for general

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pests and pathogenic agents. The third hypothesis is the natural enemy's theory, which states that predators and parasites are more attracted to intercropping than monocropping and therefore parasitized and prey populations are reduced. Intercropping does not necessarily result in a reduction in pests (Mthembu et al., 2019). In a review by Mthembu et al. (2019), intercropping reduced pests in 53 % of the tests, while increasing pests by 18 %. Pests are becoming more prevalent for a variety of reasons, including the second crop acting as a host for pests in intercropping or increasing canopy shade, which promotes pest and pathogen activity. According to another study by Antar et al. (2021), plant leftovers can potentially be a source of diseases that have been inoculated. Plant pathogen spread can be slowed by increasing species diversity in agricultural areas. Similar to natural ecosystems, intercropping systems boost biodiversity. Pests and diseases are reduced as a result of the increased diversity (Antar et al., 2021).

2.10 The impact of intercropping on economic returns

Cowpea intercropping with rice has been shown to increase grain production per unit area of land (Akhter et al., 2019; Awad and Hm, 2020; Musah et al., 2013). In Northern Ghana, intercropping cowpea and open-pollinated rice could boost productivity and meet the demand for rice and legumes. A similar study was carried out on maize and groundnut, with the intercropped treatments producing higher yields (Dwomon and Quainoo, 2012; Quainoo and Dwomon, 2012). Low-growing legumes, on the other hand, have been reported as being overshadowed by taller cereals (Dawo et al., 2007). Low fertility conditions, poor emergence, and poor growth of intercropped legumes have all been recorded in smallholder systems, limiting nitrogen and organic matter contributions to farmers' fields to levels well

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below their potential (Begam et al., 2020; Matusso et al., 2014). Because much of the above-ground dry matter and practically plant nitrogen in the harvested crop leaves the fields. Plant nitrogen is reintroduced into the cycle as organic nitrogen after being returned to the soil as plant residue. The highly productive (high harvest index) grain legumes add relatively little organic matter and nitrogen to the soil (Namatsheve et al., 2021; Song et al., 2020; Vanlauwe et al., 2019).

2.11 The effects of intercropping on light interception

Resource capture and use efficiency of cropping systems, such as cowpea rice intercrops, are measured by light interception (LI) and light use efficiency (LUE). Light is very crucial when cowpeas are intercropped with tall crops like rice. In many field crops, cumulative intercepted Photosynthetically active radiation (PAR)and accumulated biomass have a linear relationship. The light use efficiency refers to the slope of this connection (Engbersen, 2021; Kar and Kumar, 2016). According to Wang et al. (2015) and Zi-kui et al. (2015), the improved product can be the consequence of increased solar radiation interception, increased light use efficiency, or a combination of the two species during the growing season. Growing two species together in one field can occasionally boost light interception, either due to a longer period of soil covered, which is a temporal advantage or due to a more comprehensive soil cover, which is a spatial advantage, as described by Chaves et al. (2020) and Gebru (2015). Because rivalry between component crops is limited, resource usage efficiency is unlikely to be influenced in intercropping systems with component crops that differ in the growing period. In intercrop systems, the proportions of incoming PAR absorbed by component crop canopies are primarily determined by leaf area index and canopy structure

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(Gong et al., 2020; Kukal and Irmak, 2020). Although these principles are well understood (Chimonyo et al., 2015; Gou et al., 2017; Kukal and Irmak, 2020), it is also difficult to figure out how much light component crops in intercrops are capturing. Several studies have shown that cowpeas suffer from shadowing when grown alongside grain (Nelson et al., 2018; Wang et al., 2018). Cowpea grows and yields more when more light is transferred to them.

2.12 Intercropping effects on soil fertility maintenance.

One of the most difficult aspects of agricultural production is maintaining soil fertility. Intercropping is one of the choices for keeping soil fertility and crop yields high. According to Maitra and Ray (2019); Maitra et al. (2020); Matusso et al. (2014), cowpea intercropping has an impact on soil fertility maintenance through N fixation and plant uptake differences. Once the intercrop is harvested, decomposing roots and falling leaves provide nitrogen and other nutrients for the next crop. When the intercrop remains on the field and is plowed under after harvest, the intercrop's residual effect on the next crop is greatest. However, (Kermah, 2020; Kermah et al., 2018) reported that a significant amount of nitrogen is lost in the grain harvested. Soil depletion might still occur if the nutrients taken up by the plants are not replaced with manure or fertilizer. The intercropping technique not only provides nitrogen and other nutrients to the linked crops, but it also adds humus to the soil. This improves the soil structure, lowering the requirement for soil tillage while also minimizing water loss, soil erosion, and nutrient leaching.

2.13 Fertilization with inorganic nitrogen

Intensive farming systems, which rely heavily on high fertilizer inputs to maintain production, are common in modern agriculture. Inorganic fertilizers containing primarily N,

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P, and K, as well as mixtures of these nutrients, can be used to maintain or boost yields in conventional crop cultivation. Fertilizers are organic or inorganic materials that can be put into the soil to boost the availability of critical components for plant growth (Hossain et al., 2017; Itelima et al., 2018). The primary goal of inorganic fertilization is to improve crop production by increasing soil fertility in one of two ways: first, by increasing direct nutrient availability to crops, resulting in increased biomass production and organic matter returns to the soil; and second, by increasing soil fertility in one of two ways. This increases the porosity, infiltration, and hydraulic conductivity of the soil while lowering the bulk density (Demir et al., 2019; Dong et al., 2022). Second, by improving nutrient cycling, we can indirectly increase soil fertility. The chemical composition of the soil solution can be influenced by fertilizers, which have an impact on nutrient cycling by regulating the population and activity of soil microbes. The impact of fertilization and residue retention on several elements of crop yield and soil quality has been the subject of numerous research studies. Different cover crops and organic amendments on soil structure (Demir et al., 2019; Dong et al., 2022) reported that soil organic matter (SOM) content was 15 % greater in fertilized plots than in non-fertilized groups. In the long-term continuous wheat experiment at Rothamsted, a robust linear relationship between annual fertilizer used and SOM accumulation was also seen (Rodrigues et al., 2021; Saljnikov et al., 2022; Sharma et al., 2020) reported that long-term use of inorganic fertilizers can have a significant impact on SOC distribution. NPK fertilizer use is beneficial in maintaining active C and N pools in the top layers of the soil surface (0–15 cm depth), which helps to maintain C-associated nutrients in the rhizosphere, which increases nutrient availability. Atakora et al. (2014); Bua et al. (2020) and Droppelmann et al. (2017) also reported that after 50 years in the Ghana long-

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term maize trial in Sub-Sahara Africa, SOM depletion was higher in unfertilized and imbalanced treatments (NP, NK, PK) than in those fertilized with NPK. In a similar case, (Ghosh et al., 2018; Zhang et al., 2016) reported more than a 75 % increase in soil microbial biomass C on fertilized treatments compared to the control (zero fertilizer).

2.14 Denitrification and volatilization

Denitrification is a chemical reaction in which NO_3 is converted to NO_2 and then to nitrous oxide (N_2O), nitric oxides (NO), and dinitrogen gas (N_2), all of which are lost to the atmosphere. In the absence of oxygen, soil microbes employ NO_3^- and NO_2^- as electron acceptors, which is typical in saturated soil (López-Aizpún et al., 2021). Because denitrification is dependent on microbial activity, soil water, and aeration are the elements most essential to controlling it. However, soil pH can also influence it (denitrifying bacteria). On the other hand, volatilization happens when nitrogen is lost when NH_4^+ is converted to ammonia gas (NH_3), which is subsequently discharged into the environment. Temperature, soil pH, water status, and NH_4^+ levels all have an impact on this process. These processes can result in significant N losses from the soil and low nitrogen use efficiency (NUE) in cropping systems, with plants unable to fully absorb N. Volatilization of nitrogen is also undesirable because of the possibility of contamination (López-Aizpún et al., 2021). According to Ramanantenasoa et al. (2019), agricultural practices account for nearly half of the NH_3 that is volatilized. The application of N fertilizers such as urea, the application of animal manure, and the mineralization of SOM and plant residues are all sources of NH_3 volatilization (Ramanantenasoa et al. (2019).

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2.15 Nitrogen uptake by crops

Crop nitrogen absorption is critical for lowering nitrogen losses and increasing crop nitrogen use efficiency (NUE). Crop stage, seasonal influences, soil water content, and the availability and uptake of other nutrients can all influence nitrogen intake. Nitrogen treatment timed to coincide with the crop's peak N uptake efficiency can improve N utilization efficiency (Lemaire and Gastal, 2018; Li et al., 2017). Increased NUE from optimal plant N absorption can help the environment by lowering the quantity of nitrogen that has to be applied and improving long-term agricultural production. Crop yield can be harmed by the use of luxury nitrogen. As a result of luxury N uptake, where biomass increases are not proportional to N consumption, increasing N application has been shown to lower NUEs, lowering biomass generated per unit of N ingestion (Lemaire and Ciampitti, 2020). However, if there is an excess of N uptake in rice grain, maturation might be delayed, and the grain, sugar, and content at harvest can be lower as a result (Anas et al., 2020; Antille and Moody, 2021). Most N is taken up in the initial stages of crop development in rice rather than in later stages, where fewer quantities are taken up. According to Wang et al. (2016); Yu and Zhang (2018) and Zhang et al. (2018), low NUEs in rice production contribute to a 65 percent loss of applied nitrogen through multiple channels, with only about 35 percent being taken up by crops.

2.16 Losses due to leaching

Many studies have shown leaching as the principal source of huge volumes of nitrogen (NO_3) loss in agricultural systems (Padilla et al., 2018; Wang et al., 2019). One of the most serious environmental consequences of agriculture is the leaching of NO_3 from the root zone into groundwater (Dash et al., 2016; Libutti and Monteleone, 2017; Mokari et al., 2019; Salo,

2019). Because nitrates are anions and are not adsorbed in soils with high cation exchange capacity, they are more prone to leaching when transported with percolating water below the root zone. In semi-arid environments, rainfall causes nitrate leaching, which is the most common N-loss mechanism for rainfed farming systems (Bibi et al., 2016; Libutti and Monteleone, 2017). Nitrogen can also be lost as soluble NH_4^+, which results in increased sorption of NO_3^-N rather than NH_4^+, especially in soils with high anion exchange capacity. Quantifying the interaction between nitrogen and water, as well as its impact on NO_3^-N leaching, can provide crucial information for appropriate nitrogen and water management. Different approaches have been developed to measure NO_3^-N leaching, but none of them has worked in every case. Routine soil sampling, active and passive samplers, drainage lysimeters, and field-scale drainage infrastructure are all examples of these procedures (Singh et al., 2018). Nitrogen application and the volume of drainage water moving out of the root zone have a strong relationship with nitrate leaching. It's notably tied to a history of over-applying nitrogen fertilizer to crops. It can be aided by periods of crop absence, such as during the minor (dry) season when there are no crops planted to absorb mineralized N, allowing it to be lost to percolating water.

2.17 Intercropping's effect on soil moisture conservation and water use efficiency (WUE)

Soil moisture is an important component in agriculture for increasing yields on crops. It is a result of the fact that water in the soil serves an important function in soils, including mineral weathering, organic matter decay, and chemical reactions that produce soluble nutrients in the plant-soil system, in addition to serving as a medium for nutrient translocation from plant roots to the soil (Namatsheve et al., 2021). The soil must retain a significant amount of water

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following rainfall. In rain-fed agricultural systems, soil water infiltration and storage in the root zone determine overall water availability and efficiency in crop production (Namatsheve et al., 2021; Xiao et al., 2016), and improving agricultural production will rely on efficient capture, management, and use of rainwater resources (Namatsheve et al., 2021; Zahoor et al., 2019). According to Sarkar et al. (2020), increasing water use efficiency in this system will result in increased resource use efficiency. Because of the higher leaf area index and bigger leaf area in the beginning, rice-cowpea intercropping has been identified as a water-saving crop (Etany et al., 2016; Namatsheve et al., 2021). Intercropping systems, according to Kocira et al. (2020), may encourage full utilization of farmland water by plant roots, boost root zone water storage, reduce inter-row evaporation and excessive transpiration, and generate a unique microclimate favorable to plant growth and development. According to Bekele et al. (2021); Ma et al. (2020) and Gao, et al. (2020), the soil moisture content in the soil was dramatically lower in the sole crop of maize than in the intercropped field, while soil moisture content in the soil was significantly higher in the sole crop of cowpea due to maize's higher evapotranspiration potential than cowpea. According to Miao et al. (2016); Mao et al. (2012) and Chai et al. (2011), intercropping cereal with legumes can help save soil moisture by providing enough soil coverage and reducing evaporative water loss, resulting in high water use efficiency by the component crops and higher yields. Water use efficiency is defined by agronomists as the crop yield per unit of water consumed. The increasing scarcity of and competition for water resources in agriculture is forcing us to create more water-efficient production techniques, particularly in rain-fed areas (Jafari Shalamzari and Zhang, 2018; Kansanga et al., 2019; Zhang et al., 2018). This can be accomplished by using crop management practices that reduce

evapotranspiration, surface run-off, and drainage, as well as effective nitrogen management that promotes rapid early crop growth, which shades the soil and reduces additional evapotranspirative losses (Chapagain, 2014; Etany et al., 2016; Jafari Shalamzari and Zhang, 2018) and breeding and selection to increase biomass for improved crop transpiration efficiency (Chapagain, 2014; Etany et al., 2016). Intercropping enhances water uptake and storage in root zones by stimulating crop growth that shades the soil, producing a protected climate, and lowers inter-row evaporation and excessive transpiration by promoting crop growth that shades the soil, creating a protected climate (Chapagain and Riseman, 2015; Etany et al., 2016). According to Chapagain (2014), the inherent WUE of wheat is improved when cultivated in an intercrop with the common bean. According to Macedo et al. (2021) and Singh et al. (2018), continuous rice farming and forage legume systems were the most productive and efficient in terms of water use. When soil water was not a constraint, (Sylvestre et al., 2021) discovered that water utilization efficiency in a rice-cowpea intercrop was higher than in sole crops. Under water-stressed conditions, however, the higher WUE of the intercrop relative to the sole cereal can result in slower growth and lower crop yields (Matusso et al., 2014; Mbava et al., 2020). Soil water retention capacity, water storage at the root zone, and crop water use efficiency all improve, allowing smallholder farmers to obtain high yields while working with limited water resources.

2.18 General description of rice

2.18.1 The rice plant

Rice developed from a semi-aquatic perennial ancestor, and the Gramineae family split up before grasses moved from the forest floor to more open settings (Ahmed and Ahmad, 2017; Bah, 2015; Vinod et al., 2019; You and Xiong, 2015). Rice, like other cereals such as wheat

and barley, is classified as a C_3 grass, but maize and sorghum are classified as C_4 grasses. C_4 species have a more effective photosynthetic pathway than C_3 species, which means they produce more biomass per unit of collected energy and per unit of transpiration. Rice's wetland heritage is evident in several physical and physiological traits that set it apart from other crop species. Shoot and root structure, water loss patterns, and growth responses to soil water status less than saturation are all key variations between rice and other cereals (Ahmed and Ahmad, 2017; Vinod et al., 2019). Rice leaves are typically narrow, with no palisade or spongy parenchyma differentiation of mesophyll cells. Stomata are 10 times more numerous than in the leaves of dry-land grasses. Stomata are tiny, and cultivars differ in their response to the environment. Rice cuticles are thin, with a wax content of less than 5% of that of other crops, and cuticular resistance is minimal. The cuticles on rice panicles are also thin. Panicle flowers lose approximately 30% of the water transpired by lowland rice after flowering. Rice is very vulnerable to water scarcity. Growth and yield formation are hampered when the soil water content falls below saturation (Tao et al., 2007; Tao et al., 2015). Leaf area expansion is inhibited in most cultivars when the soil dries below saturation, and in cultivars with aerobic adaptation when only around 30% of the available soil water has been taken (Datta et al., 2017; Ouyang et al., 2021; Ullah et al., 2019). When compared to other crops, stomatal closure begins at a higher leaf water potential, and transpiration begins to diminish progressively at around 0.75 MPa (Abdul-Ganiyu et al., 2016). Leaf rolling and rapid senescence are also induced by water stress (Esmaeilzadeh-Moridani et al., 2022; Zaman et al., 2018). Reduced light interception, as a result of reduced leaf area (due to reduced leaf growth, rolling, and senescence), lowers overall crop photosynthesis and thus total biomass

production. Closing stomata affects both transpiration and leaf photosynthesis, lowering crop radiation use efficiency and, as a result, total biomass production.

2.18.2 NERICA rice variety

Oryza sativa is grown all over the world and comes in two ecogeographic races: indica, which is suitable for the tropics, and japonica, which is adapted to temperate regions and tropical uplands, and *Oryza glaberrima*, which is produced in West Africa. *Oryza sativa*, which originated in China, India, and Thailand and is today an important food crop all over the world, may be traced back to the years 7000 BC (Cooper and Deakin, 2020; Nourollah, 2016). *Oryza glaberrima* is a plant that is only found in Africa, and it first appeared approximately 1500 years ago in the swampy basins of the upper Niger River delta in West Africa (Agnoun et al., 2012; Carney, 2020; Seck et al., 2012). NERICA (New Rice for Africa) was produced in the mid-nineties through crosses between *Oryza Glaberrima and Oryza sativa* species specially targeted at upland and dry-land areas of Sub-Sahara Africa (Asuming-Brempong et al., 2011; Dibba et al., 2012). As a leading specialist in many types of rice research in Africa, the Africa Rice Centre created NERICA (New Rice for Africa), which is the first worldwide success in crossing *Oryza glaberrima* with *Oryza sativa*. NERICA combines weed competitiveness, drought tolerance, resistance to local pests and diseases, and the capacity to thrive under low input circumstances with *Oryza Sativa's* high yield potential. Africa rice center has designated 18 upland NERICA varieties and 60 low-land NERICA varieties, which are all being evaluated on farmer's fields across SSA to see irrigation, agricultural machinery, fertilizers, high yielding variety of seeds (HYV), plant protection, research new techniques, marketing facilities, multiple cropping, price incentive,

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government efforts, other reforms, credit facilities, and land reclamation how well they perform and how well they tolerate biotic and abiotic challenges. NERICA cultivars were planted on 2000 acres over six years, assisting in the increase of rice production in SSA (Ahmed, 2019; Dawe et al., 2010).

2.18.3 Rice crop growth and development

Lowland (or paddy) rice is grown in fields with saturated soils and ponded water, whereas fields with well-drained soil are cultivated for upland rice, non-saturated soils, and no ponded water. Rice is grown all year in the tropics as well as in the subtropics and temperate zones during the summer. Rice is grown on puddled fields in the lowlands. Puddling is a technique that involves harrowing or rototilling in shallow water to eliminate weeds, reduce soil permeability, and make transplanting easier (Chareesri et al., 2020; Maclean et al., 2013). The land is leveled after puddling in wet weather. A typical vertical cross-section through a puddled rice field reveals a layer of ponded water measuring 0 - 0.10 m, a puddled, muddy topsoil measuring 0.10 - 0.20 m, a plow pan formed by decades or centuries of puddling, and undisturbed subsoil. Rice roots are typically shallow and enclosed inside the puddled layer (Maclean et al., 2013).

In most rice locations, transplanting is the most common method of crop establishment. Rice is grown in a separate seedbed before being harvested. Pre-germinated seeds are dispersed at a rate of 500 to 800 kg ha^{-1} into either flooded or wet soil surfaces in the nursery (Joint, 2018; Mahajan et al., 2017; Mboyerwa et al., 2021). Plant densities of 40–50 kg ha^{-1} are similar to seeding rates of 40 – 50 kg ha^{-1} at transplanting (12–25 days after establishment for contemporary cultivars, 40 days or more for traditional cultivars). Hand transplanting

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two to three seedlings into hills 0.15 to 0.30 m apart is standard procedure. Hybrid rice is often planted as one seedling per hill, but certain local cultivars are sown as five to six seedlings per hill. Depending on nutritional status, cultivar, and seedling density, each plant produces three to seven tillers. The number of grain-bearing panicles per m^2 in a good crop stand will be 400-600 panicles per m^2 in the dry season and 300-400 panicles per m^2 in the wet season (for common indica cultivars in the tropics) (Mahajan et al., 2017). Wet or dry seeding can also be used to establish rice in the field (by broadcasting pre-germinated seeds onto wet or flooded soil or sowing dry seeds in dry or moist soil). At a rate of 80 to 250 kg ha^{-1}, seeds are dispersed or sown in rows 20–30 cm apart (Mahajan et al., 2017). Direct seeding has become more popular in Asia in recent years. Seeds are frequently broadcast from airplanes in commercial agricultural fields in the United States and Spain. Rice cultivar and location determine the length of the growing cycle (from germination to maturity), which can range from 90 days for short-term modern tropical cultivars to 180 days for traditional or modern cultivars in subtropical and temperate regions. Changes in the time from germination to commencement of flowering (60 to 150 days) determine cultivar variances in growth duration, although the time from commencement of flowering to maturity is rather stable, lasting around 30 days in the tropics but can be as long as 60 days in the subtropics (Joint, 2018; Maclean et al., 2013), halting at average temperatures below the basic temperature for rice, which is tentatively established at 8 °C. Most tropical cultivars die when the average daytime temperature goes below 12 °C for more than three days in a row during the early vegetative development phase. When the temperature at flowering falls outside the range of 8 to 35 °C, the pollen is generally damaged. While many ancient rice

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cultivars are photoperiod sensitive (flowering is induced by shorter day lengths), most current high-yielding rice cultivars are not (Maclean et al., 2013; Mahajan et al., 2017).

2.18.4 Yield of rice

Rough rice with a moisture percentage of 14% is commonly used to express rice yield. The hull (approximately 20% by weight) and the whole grain are both included in rough rice. The outer hull is removed from brown rice, but the outer bran layers of the grain (11/17 percent by weight of rough rice) remain. Milling removes all or part of the bran and germ from rough rice, leaving only the germ and starchy endosperm (69 percent by weight of rough rice) (Mahajan et al., 2017). In Asia, country-average irrigated lowland rice yields range from 3 to 9 t ha^{-1} (rough rice), with an average of around 5 t ha^{-1}. Under continuously flooded conditions, modern tropical cultivars with a short duration (100-115 days) can yield 8 to 10 t ha^{-1} in the dry season and 6 to 8 t ha^{-1} in the wet season. In subtropical and temperate climes, good yields of long-duration (120-150 days) cultivars are around 12 tonnes ha^{-1}, with maximum yields of up to 17 tonne ha^{-1} reported (Yunnan province in China and Australia), though such purported record yields are sometimes open to doubt (Lyu et al., 2020; Nie and Peng, 2017). The only source of considerable yield gain in recent years has been hybrid rice, which has increased production potential by 5 to 15 percent over inbred cultivars in the same environment. Nepal's lowland rice yields are similar to Ghana's at 3.2 t ha^{-1} on yield. This is most likely due to water shortages and oxygen deprivation caused by flooding (Mahajan et al., 2017). In favorable conditions, rainfed lowland rice yields an average of 4-5 t ha^{-1}. However, yields are significantly lower when abiotic stressors (mostly drought) occur frequently, averaging just 2 t ha^{-1}. Upland rice yields are around 1 t ha^{-1}, but aerobic rice

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yields can reach 4 to 6 t ha^{-1} with a nitrogen application of roughly 90 kg N ha^{-1}. Cultivar, location, season, and growth circumstances all have an impact on the harvest index (HI). The HI of current, short-duration tropical cultivars ranges from 0.45 to 0.5 in the dry season and from 0.35 to 0.4 in the rainy season. Many long-duration cultivars grown in rainfed lowlands have an HI of around 0.35. In China, the HI of current hybrid rice is 0.4 to 0.5. Drought reduces HI, which in extreme cases can drop to near zero (Nie and Peng, 2017; Šebela et al., 2018; Surmaini et al., 2015).

2.18.5 Characteristics of rice varieties

Short, medium, and long-grain (kernel) kinds of rice exist (Abayawickrama et al., 2017; Roy et al., 2015a, 2015b). Classification of grain types is based on the length-to-width ratios of rice kernels. long, medium, and short-grain rice length-to-width ratios of paddy (raw rice), brown, and processed kernels.

2.18.6 Improved rice varieties in Ghana

Since the 1980s, Ghana has had twenty-seven rice cultivars officially released (Bissah et al., 2019). All of the types published are advanced cultivars from CSIR, Africa Rice Center, the International Rice Research Institute (IRRI), or other countries research institutes. The majority of varieties issued are for lowland rice ecologies, with highland rice ecologies being issued just in 2009. NERICA 1 through NERICA 14 (all from Africa Rice), Emo teaa (early maturing, long grain, all from Africa Rice), and Otoo mmo (all from Africa Rice) are all available for upland locations (resistant to weed and disease, from Africa Rice). In 1982–1986, six rice varieties, GRUG7, GR 18, GR 17, GR 19, GR 20, and GR 21, were released

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for lowland rice ecologies (Ragasa et al., 2013). 1–5% (80–500 t) came from Faro 15, Sikamo, Digang, WITA 7, and Bodia. Aromatic short, Jet 3, Togo Marshall, NERICA 1, NERICA 2, and IR 64 were among the types that had certified seed output of 1–40 t total over 11 years. In the last few years (2013–2019), many types have been authorized for seed production: CRI-Dartey, CRI-Kantinka, CRI-Oboafo, CRI-Emopa, CRI-Mpuntuo, CRI-Enapa, Legon Rice 1, CRI-Amankwatia, AGRA rice.

2.18.7 Upland rice-based cropping systems and the environment

Rice is grown in a variety of agro-ecological zones and ecologies, from irrigated or submerged conditions in coastal mangrove swamps and interior valleys to seasonally flooded plains, to completely rainfed uplands, thanks to its versatility (Defoer et al., 2004; Niang, 2019). In West Africa, there are three major manufacturing contexts. Upland rice, rainfed rice, and irrigated rice are the three types. With 39 % of the total rice-producing area, the upland ecosystem is one of the most important rice-producing habitats. Lowland rainfed rice accounts for 38 % of total production and is quickly expanding. Deepwater rice, mangrove rice, and irrigated lowland rice account for the remaining 23 % of the rice-growing area. Upland rice deserves special attention because of its size (1.8 million ha) and regional output (1.6 million t). Cropping systems differ according to the climate, land profile, and available resources (Callo-Concha et al., 2012; Kernecker et al., 2020; Sujatha et al., 2016; Tóth et al., 2020). Farmers are obliged to migrate from one location to another when their yields diminish due to decreased fertility and increased weed infestation. However, if population pressures are high, this system will collapse (Abah et al., 2017; Naab et al., 2013). Due to population growth and rising land problems, farming methods have evolved into

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fallow rotations with significantly shorter fallow periods. The length of the fallow period has increased from 15 -20 years in 2015 to 3–8 years today (mainly in the savanna zone). As a result, average upland rice yields have decreased by 25% (Saito et al., 2006; Saryoko et al., 2019; Zenna et al., 2017). Reduced organic matter and nitrogen supplies, rapid soil nutrient leaching, increased weed pressure, soil erosion, and degradation are all factors that have contributed to the drop-in yield. Due to a lack of resources to purchase inputs, farmers have not adjusted their agricultural patterns despite the rising demand on the land resource base. As a result, West African upland rice yields are projected to be less than 1 t ha^{-1} in 2020 (Center, 2011).

2.18.8 Major constraints to sustainable rice production.

To replenish fertility and avoid the build-up of insect pests and weeds in upland rice-based cropping systems, periods of bush fallow are still used (Fairhurst, 2012; Nadeem et al., 2019; Vanlauwe et al., 2015). According to recent surveys, fallow periods have shrunk so drastically in shifting agriculture that they no longer result in soil fertility restoration (Assigbé et al., 2012; Bado and Bationo, 2018; Hauchhum and Tripathi, 2019; Saito et al., 2006). This approach is no longer sustainable because of significant yield reductions, nitrogen depletion, and persistent weeds and pests. In the savanna zone, hand-weeding accounts for 40% of total rice labor (Paresys et al., 2018; Pokuaa, 2016). Rice yield losses of around 20% in the moist or Guinea savanna zone, 30 % in the forest-savannah transition or derived savanna zone, and 41 % in the forest zone are caused by current levels of land use intensification (Niang, 2019; Paresys et al., 2018; Pokuaa, 2016). Permanent highland cultivation leads to a significant loss in soil productivity and, as a result, poor crop yields in

low-input agriculture systems (Dobermann, 2004; Tsujimoto et al., 2009; von Arb et al., 2020). Nutrient losses as a result of poor management and nutrient depletion are the primary causes of degradation (Bünemann et al., 2018; Lal, 2015), resulting in a soil-type-dependent fertility reduction. According to Erskine (2021) and Sangakkara and Nissanka (2008), low-input but sustainable land-use strategies must be developed due to the current intensity of land use, the fragility of many upland soils, and the lack of resources available to smallholder farmers. Long-term upland rice productivity, on the other hand, is unlikely to be achieved with existing approaches, according to studies (Bruun et al., 2006; Erskine, 2021; Sangakkara and Nissanka, 2008). Rice production systems must be strengthened in a way that conserves resources while allowing for long-term productivity increases to meet rising food demand. New technological solutions must be cheap for smallholders and fit the demands and management skills of West African rice farmers without ignoring their perceptions and production goals to achieve adoption (Donkoh, 2020; Donkoh et al., 2019; Reij et al., 2013).

2.19 Modelling carbon and nitrogen dynamics in upland rice-cowpea intercropping systems

2.19.1 Crop modeling overview

Crop simulation models use mathematical equations to describe the results of interactions between plants and their surroundings, as well as internal plant reactions. They have gained widespread acceptance as a valuable tool for agricultural research and management across the globe (Bhatia, 2014; MacCarthy et al., 2018; Mulla et al., 2020). Because the connection between a crop and its environment is frequently difficult to comprehend due to the complexity of agricultural systems, crop models are useful tools for predicting and analyzing

overall agroecosystem performance for specific activities. According to Hoffmann et al. (2020); Sekyi-Annan et al. (2017) and Webber et al. (2014), crop growth model outputs in connection with the weather, soil conditions, and management approaches can be used to assess the long-term viability of agricultural production. Agricultural models can aid in the exploration and development of sustainable land management strategies in a variety of agroecological and socio-economic circumstances. Models' capacity to examine system performance at different locations, for changing season lengths, and for uncertain climatic variables might boost research efficiency (Deihimfard et al., 2018; Sohn et al., 2019; Yan et al., 2020). Model development and application can be utilized as research tools to assist in identifying knowledge gaps and designing more efficient and targeted studies. Models can aid in the identification of possible risk regions for more in-depth field studies. Crop models are increasingly being used to investigate possibilities and solutions for food security, climate change adaptation and mitigation, and sustainable production systems all over the world (Ginaldi et al., 2019; Holzworth et al., 2014; Islam et al., 2016; Tui et al., 2021).

2.19.2 APSIM model overview

The Australian Agricultural Production Systems Research Unit (APSRU) created the Agricultural Production Systems Simulator (APSIM) model. It is a modular framework comprised of a set of biophysical modules that simulate physical and biological processes in farming systems, as well as a set of management modules that allow the user to specify certain management rules that characterize a scenario being simulated and control its execution (Holzworth et al., 2014). As a function of climate, cropping history, and soil management, the model describes crop growth, soil water, soil N, soil C, and biochar

dynamics. It enables the plugging in and out of individual modules of important farming system components (Holzworth et al., 2014; Keating et al., 2003). While the crop is the focal point in conventional crop development models, the essential points in APSIM are the state of the soil, as well as changes in Climate adaptation and management. The APSIM model is especially popular, owing to its user-friendly interface. Simulation experiments can be carried out without the assistance of a computer engineer, and they are frequently used in conjunction with field experiments. Due to, but not entirely, economic relevance and data availability, the scope of model development has primarily focused on monoculture cereals such as wheat, barley, maize, and rice. According to various scenarios, sustainable intensification strategies frequently favor legumes (Franke et al., 2018; Van Loon et al., 2018), as well as multi-species systems (Altieri and Nicholls, 2004; Masvaya et al., 2017). As a result, modeling groups have begun to investigate the integration of legumes into present systems, as well as niches (Sennhenn et al., 2017a; Sennhenn et al., 2017b), yield gaps, and prospective improvement measures (Hajjarpoor et al., 2018). Intercropping is becoming more relevant as part of the global sustainability agenda and movements, even though research on separate legume systems is well established (Chimonyo et al., 2016; Mao et al., 2015). Studies that combine modeling with intercropping, on the other hand, are uncommon (Carberry et al., 1996; Chimonyo et al., 2016), emphasizing the thesis's distinctive scientific contribution. With legume demand increasing to complement cereal production (Varshney et al., 2018), intercropping presents itself as an obvious opportunity to exploit and play a key role in global legume integration programs. The availability and competition for resources are important factors in determining the conditions in which optimal efficiency can be achieved (Sennhenn et al., 2017a; Sennhenn et al., 2017b), especially in multi-species environments. Crop modeling has become an

important technique for understanding the interaction between the environment, phenotype, and genotype in cropping systems, as such traits are sometimes difficult to quantify in the field alone (Hammer et al., 2010).

2.19.3 Soil water model

The soil models water movement and infiltration, evaporation, runoff, drainage, temperature changes, nutrient cycling, and solute mobility in the soil profile (Holzworth et al., 2014; Keating et al., 2003; Rinaldi and He, 2014; Shaygan et al., 2018; Vereecken et al., 2016). For the soil water balance and solute transportation in APSIM, there are two modeling methodologies. Richard's equation methodology and the cascade soil water balance (Keating et al., 2003; Longo et al., 2021; Rinaldi and He, 2014). Water flow is defined by the flow from saturated to unsaturated soil layers. The cascade methodology is termed SOILWAT, it operates on a daily time scale. Drained upper limit (DUL), lower limit (LL-15), and saturation levels of the soil are all measured (SAT). Depending on the soil's water potential, water can flow uphill or downward between layers. SOILWAT 15 also handles the distribution of soil solutes like nitrogen, and its transport with water between layers is governed by a user-defined efficiency factor. The PERFECT model was used to design the majority of operations in SOILWAT (Amarasingha et al., 2015; Archontoulis et al., 2014; Gaydon et al., 2012). This includes the module's ability to alter surface runoff and possible soil evaporation concerning surface residues and crop cover. Small rainfall events are lost through first-stage evaporation, while second-stage evaporation is a gradual process that allows for more flexibility in defining long-term soil water changes in response to soil

features and environmental impacts. Soil water conductivity (SWCON) determines the amount of water above the DUL that drains to an adjacent soil layer in one day.

2.19.4 APSIM-Cowpea

The APSIM cowpea modules were created using an algorithm from the cowpea modules (Chimonyo et al., 2016; Nelson et al., 2021; Robertson et al., 2002). It replicates cowpea growth on a daily time scale, as it reacts to soil water, nitrogen, and weather (Keating et al., 2003). Cowpea has 11 growth stages and nine phases (periods between stages), with the start of each stage influenced by the temperature (except from sowing to emergence, which is determined by soil moisture). Thermal time (in degree days) is estimated for each day using phenology methods that interpolate hourly air temperature estimations from the daily minimum and maximum temperatures. The final estimated leaf area index (LAI) increase is dependent on water, N, and C availability, as well as canopy development, which is determined by temperature. The smallest of two potential biomass increment values, one determined, is used to estimate biomass buildup (Archontoulis et al., 2014).

2.19.5 APSIM-rice

Building models of farming systems to examine the agronomic, economic, and environmental impacts of farming at various scales has become more essential with the rising focus on sustainable landscapes in which farms are an integral aspect of the landscape. These comprehensive models can anticipate the implications of various situations, such as different farm management alternatives and the implications of policy, market, resource, and other regulatory changes. Simulating the long-term viability of rice-based agricultural systems is

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also becoming increasingly popular, particularly in Asia. The ability to model nitrogen dynamics, crop sequence and inter-crop interactions will be possible (Costa et al., 2020; Jing et al., 2007; Jing et al., 2010; Keating et al., 2003). APSIM (Agricultural Production System Simulator), an Australian cropping system model, can forecast crop growth, yield, nitrogen uptake, nitrogen dynamics in soil, and crop residue rotation impacts over time (Keating et al., 2003). APSIM Generic Crop Library and Infrastructure Culture Module can be used to assess system-related processes (Suriadi, 2010). APSIM, on the other hand, is based on dryland agriculture systems rather than lowland rice production systems, and it has just recently been applied to tropical cropping systems. Furthermore, the APSIM was not created to model upland or lowland paddies (Keating et al., 2003). Because it comprises nitrogen change and leaching between a waterlogged zone and oxidized and reduced soil layers, lowland rice has substantially more complex carbon and nitrogen dynamics than other crops. In addition, the APSIM-Rice module models rice development about climate, soil water, and soil nitrogen (Keating et al., 2003).

Grain yield, plant biomass, water use, crop N uptake, and partitioning to various plant sections are all estimated using a daily time step in the model (Gaydon et al., 2017; Radanielson et al., 2018; Zhao et al., 2014). RUE is in charge of dry matter accumulation. Assimilates are produced by intercepted radiation and are partitioned into different plant sections such as the leaf, stalk, roots, and grain depending on the crop stage. The growth of the leaf canopy is calculated as a function of time and temperature, and it increases the leaf area index (LAI). Temperature, radiation, moisture, and the amount of nitrogen in the soil all affect these processes (Archontoulis et al., 2014; Webber et al., 2020). Extreme temperatures, poor soil moisture, or low soil nitrogen levels can impede canopy formation

and photosynthesis, lowering the crop's RUE. Using exchanges with relevant APSIM soil modules that track the state of these variables, the rice module calculates N uptake from the soil as well as crop water use. Other causes, like aging, light competition, and moisture stress, can cause leaf senescence, which is retained as thrash in the model alongside non-millable stalks and leaf sheaths. In the 'BIOM' module, this eventually separates from the plant and becomes surface biochar.

The APSIM rice module simulates various elements of rice management, including ratooning and trash management. Extreme temperatures, poor soil moisture, or low soil nitrogen levels can impede canopy formation and photosynthesis, lowering the crop's RUE. Water from the soil (Holzworth et al., 2014; Keating et al., 2003). For the soil water balance and solute transportation in APSIM, there are two modeling methodologies. Richard's equation methodology and the cascade soil water balance (Keating et al., 2003). Water flow is defined by the flow from saturated to unsaturated soil layers. The cascade methodology is termed SOILWAT, and it operates on a daily time scale. The drained upper limit (DUL), lower limit (LL-15), and saturation levels of the soil are all measured (SAT). Depending on the soil's water potential, water can flow uphill or downward between layers. SOILWAT 15 also handles the distribution of soil solutes like nitrogen, and its transport with water between layers is governed by a user-defined efficiency factor. According to Gaydon et al. (2012), the PERFECT model was used to design the majority of operations in SOILWAT. The module's ability to alter surface runoff and possible soil evaporation to biochar and crop cover is one example. Small rainfall events are lost through first-stage evaporation, while second-stage evaporation is a gradual process that allows for more flexibility in defining long-term soil water changes in response to soil features and environmental impacts. The

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amount of water above DUL that drains to an adjacent soil layer in one day is determined by the soil water conductivity (SWCON). This is an example of creativity.

2.19.6 Biochar model

The biochar module covers biochar cover and tillage, as well as surface biochar breakdown and C and N transfers from biochar to soil (Brtnicky et al., 2021; Dokoohaki et al., 2018). Organic materials include everything above ground that can be burned or integrated into the soil as organic matter (OM). When new organic materials are introduced, new values are calculated to represent the total accessible mass of organic materials and the C: N ratios. Because biochar on the soil surface has the potential to affect soil hydrology and nitrogen cycles, crop models must appropriately forecast biochar breakdown. The pace of biochar decomposition is influenced by several parameters, including the crop's specific decomposition rate and the residues' soil contact fraction factor. The C: N ratio of organic components, as well as the temperature, can affect the rate of crop breakdown (Bonanomi et al., 2019; Esmaeilzadeh and Ahangar, 2014).

2.19.7 Soil nitrogen model

The soil nitrogen module (Soil-N) mimics the availability of nitrogen from previous crops' biochar to a crop, which the model accomplishes by modeling N mineralization in the soil (Xiu et al., 2021). In terms of soil C and N flux, it reflects the dynamics of SOM. In the soil-N module, soil organic matter is divided into three pools. There are three types of pools: one that decomposes quickly (BIOM), one that decomposes slowly but steadily (HUM), and one that is stable (INERT). A distinct pool is formed by newly integrated organic matter from

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roots and leftovers from the preceding crop (FOM) (Dhaliwal et al., 2019; Naresh et al., 2017). Mineralization, immobilization, denitrification, and urea hydrolysis are all processes that the soil N module mimics in APSIM. The three pools in APSIM were created because a flaw in the CERES model caused unrealistic mineralization rates, making long-term SOM simulations erroneous (Campbell and Paustian, 2015; Gaydon et al., 2017; Keating et al., 2003; Maseko, 2018). APSIM's SOM breakdown is prevented by the INERT pool, which is stable and not vulnerable to decomposition.

2.19.8 Long-term trials in agricultural research are important.

Long-term trials can help develop economically and environmentally viable management techniques to address existing practices' rising production costs and environmental concerns. Keeping these trials operational and accessible for future generations can serve as a scientific legacy and act as the foundation for crucial studies. This research found that modeling has the potential to aid in the understanding of agricultural systems' complicated C and N dynamics. Long-term records obtained by these experiments can aid in the development of mathematical models that may be used to assess the effects of various management strategies on yields and quality. Due to the challenges of possible maintenance funding shortages, the usefulness of these studies might often be questioned. It is critical to creating fresh research pathways that will justify the continuance of current trials to offset the cost of maintaining them. Although the long-term upland rice-cowpea intercrop trial has been thoroughly researched in the past, the upland rice-cowpea intercrop trials at the University for Development experimental fields have not. More research on these trials is needed, as their use can grow over time if they serve many goals.

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2.19.9 Use of the APSIM model in simulating long-term carbon and nitrogen dynamics

The inability to forecast C and N variations over time is hampered by the intricate interaction of the natural environment and agricultural methods. By modeling cropping systems, we may investigate the interactions between climate, soil, and crop management strategies as well as their impacts on C and N dynamics in cropping systems. Long-term C and N dynamics have been simulated using the APSIM model, as well as other crop models. It's been difficult to estimate the quantity of nitrogen leaching out of the root zone directly, but crop models can help. These models can help in determining the root causes and analyzing management techniques to mitigate the problem, but they are not without flaws (Archontoulis et al., 2020; Puntel et al., 2016). The APSIM model has the capabilities needed to estimate changes in soil C and N as a result of management techniques and the environment. According to reports, the APSIM model can accurately mimic soil C dynamics in cropping systems (Gaydon et al., 2017; Luo et al., 2014). However, there are inherent uncertainties in soil C simulations that must be considered when interpreting the results. After land conversion to agriculture, soil C loss is projected to be rapid (Hoffmann et al., 2020; Swanepoel et al., 2018; Wang et al., 2014; Yin et al., 2020), However, an equilibrium stable state is predicted to be established after some time. Tillage absorbs organic matter (biochar) into the ground, according to Bartel et al. (2020); Singh et al. (2018), and Wang and Luo, 2021) in APSIM, and the breakdown of soil C following tillage can be underestimated due to changes in the soil environment caused by tillage, which may accelerate decomposition. A scenario on soil C changes in the top 0.3 m of the soil profile in an APSIM simulation of long-term C dynamics in wheat revealed that soil C has still not found an equilibrium after 120 years of simulation (Bartel et al., 2020; O'Leary et al., 2016;

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Pravia et al., 2019). In a long-term upland rice-cowpea intercrop simulation, an increase in SOC was associated with an increase in soil N fertility, which was influenced by biochar management and fertilizer N application (Essegbey and MacCarthy, 2020; Ullah et al., 2021; Wortmann and Sones, 2019; Wortmann and Sones, 2017). In cropping systems that retain biochar, nitrogen fertilizer application can boost biomass production and, consequently, crop yields. By net immobilizing N during SOM decomposition, this biochar can behave as a soil N sink, limiting the quantity of N vulnerable to leaching. It's challenging to optimize C and N dynamics in cropping systems simultaneously since it's difficult to characterize mineralization and immobilization processes in terms of carbon-nitrogen interactions (Abrar et al., 2021; Crews et al., 2016; Luo et al., 2014; Seiter and Horwath, 2004). The APSIM model predicted that rainfed crops would have lower N leaching than biochar treatments due to high N usage in rainfed crops, which would prevent extra N from being leached in a high rainfall event (Descheemaeker et al., 2020; Lorenz and Lal, 2018; Martinez-Feria, 2018).

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CHAPTER THREE

3.0 ASSESSING UPLAND RICE, BIOCHAR, AND SOIL NUTRIENT MODELS IN THE GUINEA SAVANNA ZONE (NYANKPALA) GHANA.

Frimpong-Manso J[1]* and Ganiyu SA[2]

[1]*CSIR-Soil Research Institute, Kwadaso-Kumasi, Ghana*
[2]*Department of Agricultural Engineering, University for Development Studies, Ghana*
**Corresponding Author's Email: frimpong1977_1@yahoo.com*

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Author Statement

Frimpong-Manso Judith (Candidate)

Conceived and designed the research, analyzed and validated the result, and drafted and revised the manuscript.

Ing. Prof. Abdul Ganiyu Shaibu (Supervisor)

Supervised the work and reviewed the manuscript

Abstract

The Agricultural Production System simulator (APSIM) is a cropping modeling program that is employed to address research on intercropping systems. We tested it in the Guinea Savannah zone to increase nutrient and nutrient use efficiency to alter agricultural practices in a rice-based farming system. Our approach was to calibrate and test the models Upland rice-*Oryza sativa* and cowpea-*Vigna unguiculata* intercrop, relationships between crop development and soil nitrogen (N), organic material on the surface, biochar, as well as the assessment of model projections against independent data sets. During calibration, parameters for crops and soil were developed to ensure that the model adequately captures soil nutrient dynamics under three different biochar plus half rate of inorganic fertilizer root mean square error (RMSE). Soil inorganic N dynamics RMSE 0.18 and 0.216 kg N ha^{-1} for 2018 and 2019, respectively, contrasting soil N mineralization patterns when biochar and inorganic fertilizer applications are combined. RMSE 3.86 and 3.18kg N ha^{-1} in 2018 and 2019, straw N uptake RMSE 6.71 and 6.67 kg N ha^{-1} in 2018 and 2019, and grain N uptake RMSE 478.62 and 605.33 kg ha^{-1} in 2018 and 2019, respectively. The calibrated model was evaluated against independent data on grain yield RMSE 315.18 and 460.04 kg ha^{-1} for 2018 and 2019 respectively, straw production RMSE 183.64 and100.08 kg ha^{-1} for 2018 and 2019 respectively, and with a highly acceptable yield, particularly concerning return-N relations. APSIM has proven to be a reliable model for research and decision-making to improve production systems in upland rice-cowpea intercrop in Nyankpala.

Keywords: Agricultural Production System simulator (APSIM), upland rice, root mean square error (RMSE); nutrient use efficiency; biochar.

3.1. Introduction

Rice (*Oryza sativa)* is one of the most significant food crops in the world. Demand for rice has been rising in Africa. In the past 16-year period (1985 to 2001), rice imports to Africa increased from the initial 3 million tons to over 7 million tons per annum thus, in terms of food security, it's becoming a significant crop. In Ghana and other West African countries, cereal, and grain crops, including rice, is an essential component of staple food. There are concerns about the steady decline in grain yields in Sub-Saharan Africa due to soil degradation which severely threatens crop production and consequently, food security (De Jager et al., 2013). Degradation of cropland is mainly due to continuous cultivation without appropriate

soil management practices (Bationo et al., 2007). Cereal production in semi-arid areas of Ghana, as in other savannah regions of West Africa, is heavily affected by inadequate or poorly dispersed rainfall, and low levels of nutrients such as Nitrogen (N), Phosphorus (P) in soils (Asekabta, 2018). Moreover, P deficiency reduces the response of crops to mineral N (MacCarthy et al., 2009; Haji, (2016). Having sustainable yields would require substantial investments in mineral fertilizers (Zhang et al., 2011) because nutrient recycling does not make up for the removal of these nutrients from the soil by harvesting. While soils are depleting in nutrients, the use of mineral fertilizers to enhance crop production is low in this area (De Jager et al., 2019).

Recently, biochar has gained substantial consideration as a soil amendment, owing to its agronomic support and carbon sequestration potential. Biochar has beneficial properties such as high surface area (Laird et al., 2010), small particle sizes (Dokoohak et al., 2017), low bulk density (Downie et al., 2012), high organic carbon content (Herath et al., 2014), etc., which together contribute to its ability to reduce soil bulk density, raise porosity and aid

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coarse-textured soils by increasing their water holding capacity (Basso et al., 2013). Short-term variations in the physical and hydrological properties of soils have been achieved through biochar incorporation in several laboratory and on-station trial studies (Streubel et al., 2011).

The Agricultural Production Systems Simulator (APSIM) model features a user-friendly interface that provides advanced flexibility in the implementation of simple and complex simulations without the need to write additional codes, i.e., intercropping systems (McCown et al., 2016; Nelson, 2020) inclusive of annual or perennial species. The transition from the seasonal and sequential analysis is straightforward and the model also provides a rich graphical interface (Archontoulis et al., 2014; Martinez-Feria et al., 2018). Cropping systems models such as APSIM (Holzworth et al., 2014; Keating et al., 2003) include intercropping of grain, legumes, and applications of organic (biochar) and mineral fertilizers, describing the dynamics of crop growth and soil nutrients. The model has been used successfully in the pursuit of strategies for more efficient production, improved risk management, crop adaptation, and sustainable production (Keating et al., 2003; Van Ittersum et al., 2016). The main objectives are to investigate modeling dynamics and accumulation of N in the plant and the yield response to three different sources of biochar and fertilizer under rainfed conditions.

3.2 Materials and Methods

3.2.1 Field Experiment and Measurements

3.2.2 Study area

A field experiment over two consecutive cropping seasons (2018-2019) was conducted. The research site was located at the Farming for the Future, University for Development Studies (UDS), Nyankpala near Tamale in the Northern Region of Ghana (latitude 09.246070N and longitude 000.589920W). The area has a unimodal rainfall pattern with an annual rainfall of 800-1100 mm (Kombiok et al., 2005). The dry season starts from November to March with day temperatures ranging from 33 °C to 39 °C, with night temperatures ranging from 20 C to 26 °C (Kombiok et al., 2005). The mean annual daytime relative humidity is 54% while the altitude of the area is 252 m above sea level. The site is underlain by Upper Voltaian sediments. The area is covered with red and orange-brown drifts partly eroded in places and exposing a layer of shallow ironstone and sandstone brash (Adu, 1995).

The layer is often separated from the underlying sandstone by a thin stone lime (Adu, 1995). The soil profile has been classified as Nyankpala series (Ferric luvisols and Plinthic acrisols) (ISSS/ISRIC/ FAO, 1998; FAO-UNESCO, (1988). They are shallow to very shallow soils overlying in situ developed iron pans within 55.9 cm. It is also moderately shallow to moderately deep concretionary and or gravelly, heavy to medium textured soils overlying mostly highly weathered granite shales (Asiamah, 2008). Characteristically the soils are acidic, with low nitrogen and phosphorus content. They are susceptible to moderate erosion and should not, therefore be left bare. They are inherently infertile and will need to be fertilized to obtain the optimum yield (Adu, 1995).

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3.2.3 Biochar preparation

Three different sources of feedstocks were produced from slow and high pyrolysis of groundnut shells, corn cobs, and poultry manure at 400 °C – 700 °C with a dwelling time of 24 hours in oxygen-limited conditions in a reactor, followed by water and air cooling of charred feedstock to room temperature and the biochar was grind into fine particles. The chemical characteristics of the biochar applied are shown in Table 3.1. Organic carbon was determined by the wet combustion method according to Walkley and Black (1934). Total nitrogen was determined by the Kjeldahl method. Phosphorus and Potassium were determined in plant ash using flame photometry (Pratt, 1965). Available phosphorus was determined according to Bray and Kutz (1945).

3.2.4 Experimental design and treatments

The field experiment was established in June 2017 and initiated with a single application of the three different sources of biochar to the experiment. The experiment was laid out in randomized complete blocks design (RCBD) with 4 replications. The crops were Nerica 14 (African upland rice) days of maturity were 85 days for the rice (*Oryza sativa* L.) and erect cowpea (padituya) type (*Vigna unguiculata* L.). Nerica 14 seeds were soaked in water to separate unfilled grains from filled grains and then dried at room temperature for 24 hours. The seeds were drilled in rice husk biochar at 3 cm below the biochar surface in rows 30 cm apart and this was to maintain moisture for good germination. Weeds were controlled by hand twice before transplanting. After three weeks, transplanting was done on the 28th for rice and the 29th for cowpeas in July 2018 and the 21st and 22nd of July, 2019 at a rate of two seedlings per hole. The planting distance for rice was 20 cm x 20 cm and for cowpea 60 cm x 20 cm. The combination of the rice and cowpea was in a 3:1 ratio. The treatment includes

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a control (no input), fertilizer and cowpea intercrop either applied alone or in combination with the three different sources of biochar. Biochar levels were 5 t ha^{-1} each and were incorporated into the soil at the same time. Inorganic fertilizer was applied at a rate of 90, 60, 60 and 45, 30, 30 kg ha^{-1} NPK, as straight fertilizer and then top-dress with nitrogen levels in the form of urea 30 kg ha^{-1} N eight (8) weeks after transplanting. Weeds were controlled by hand on four counts during the season.

The data used in the current study cover the main crop and soil processes soil sampling at 0-30 cm depth for both chemical, and physical analysis (bulk density and porosity were determined weekly till harvesting (Table 3.2). Ten plants were randomly selected on each plot and plant height at maturity, the number of panicles, the number of tillers, and number of grains per panicle were determined.

Data was collected every week from 30 days after transplanting to heading. At maturity 1 m^2 in each plot was harvested for yield. Data collected at maturity included measurements of plant height, number of panicles, and number of plants within a $1m^2$ area. Five panicles were randomly selected for the number of spikelets, panicle length, number of grains per spikelet on a panicle, weight of unfilled and filled grains, total grain weight, and 1000 grain weight, and straw weight. Data were determined by APSIM modules version 7.

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3.2.5 Biochar Types

Table 3.1: Basic biochar properties used for simulations

Feedstock	Pyrolysis	pH 1:5	C.E.C me $100g^{-1}$	N %	P %	K %	C: N ratio (-)	Fraction C (0-1)
Biochar Corn cobs	High	6.67	118.26	0.95	0.21	0.45	11.0	0.129
Biochar Poultry manure	High	9.29	125.63	2.19	0.5	0.47	10.5	0.324
Biochar Groundnut shells	Low	11.13	85.52	1.34	0.13	0.74	12.3	0.243

3.2.6 Climatic weather during the cropping Season 2018-2019

The rainy season's peak happened in July for the current time slice, while a change in the rainfall peak toward August was predicted for the future time slice. The months of August, October, and November are expected to see significant increases in monthly rainfall in the future. The month with the most rainfall was August (Figure 3.1). Since sandy loam soils dry out rapidly due to their low permanent wilting point, accessible water, and water storage capacity, good crop yields are strongly dependent on a well-distributed rainfall pattern. In the wet season of 2018-2019, Figure 3.1 depicts the study area's seasonal water balance. In 2018-2019, the total rainfall was 133.29 mm, while the total evapotranspiration was 37.10 mm. The upland rice was planted in June 2018 and 2019 and harvested in November of the same month. From July through October, 61.81 mm of rain fell, while 3.07 mm of evapotranspiration (Figure 3.1). During the rice growth phase, from July to August, the table shows a favorable moisture balance. From July to August, rainfall increased and evapotranspiration decreased dramatically. However, because the September rainfall was lower, there was a slight water deficit after August. During the upland rice growing season, there was drought. As a result, biochar amended had a higher yield than non-biochar

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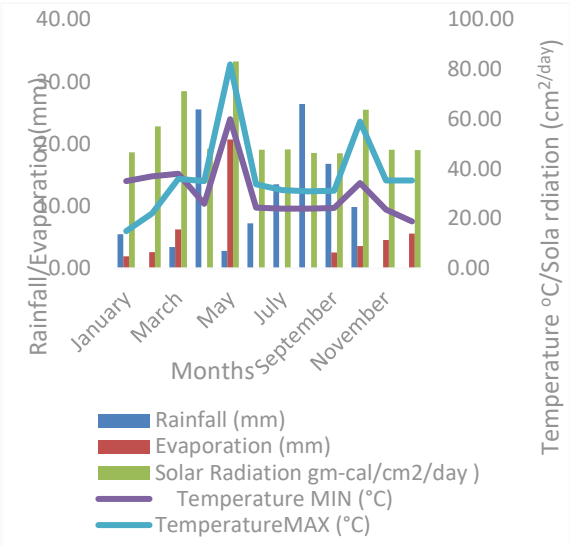
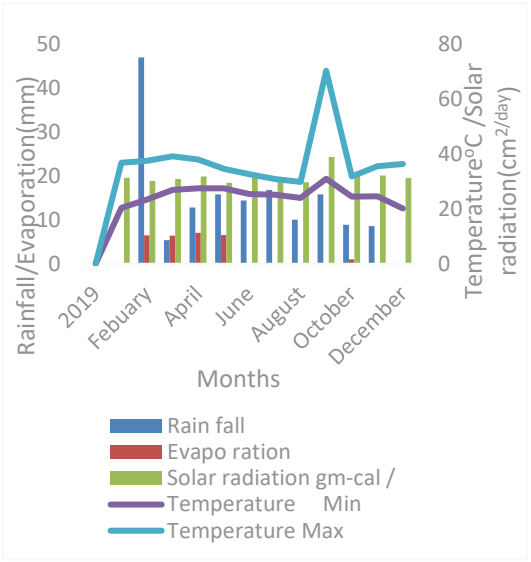
amended. The significant drop in average temperatures during the upland rice's growth phase (Figure 3.1) also contributed to a decrease in evapotranspiration, which favored the rice plant.



1a. climatic weather for 2018



1b. climatic weather for 2019

Figure 3.1. Summary of climatic weather observed at the study site from 2018 - 2019 Cropping Season

3.3 Statistical Indices for Model Performance

The goodness of fit was evaluated by calculating the root mean square error (RMSE) and absolute errors (MAE). These indices are used to measure absolute and relative errors, respectively, between observed and simulated values. The corresponding equation is available in Archontoulis and Miguez (2014).

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3.4 Results and Discussion

Table 3.2. Soil profile parameters used in this study

Soil Layer	**1**	**2**	**3**	**4**	**5**
Layer thickness (cm)	0-15	15-30	30-60	60-90	90-120
Soil water parameters					
BD (g/cm3)	1.58	1.62	1.57	1.59	1.57
SAT (mm^{-1})	0.354	0.358	0.368	0.342	0.339
DUL (mm^{-1})	0.202	0.204	0.201	0.198	0.132
LL15(mm^{-1})	0.050	0.106	0.153	0.128	0.198
Soil-C parameters					
OC (%)	0.47	0.41	0.33	0.38	0.33
pH(H_20)	4.66	4.66	4.66	4.56	4.56
Finerta	0.36	0.36	0.70	0.90	0.90
Fbiomb	0.016	0.02	0.02	0.01	0.01
Soil P parameter					
Labile P ($Mg\ kg^{-1}$)	11.6	5.8	5.0	2.0	1.0
P sorption ($mg\ kg^{-1}$)	60	80	150	180	200

Soil parameterization of ferric Luvisols at farming for the future, UDS experimental farm to specify APSIM simulations. LL, lower limit; DUL, drained upper limit; SAT, saturated volumetric water content; BD, bulk density; OC, organic carbon; Fbiom, a non-inert fraction of microbial C; and Finert, the inert fraction of organic C.

3.4.1 Treatments' effects on soil fertility

On three different sources of biochar and control plots, an analysis of variance test revealed a significant ($p < 0.05$) effect of cowpea intercrop, fertilizer, and their interactions on mineral

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N, available P, and CEC (Figure 3.5c-e). Meanwhile, the impact was stronger in soils that received biochar amendments from three different sources. When cowpea intercrop and/or inorganic fertilizer were applied with three different sources of biochar, nitrogen availability rose by 114% compared to plots that did not receive biochar additions. In addition, on biochar-amended plots, cowpea intercrop and/or fertilizer application boosted P availability to almost twice that of control plots. A limited number of experiments have been conducted on the three different sources of biochar treatments with cowpea intercrop (Farhangi-Abriz et al., 2021; Bashagaluke et al., 2020), However, research has indicated that combining biochar with inorganic fertilizer improves soil N and P availability (Oladele et al., 2019; Mensah and Frimpong, 2018). Given the low nitrogen concentration and mineralization rate of the three different sources of biochar, the application of the three different sources of biochar could not have contributed much (in terms of nutrient supply) to the increased N and P availability in soils applied with the three different sources biochar and cowpea intercrop and/or inorganic fertilizer treatments. The use of biochar from three different sources in such integrated treatment applications, on the other hand, could have reduced nutrient leaching and enhanced the soil's nutrient and water retention capacity (El-Naggar et al., 2019). Although nutrient leaching was not addressed in this study, it has been demonstrated to be reduced with the use of biochar, even on heavily weathered soils (Haider et al., 2017; Steiner et al., 2007). Table 3.1 showed, improved CEC with the three different sources of biochar was also detected, which further approves that the soil’s interaction ability and adsorption of accessible minerals and cations were enhanced with the three different sources of biochar application. It is well known that biochar application increases CEC (Tomczyk et al., 2020; Li et al., 2018). Meanwhile, in many regions of the semi-arid tropics, where soils

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with poor cation exchange capacity predominate, increasing CEC with the three main sources of biochar is critical, low-acidity sandy-loam soils that may lose their fertility quickly if fallow periods, or anything similar to fallow conditions, are not imposed (Mensah and Frimpong, 2018; Rawat et al., 2019). The substantial positive correlation established between CEC, inorganic N, and available P demonstrated the importance and influence of CEC on soil nutrient availability (Figure 3.4a-e, 3.5c-e, and 3.5a-j). This substantial relation also explains why, due to increased CEC, inorganic N and available K and S were highest, and available P was moderate when cowpea intercrop and/or inorganic fertilizer were applied with biochar (Wibbing, 2020).

3.4.2 Nutrient uptake in straw and grain

Except for the uptake of P, interactions between different sources of biochar +fertilizer influenced ($p<0.05$) the uptake of all nutrients in straw (Table 3.3a,b and Figure 3.3a-e). At the level of the intercropping system, except for the second cropping season, the interaction between different sources of biochar + 45N30P30K influenced the uptake of all four nutrients. In all, rice straws under different sources of biochar +45N30P30K with cowpea intercrop plots recorded higher ($p \leq 0.05$) nutrient uptake and nutrient concentrations than those in the control (Table 3.3a,b) in each of the cropping periods. Nitrogen uptake in the straw was 0.29% and 0.30% for both cropping seasons under biochar poultry manure+45N30P30K+cowpea plots compared to biochar poultry manure plots over the two-cropping season. Similar trends were observed for S and K with average increases in uptake of 0.13 - 0.16% and 0.38 – 0.65% respectively (Table 3.3a,b). However, the magnitude of increases in P and N uptake in the straw was lower than that obtained for S. Additionally,

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uptake of nutrients during the first cropping season was generally higher than those in the second cropping season. The uptake of N in grain was influenced by the interactions among different sources of biochar+ 45N30P30K with cowpea intercrop. The interactions between different sources of biochar +45N30P30K influenced ($p \leq 0.05$) the uptake of N, P, K, and S in grain. Additionally, the interaction between cowpea intercropping with different sources of biochar influenced ($p \leq 0.05$) the uptake of N and P. At the intercropping period level, the interaction between biochar+ 45N30P30K influenced ($p \leq 0.05$) nutrient uptake in all cropping periods for the uptake of N, K, and S except P in the first and second cropping periods. Figure 3.3 and Table 3.3a,b shows the nutrient uptake as well as nutrient concentrations in response to different sources of biochar and fertilizer per each cropping season. The average uptake of N, P, K, and S in straw was higher under the different sources of biochar +45N30P30K with cowpea intercrop by r^2=0.45, 0.45,0.41 and 0.89 respectively compared to those obtained under different sources of biochar +45N30P30K application. The trend in nutrient uptake in grain was generally similar to those observed with nutrient uptake in straw. Except for P, the uptake of nutrients was higher in the straw than in the grains. The uptake of nutrients in grain generally increased with increasing rates of N and P fertilizer. Nitrogen and phosphorus transfer from cowpea to rice plants grown in intercropping under biochar and inorganic fertilizer system, resulting in higher filled panicle number, spikelet weight, and weight of 1000 grain seeds of the rice plants in intercropping than in sole crop (Table 3.5a,b).

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Table 3.3a. Effect of biochar (5 t ha^{-1}) and inorganic fertilizer (kg ha^{-1}) on nutrient uptake in rice straw

	Rice Straw – 2018				Rice Straw – 2019			
Treatment	**N**	**SO_4**	**P**	**K**	**N**	**SO_4**	**P**	**K**
				%				
Absolute Control	0.06	0.04	0.01	0.12	0.13	0.07	0.02	0.31
90N60P60K	0.27	0.08	0.04	0.33	0.36	0.12	0.05	0.45
ChGs+45N30P30K+C	0.22	0.11	0.04	0.38	0.31	0.15	0.05	0.59
ChPM+45N30P30K+C	0.29	0.13	0.06	0.32	0.30	0.16	0.08	0.65
ChCc+45N30P30K+C	0.18	0.08	0.04	0.33	0.20	0.12	0.05	0.49
ChGs+45N30P30K	0.15	0.06	0.02	0.22	0.26	0.11	0.04	0.48
ChPM+45N30P30K	0.11	0.05	0.02	0.17	0.31	0.10	0.08	0.57
ChCc+45N30P30K	0.17	0.08	0.03	0.24	0.23	0.10	0.05	0.44

Ch-biochar, Gs-Groundnutshell, Cc-Corn cobs, PM-Poultry manure, Nitrogen (N), Phosphorus (P), Potassium (K), Sulfur, and Cowpea (C)

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Table 3.3b. Effect of biochar (5 t ha^{-1}) and inorganic fertilizer (kg ha^{-1}) on nutrient uptake in rice grain

	Rice Grain – 2018			Rice Grain – 2019		
Treatment	**N**	**P**	**K**	**N**	**P**	**K**
			%			
Absolute Control	0.12	0.04	0.02	0.18	0.05	0.03
90N60P60K	0.30	0.10	0.06	0.43	0.11	0.06
ChGs+45N30P30K+C	0.33	0.10	0.06	0.45	0.12	0.06
ChPM+45N30P30K+C	0.38	0.11	0.06	0.43	0.16	0.06
ChCc+45N30P30K+C	0.25	0.07	0.04	0.42	0.12	0.05
ChGs+45N30P30K	0.22	0.04	0.03	0.41	0.10	0.05
ChPM+45N30P30K	0.19	0.04	0.02	0.36	0.13	0.05
ChCc+45N30P30K	0.24	0.05	0.02	0.36	0.10	0.05

Ch-biochar, Gs-Groundnutshell, Cc-Corn cobs, PM-Poultry manure, Nitrogen (N), Phosphorus (P), Potassium (K), Sulfur, and Cowpea (C)

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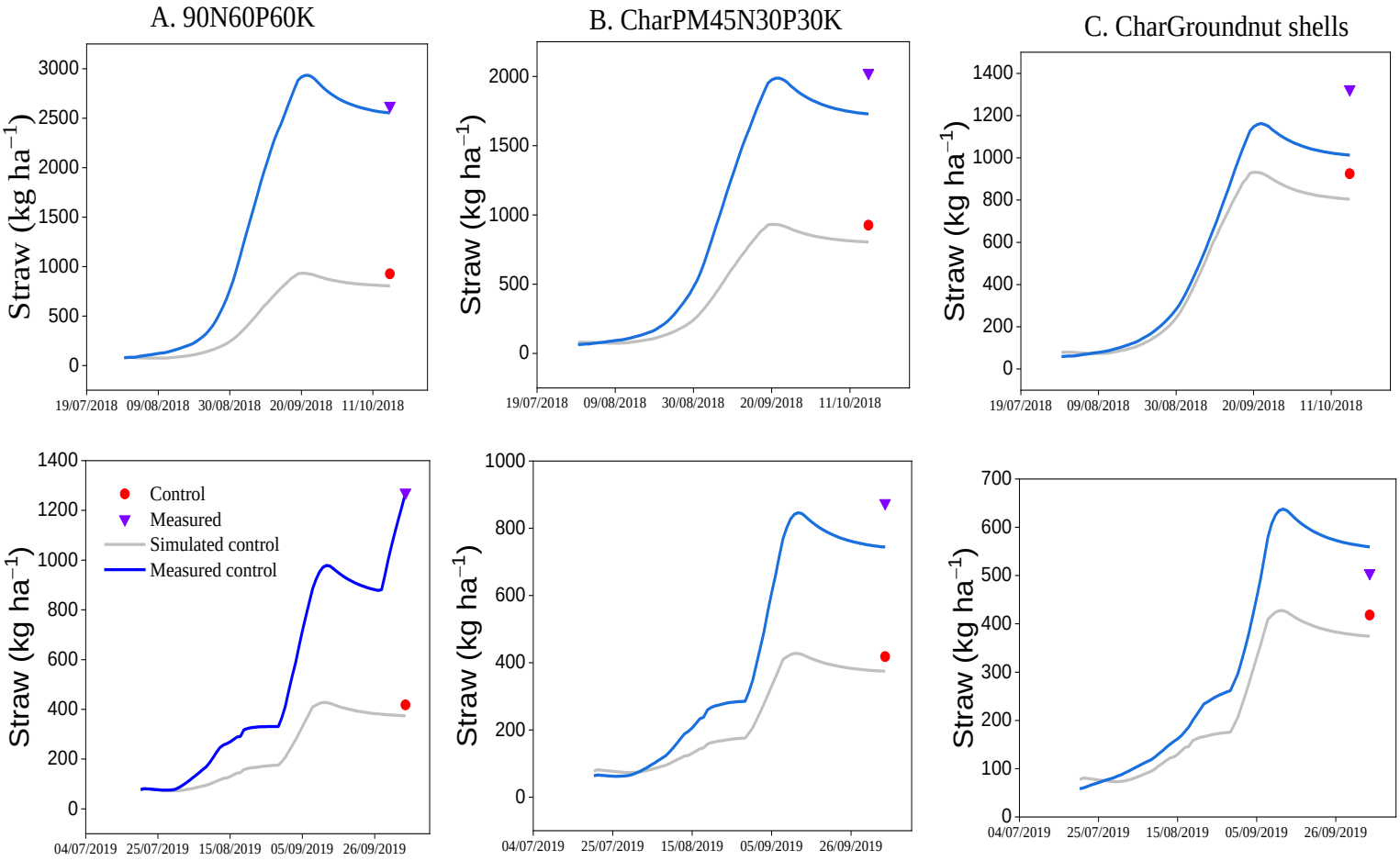

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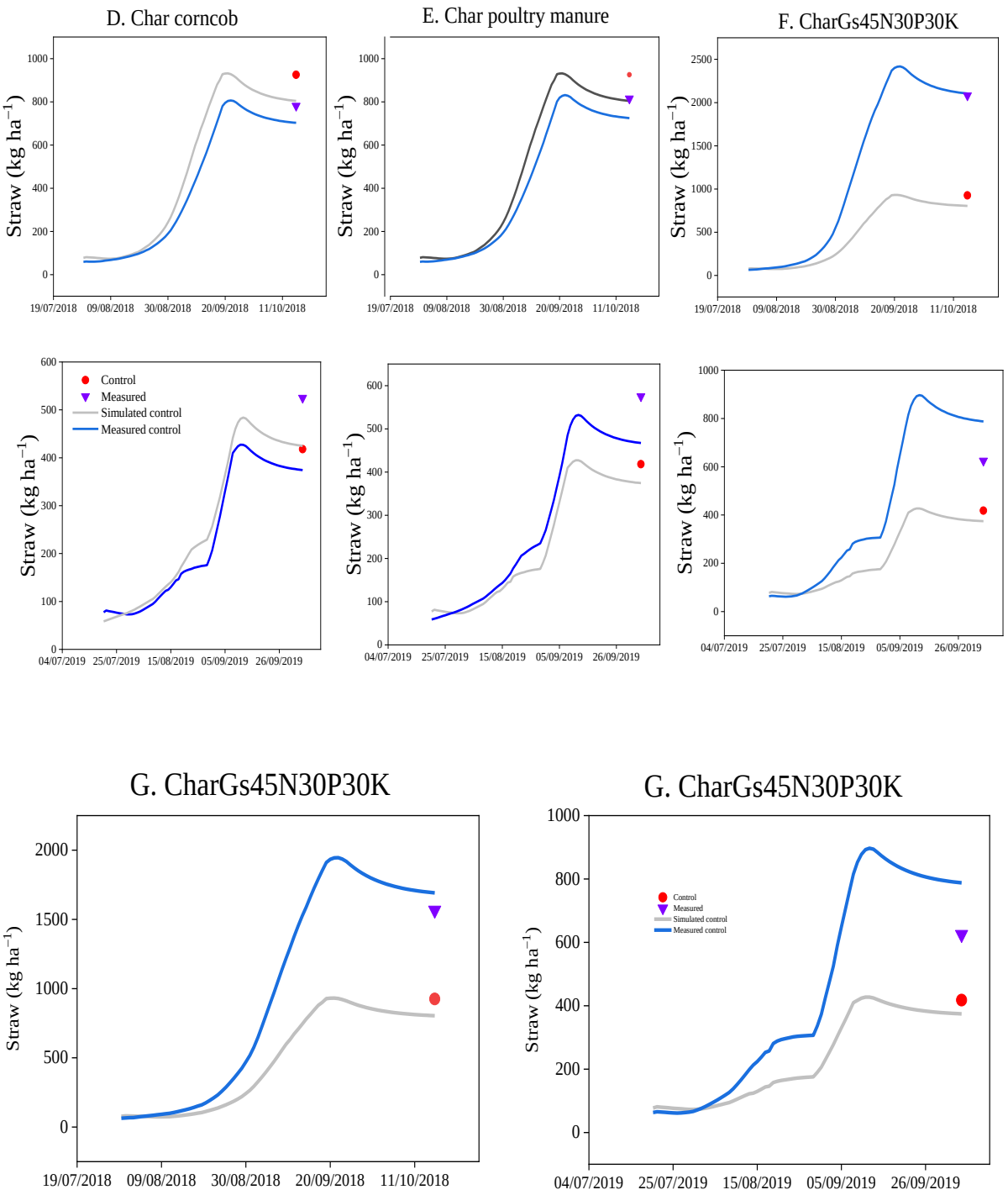

Figure 3.2. Measured and predicted straw production of rice-cowpea intercrop

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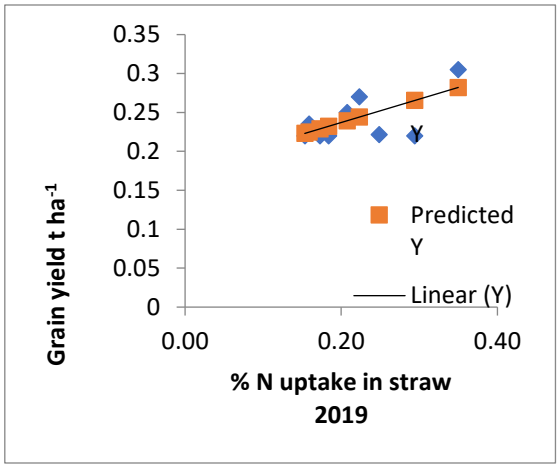
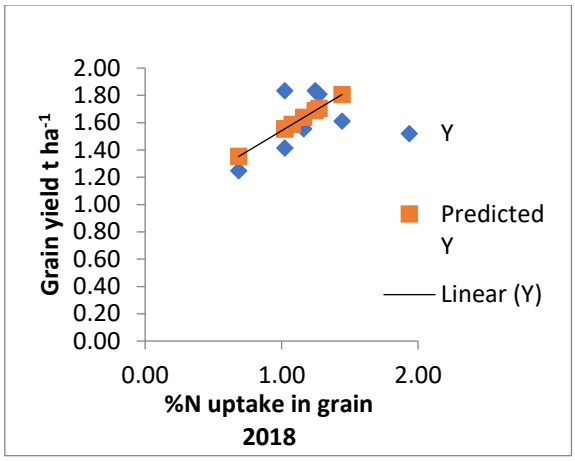
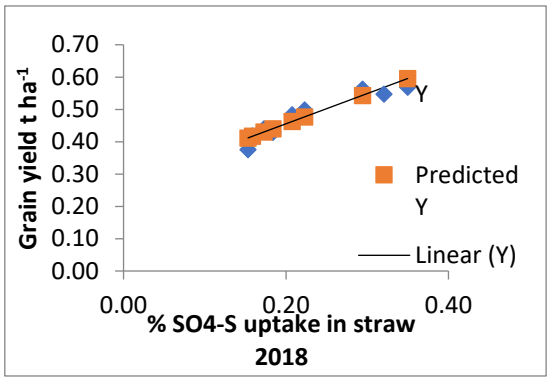


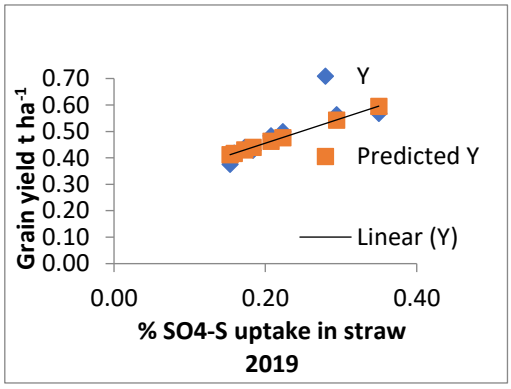
3.3a. char groundnut shells+45N30P30K. Relationship between grain yield and %N uptake straw



3.3b. char poultry manure+45 N30P30K. Relationship between grain yield and %N uptake grain



3.3c. char groundnut shells+45N30P30K. Relationship between grain yield and %SO4 uptake straw



3.3d. char poultry manure+45 N30P30K. Relationship between grain yield and %SO4 uptake

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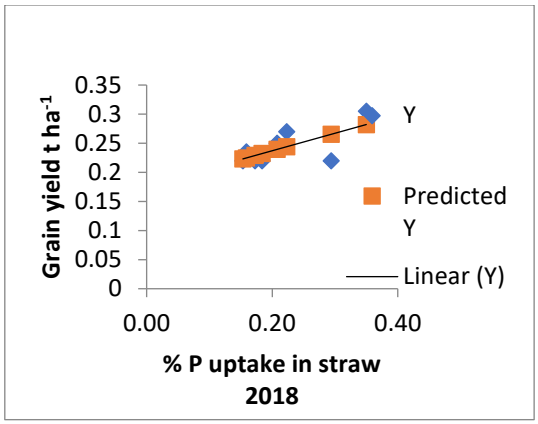
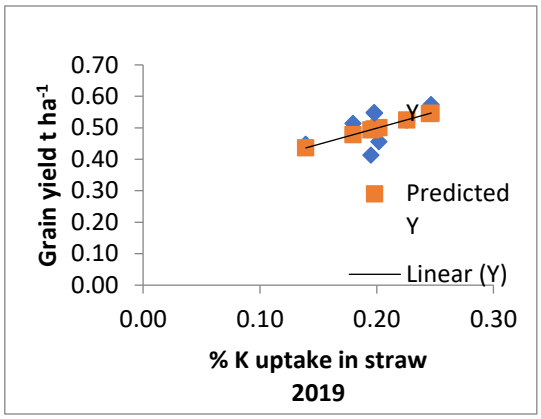


3.3e. 90N60P60K.
Relationship between grain yield and %P uptake straw



3.3f. char corncobs+45 N30P30K.
Relationship between grain yield and %K uptake straw

Figure 3. 3a-e. Relationship between uptake nutrient and % grain yields as affected by biochar and inorganic fertilizers.

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Table 3.4. The efficiency of utilization (kg ha^{-1}) of rice grain absorbed nutrients on biochar and inorganic fertilizer in the seasons 2018 and 2019.

Treatment	NUE (% N)	NUE (%N)	NUE (% P)	NUE (%P)	NUE (%K)	NUE(%K)
	2018	2019	2018	2019	2018	2019
Absolute Control	1.25	1.28	0.46	0.38	0.22	0.23
90N60P60K	16.63	20.96	16.65	21.10	16.65	23.60
ChGs+45N30P30K+C	20.39	22.32	-71.46	22.44	20.42	27.92
ChPM+45N30P30K+C	27.04	25.31	39.81	25.38	27.07	26.32
ChCc+45N30P30K+C	15.11	18.63	-1.57	18.69	15.14	20.98
ChGs+45N30P30K	4.55	16.35	0.49	16.48	4.55	17.38
ChPM+45N30P30K	1.81	16.93	-0.81	16.98	1.81	18.84
ChCc+45N30P30K	6.59	14.02	-2.69	14.07	6.59	12.76

Ch-biochar, Poultry manure(PM), Groundnut shell (Gs), Corn cobs (Cc), Nitrogen (N), Phosphorus (P), Potassium (K), and Cowpea (C), Nutrient Use Efficiency

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Table 3.5a. Quantitative simple linear correlation coefficients for quality parameters for 2018

	Total grain	Rice biomass	Rice straw	Rice chlorophyll	Rice LAI	Rice canopy
Total grain	1					
Rice biomass	0.09	1				
Rice straw	0.62**	0.16	1			
Rice Chlorophyll	0.71**	0.19	0.75**	1		
Rice LAI	0.65**	0.33	0.59**	0.65**	1	
Rice canopy	0.54**	0.28	0.62	0.51**	0.73**	1

*** and ** refer to significance at 5 and 1% confidence levels, respectively**

Table 3.5b. Quantitative simple linear correlation coefficients for quality parameters for 2019

	Total grain	Rice biomass	Rice straw	Rice chlorophyll	Rice LAI	Rice canopy
Total grain	1					
Rice biomass	-0.010	1				
Rice straw	0.59**	-0.12	1			
Rice chlorophyll	0.73**	0.12	0.65**	1		
Rice LAI	0.61**	0.03	0.53**	0.70**	1	
Rice canopy	0.75**	-0.15	0.73**	0.83**	0.54**	1

*** and ** refer to significance at 5 and 1% confidence levels, respectively**

3.4.3 Validation results for grain yield and straw

The observed three different sources of biochar, inorganic fertilizer, and cowpea intercrop varied between RMSE= 315.176 and 460.0358 kg ha^{-1} in 2018 and 2019, respectively, for grain yield. In response to a wider range of applied N+P for upland rice, the model could reasonably simulate the fluctuation of three different biochar, inorganic fertilizer, and

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cowpea intercrop sources (Figures 3.1b, c, d, and Figure 3.4). However, as exhibited in Figure 3.4, the model tends to slightly underestimate three different sources of biochar+45N30P30K. In figure 3.4 the RMSE of grain yield was 315.18 and 460.04 kg ha^{-1} for 2018 and 2019, respectively. The RMSE of straw was 183.64 and 100.08 kg ha^{-1} for 2018 and 2019, respectively in figure 2.

As shown in Figures 3.2(a, e, f, g) and figure 3, straw and grain yield (excluding some data points) fit wider one-to-one line with optimum 90N60P60K and three different sources of biochar+45N30P30K+ cowpea intercrop data, but the model overestimated when grain yield data were included. On the contrary, the predicted grain yield at the three different sources of biochar was largely overestimated regardless of the three different sources of biochar, inorganic fertilizer, and cowpea intercrop. There was good fitness between simulated and observed three different sources of biochar+45N30P30K when only optimum grain yield data were used (Figure 3.2b, c, d, and Figure 3.4). There was good fitness between simulated and observed three different sources of biochar+45N30P30K when only optimum grain yield data were used (Figure 3.2b, c, d, and Figure 3.4). However, when 90N60P60K was also included in the validation, model performances were reduced. The RMSE of grain yield was 315.18 and 460.04 kg ha^{-1} for 2018 and 2019, respectively. The RMSE of straw was 183.64 and 100.08 kg ha^{-1} for 2018 and 2019, respectively. The result exhibited that the model performance generally decreased when the data of 90N60P60K conditions were included. The goodness of fitness was reduced and RMSE increased for almost all of the growth parameters concerned in Figures 3.2 and 3.4. In general, the simulation results overestimated

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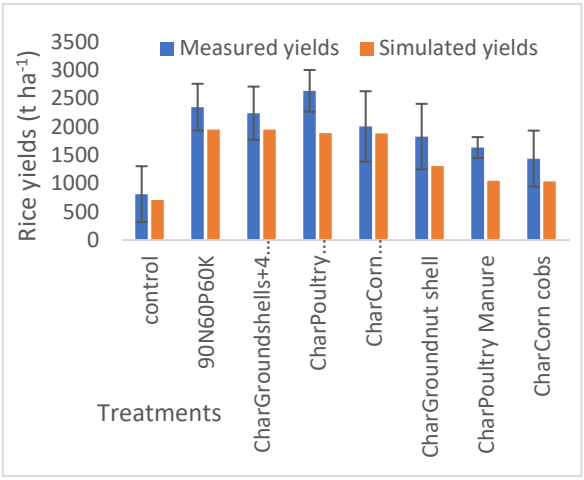
the three different sources of biochar+45N30P30K+cowpea and 90N60P60K yielded for both treatments, while biochar+45N30P30K was underestimated.

3.4.4 Modeling upland rice growth and grain yield

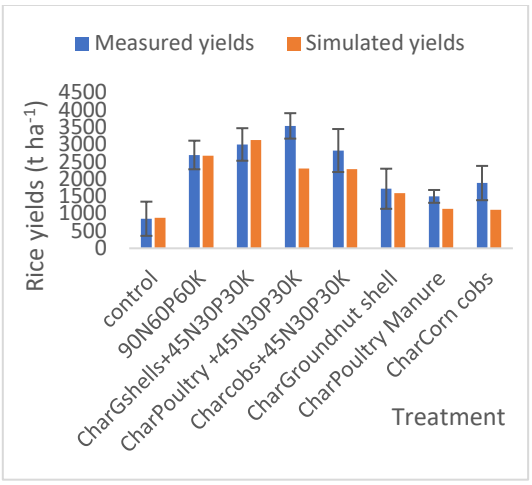
Phosphorus modules of other models like CENTURY was developed for soils where N-limiting conditions are mainly characterized by a minor impact of P-dynamics on crop growth (MacCarthy et al., 2009). However, APSIM seemed more appropriate for this study area as it was developed from data that were generated primarily from the semi-arid tropics, where resource-poor smallholders face limiting P conditions in soils (MacCarthy et al., 2009). Sahrawat et al. (2005) reported a reduction in plant response to P due to the high sorption capacity of P from soils and also observed that zinc deficiency in soils impeded corn responses to P application. The experimental field was categorized with soils that were low in P sorption capacity. Obodai (2018) also reported that the presence of 'laterite soil' rich in iron and aluminum reduces the response of P by being well for P, which does not make it accessible to crops. This was not a problem observed in this study because laterite soils were barely present in the soils at a depth of 0-30 cm. Nitrogen is the nutrient that most restricts agricultural production in the study area and is visible in the performance of cereals (figure 3.4i, ii). All the same, its efficiency is diminished by the low P status of the soil. Both nutrients were considered the most restrictive for crop production (Tetteh et al., 2017). When farmers have the option of choosing a nutrient to focus on, based on their limited resources, it would make sense to opt for nitrogen fertilizers as they provide more revenue.

APSIM had a high predictive performance for grain yield with an internal model efficiency of 0.64. An inaccurate phenology prediction predisposes vital physiological growth

processes to be incorrectly timed with erroneous dates that could coincide with adverse weather conditions. The phenological growth of upland rice was generally predicted well. The delay in flowering observed under conditions of low intake (lack of application of biochar and inorganic N and P) in absolute control, however, was overstated by the model. This proposes the need for N and P stress factors influencing phenology to be improved with considerations for highly weathered low input soils. Tetteh et al. (2017); Martey et al. (2014) also reported in their study of small-scale farms in semi-arid Ghana that the model predicted low cereal yields at low fertilizer utilization rates. This has been attributed to poor efficiency in the internal use of APSIM corn module nutrients at low soil N levels. APSIM has also been described to have performed creditably in predicting soil organic carbon dynamics in the semi-arid area of Africa (Delve et al., 2009; Micheni et al., 2004). The level of N and P contents in straw were also well predicted in this experiment (figure 3.3a-e). This indicates good model performance in the prediction of soil processes such as soil water dynamics that are essential for the transport of nutrients from the soil to the root zone of plants as well as the transformation of nitrogen. The high (3.54 t ha^{-1}) general modified internal coefficient of efficiency in predicting upland rice grain and total biomass production and the ability of APSIM to simulate straw N and P contents, provide sufficient precision for a relative assessment of the long-term impact of farmers' management practices on future grain yield production. Figure 3.4a - d Measured and predicted upland rice grain and cowpea yields as affected by biochar and inorganic fertilizers.

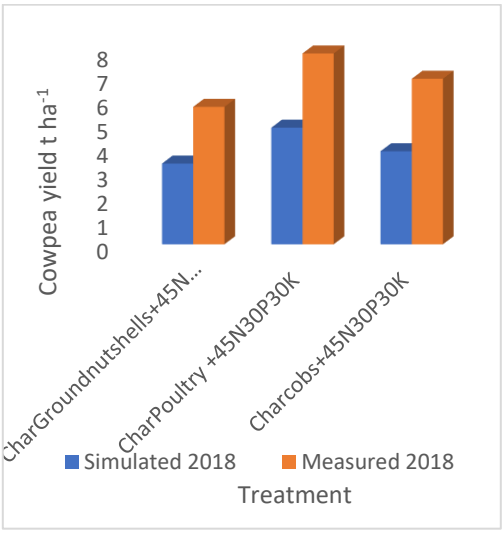


3i Simulated and measured grain yield for 2018

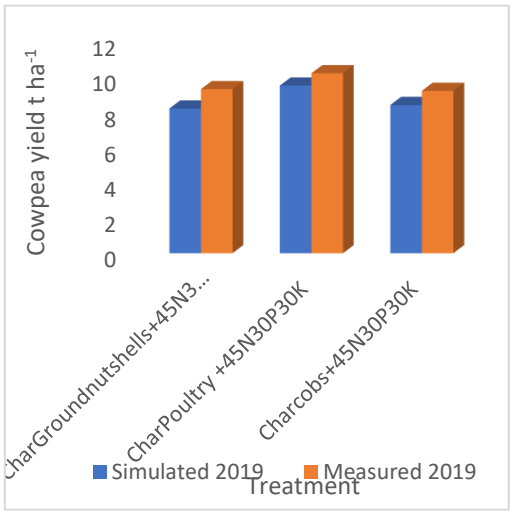


3ii Simulated and measured grain yield for 2019

Figure 3.4i, ii. The simulated and measured upland rice yield as affected by the three different sources of biochar and inorganic fertilizer



3a Simulated and measured cowpea yield



3b Simulated and measured cowpea yield

Figure 3.4ab. The simulated and measured cowpea yield was affected by the three different sources of biochar and inorganic fertilizer.

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3.4.5 Physiological efficiency of NPK and apparent recovery efficiency of NPK applied

The efficiency of the fertilizer applied was evaluated by the physiological efficiency of nitrogen (PEN) fertilizer and the apparent recovery efficiency (ARE) of NPK fertilizer used. The PEN was influenced ($p \leq 0.05$) by the single effects of the cropping season, N and K fertilizer, and three different sources of biochar (Table 3.4 and Figure 3.5a, b, c, and 3.5j). At the level of individual cropping seasons, three different sources of biochar, N, and K, influenced PE positively (Table 3.4 and Figure 3.5a-c). There was a general trend of PE decreasing with increasing P fertilizer applied for the second cropping season. Increasing P use from 30 kg P ha^{-1} resulted in a PEP decline of between 34 % under different sources of biochar and between 25 and 40 % under different sources of biochar+45N30P30K across the cropping season. PENs on three different sources of biochar+45N30P30K with cowpea intercrop were between 50 % and 60 % higher than those obtained under three different sources of biochar+45N30P30K application. The magnitude of PE in N and K was generally higher in the first and second cropping seasons. Except for the second cropping season, the highest ($p \leq 0.05$) PE K in each cropping season was obtained under three different sources of biochar + 45N30P30K with cowpea intercrop that received 30 kg K ha^{-1}. PE was influenced by the soil organic carbon content of the soil and grain N and K uptake (Table 4.3 and 4.4). The single effects of the cropping season, three different sources of biochar+45N30P30K with cowpea intercrop influenced the apparent recovery efficiency of N (ARE) (Table 3.4 and Figure 3.5a-j). At the level of the individual cropping season, the single effects of biochar +45N30P30K with cowpea intercrop influenced ($p \leq 0.05$) ARE except for the second cropping season. Three different sources of biochar+45N30P30K with cowpea intercrop resulted in increased average ARE per season ranging between 20 and

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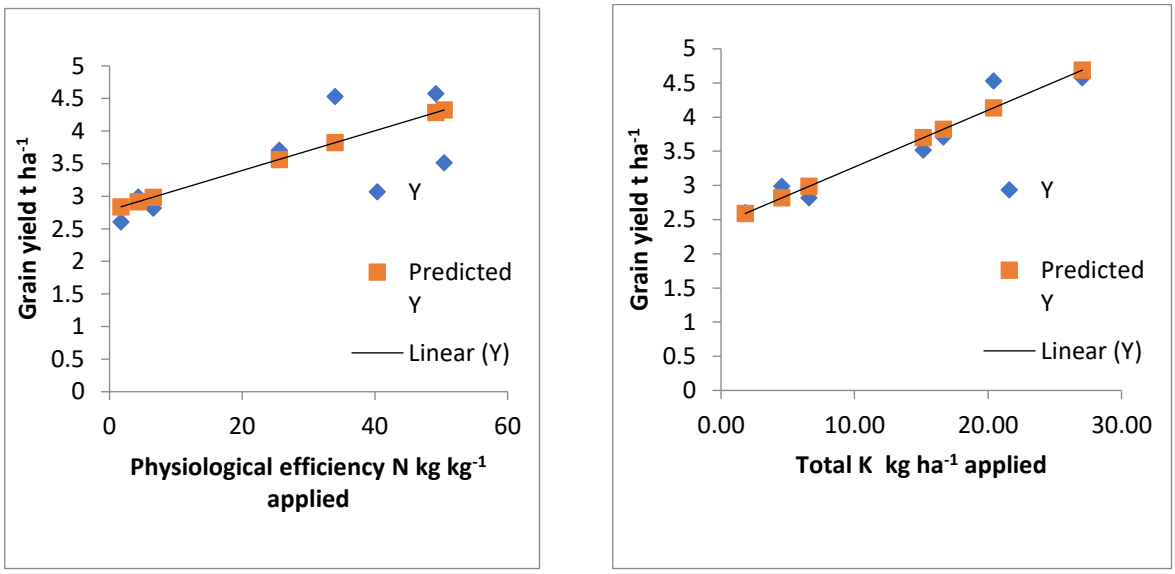
30% compared to the use of three different sources of biochar. Generally, ARE decreased with increasing P rates irrespective of the three different sources of biochar+45N30P30K with intercrop cowpea (Table 3.4 and Figure 3.5c-e and 3.5i-g). ARE were lower in the 2018 cropping season than in the 2019 cropping season. ARE also declined in the 2018 cropping season as the K rate of 30 kg ha^{-1} was increased, but in 2019 K was increased. ARE was significantly influenced by N uptake in the grain (Table 3.3 and Figure 3.5c-e and 3.5i-g). Nitrogen and phosphorus transfer from cowpea to rice plants grown in intercropping under biochar and inorganic fertilizer systems resulted in greater panicle number, spikelet weight, and weight of 1000 grain seeds of rice plants grown in intercropping than solely sole crop (Table 3.5a, b).



A B

Figure. 3.5a. Relation between grain yield and physiological efficiency (b) between grain yield and total applied K of three different sources of biochar and inorganic fertilizer

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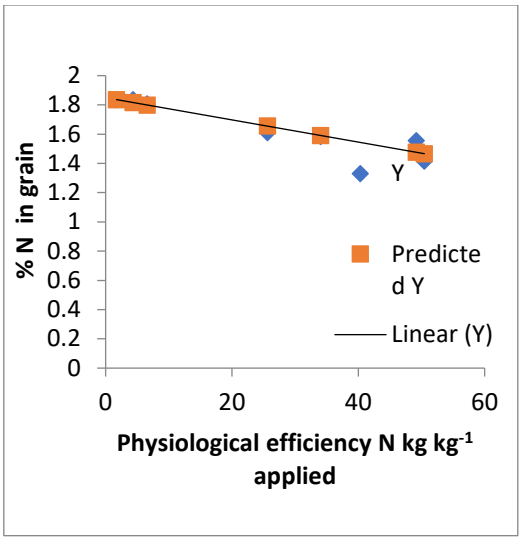

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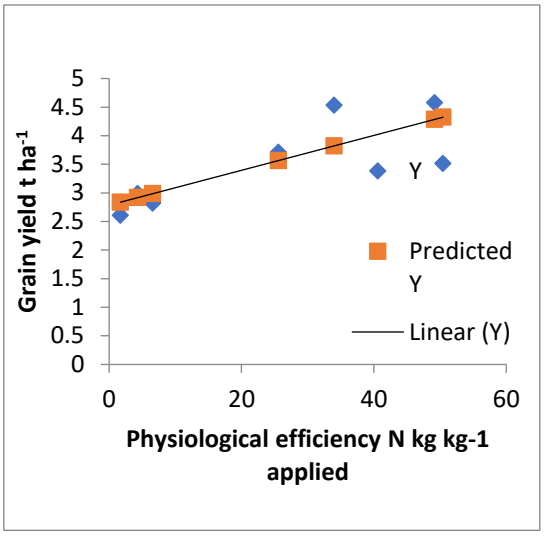
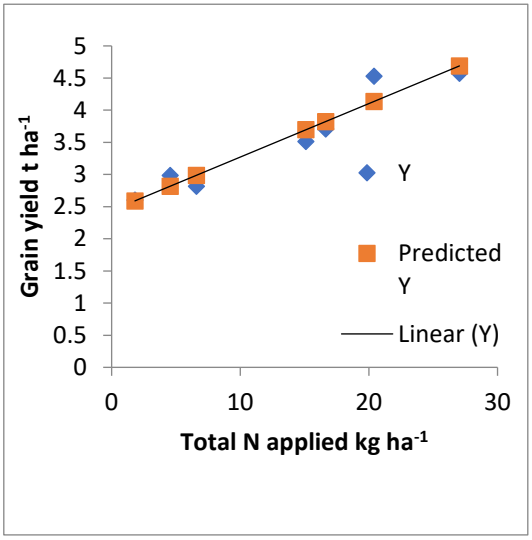


B

Figure 3.5b. Relation between % N grain contents and physiological efficiency applied (b) grain yield and physiological efficiency of three different sources of biochar and inorganic fertilizer



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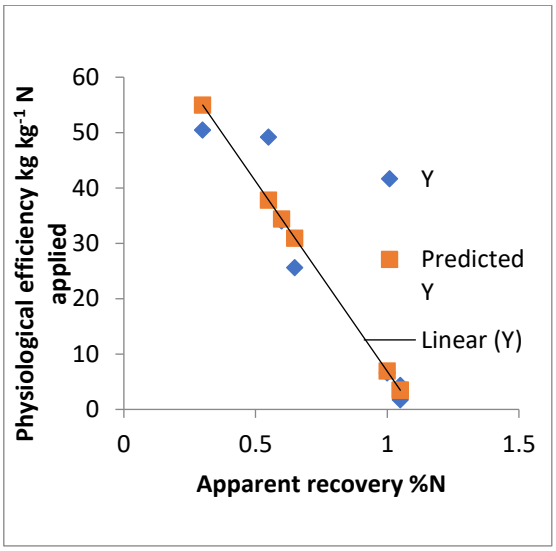

B

Figure 3.5c. Relation between N response in rice, (a) grain yield and total N applied (b) physiological efficiency and apparent recovery % N applied of three different sources of biochar and fertilizer.

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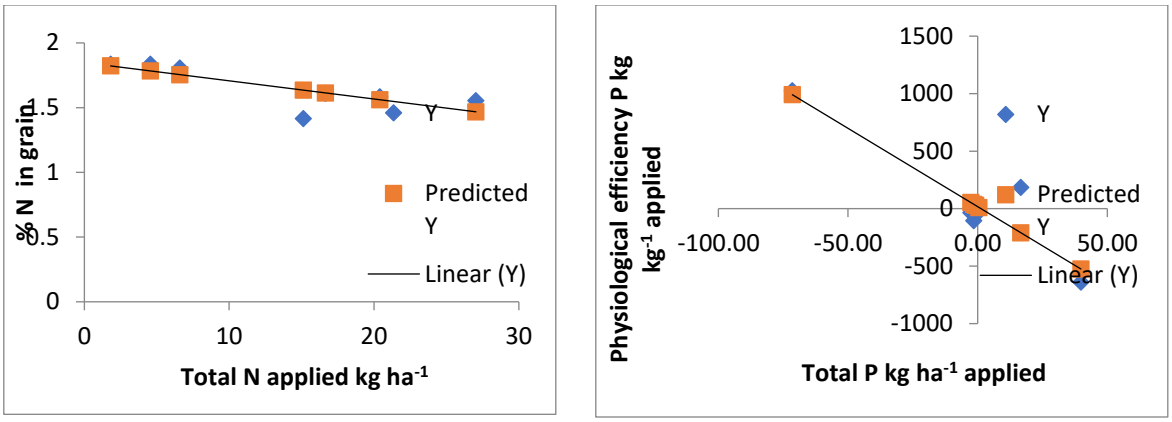
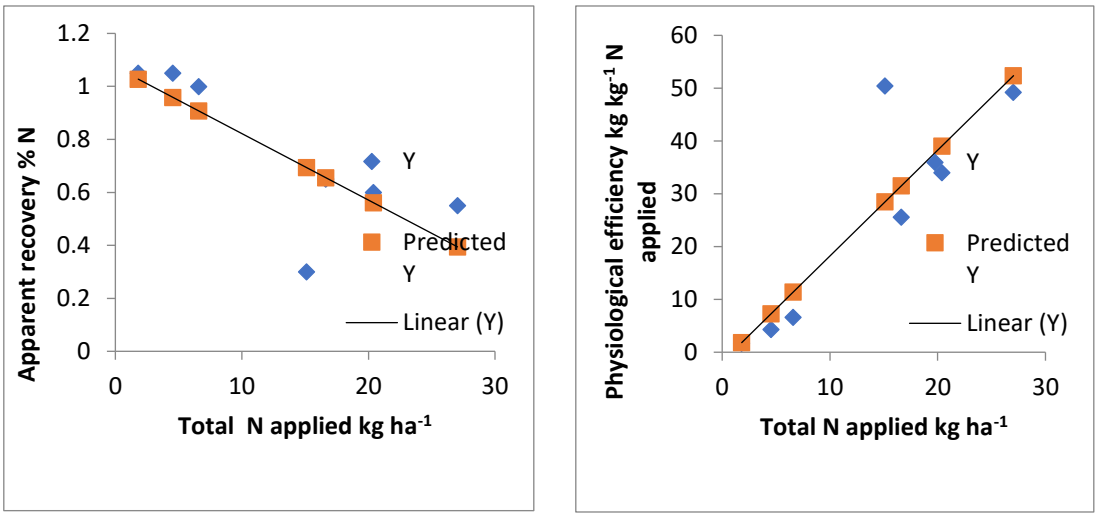


A B

Figure 3.5d (a) Relation between % N in grain and total N applied (b) physiological efficiency and total P applied of three different sources of biochar and inorganic fertilizer.



A B

Figure 3.5e (a) Relation between apparent % N recovery and total N applied (b) physiological N efficiency and total N applied of different sources of biochar.

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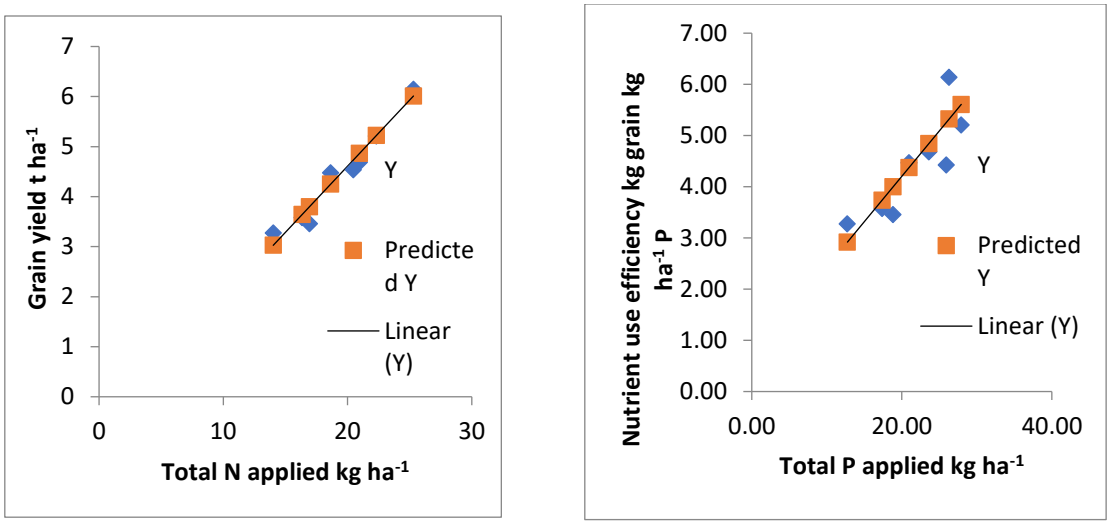
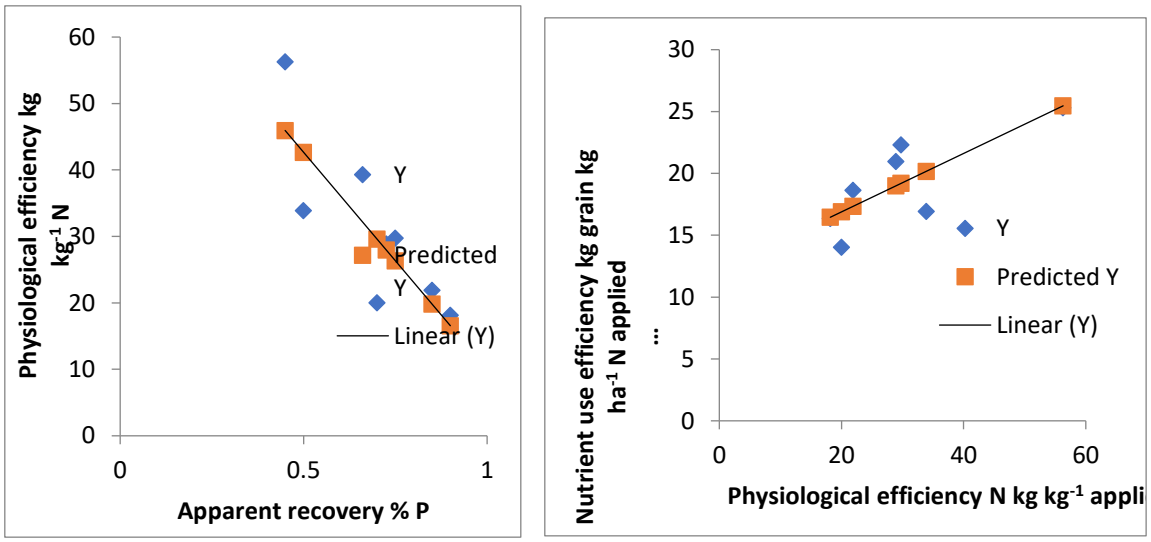


Figure 3.5f (a) grain yield and total N applied (b) nutrient use efficiency P and total P applied of three different sources of biochar and inorganic fertilizer.



A B

Figure 3.5g (a) Relation between physiological N efficiency and apparent N recovery (b) nutrient use efficiency N applied and physiological efficiency N applied of three different sources of biochar and inorganic fertilizer

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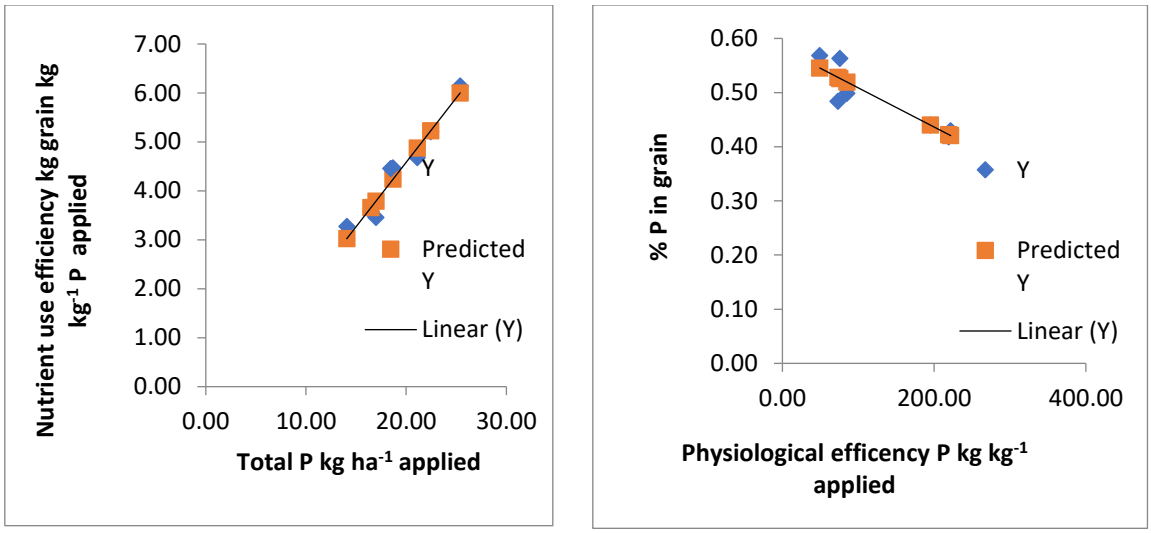
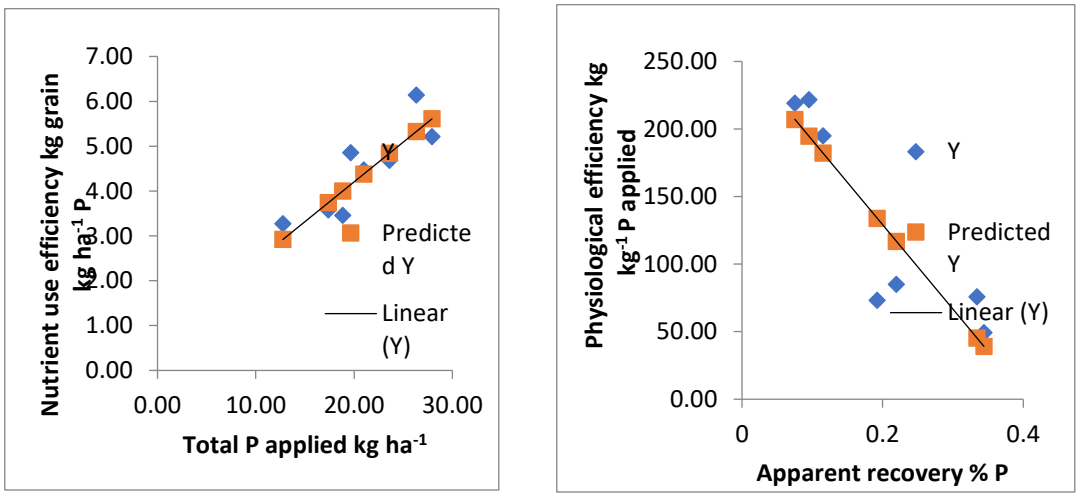


A B

Figure 3.5h (a)Relation between nutrient use efficiency of P in grain and total P applied (b) % P in grain and physiological efficiency P applied of different sources of biochar and inorganic fertilizer.



A B

Figure 3.5i (a) Relation between nutrient use efficiency P in grain and total P applied (b) physiological efficiency P applied and apparent recovery % P of different sources of biochar

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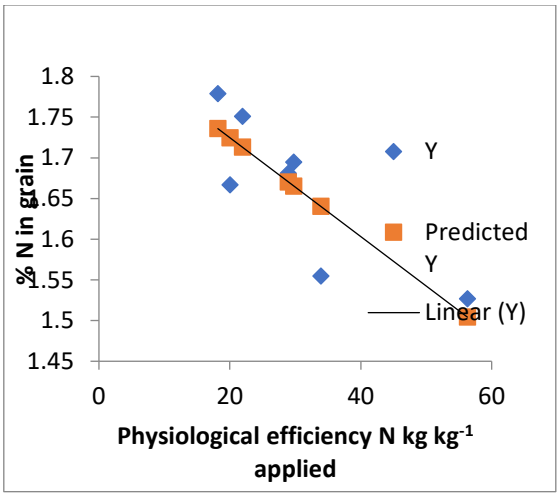

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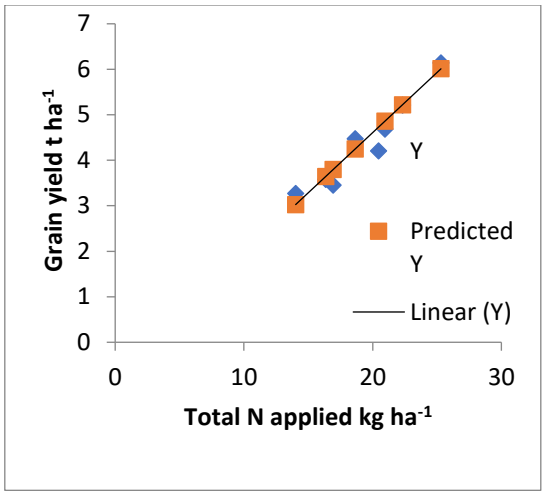

B

Figure 3.5j (a)Relation between % N in grain and physiological efficiency P applied (b) Grain yield and total N applied of three different sources of biochar and inorganic fertilizer

3.5 Conclusion

In Guinea Savannah, this study looked at how integrating three different sources of biochar and inorganic fertilizer into a cowpea intercrop could improve soil fertility and crop yields, improve SOC storage, NPK recovery, and physiological use efficiency, and boost rice yields. In the short term, integrating three different sources of biochar and inorganic fertilizer enhanced SOC storage, productivity, and average PE and ARE over the world averages of 20 kg grain kg^{-1} N and 60 %, respectively. High temperatures, on the other hand, increased evaporation, resulting in unfilled grains from both sole fertilizers use and integrated fertilizer and three different biochar sources. To ensure higher yield, the choice of intercropping is crucial to avoid the rice plant's reproductive period coinciding with temperatures exceeding 34 C. The utilization of three different biochar sources in upland rice has the potential to be employed as a climate change adaptation and mitigation measure. The fact that the beneficial effects of three different sources of biochar application lasted for two cropping seasons after a one-time application shows that biochar can help improve fertilizer efficiency in semi-arid

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tropical agricultural systems. To determine how long biochar will survive in the soil and have an impact on the environment, a long-term study is required (polycyclic aromatic hydrocarbons in soils and Greenhouse gas emission). Before disseminating the technology to farmers, proper training of extension officers will be required to ensure efficient production and application of the three different sources of biochar technology to increase productivity in upland rice. APSIM can serve as an investigative and decision-making tool in this environment to help achieve several productivity goals.

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CHAPTER FOUR

4.0 SIMULATING PLANT GROWTH RESPONSE TO BIOCHAR ON UPLAND RICE-COWPEA INTERCROP IN A FERRIC LUVISOLS SOIL IN GHANA

Frimpong-Manso J[1]* and Ganiyu SA[2]

[1]*CSIR-Soil Research Institute, Kwadaso-Kumasi, Ghana*
[2]*Department of Agricultural Engineering, University for Development Studies, Ghana*
*Corresponding Author's Email: frimpong1977_1@yahoo.com

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Author Statement

Frimpong-Manso Judith (Candidate)

Conceived and designed the research, analyzed and validated the result, and drafted and revised the manuscript.

Ing. Prof. Abdul Ganiyu Shaibu (Supervisor)

Supervised the work and reviewed the manuscript

Abstract

In the Guinea Savannah zone, a field experiment was carried out on ferric luvisols, to compare the growth and yield of rice-cowpea intercrop in which three different biochar sources (groundnut shells, poultry manure, and corn cobs) were enhanced with inorganic fertilizer to boost their cowpea N and P content and were integrated into the soil at a rate of 5 t ha^{-1} with a depth of 20 cm. It was carried out in the 2018-2019 cropping season. A randomized complete block with 4 replications was used. The Agricultural Production Systems Simulator (APSIM) was tested against this dataset. The effect of biochar treatments greatly increases the growth of rice. The model performed better in simulating the experimental P response of the upland rice at high N levels. The yield of rice was predicted (r^2=0.74 and 0.85) in 2018 and 2019 respectively. Biochar amendments to input parameters for the P model, particularly about P amount and uptake for subterranean soil layers were enhanced and fit between experimental and predicted results. The findings showed that cowpea intercrop could be combined with three different sources of biochar to improve soil fertility and crop productivity in areas where N and P are restricted. APSIM performed well in predicting the growth of cowpea well-supplied with P, and the residual biochar and N benefits to a succeeding upland rice crop, including the response to additional inputs of N fertilizer. The data sets from the APSIM model in rice-cowpea intercrop for N and P are efficient and can be recommended for usage in other cropping systems.

Keywords: Agricultural Production Systems Simulator (APSIM), soil layer, biochar source, amendment, rice-cowpea intercrop system, C: N ratio.

4.1 Introduction

In most tropical agricultural soils, severe soil fertility depletion and decreased agricultural output due to nutrient imbalances and a decrease in soil organic matter (SOM) are key restrictions (Lal, 2015, 2020). Biochar improves crop biomass and yields by improving chemical, physical, and biological soil qualities (Glaser et al., 2002; Kookana et al., 2011). Biochar augments soil characteristics by decreasing acidity and improving P and K availability. The application of biochar (charcoal or biomass-derived black carbon (C) to soil is further proposed as a novel approach to establish a significant, long-term, sink for atmospheric carbon dioxide in terrestrial ecosystems. Biochar has many advantages over other additions in terms of soil ecosystem functions, including the ability to improve soil fertility and nutrient retention more effectively than uncharred organic matter (Lehmann et al., 2006).

Biochar can comprise substantial amounts of carbon and P as well as N. For this reason, P is occasionally added because of greater limitation to crop growth compared to N in low-input farming systems. The nitrogen concentration of small-scale farms has been discovered to be low (Simpson et al., 2011; Laird et al., 2009; Ayaga et al., 2006), and questions rise as to whether a farmer would get higher production from the application of biochar to a cowpea crop in its place of rice, and to what degree is the residual N benefit of the cowpea to the following upland rice crop improved by the cowpea responding to the applied biochar. Organic materials like biochar and biochar compost are used to lower production costs also improve soil health and increase productivity per unit area on a long-term basis (Agegnehu et al., 2017). Research/studies by Musah et al., (2013) in the Guinea Savannah zone in Ghana

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have addressed these two queries. That is the case of low and high pyrolysis quality of biochar used in upland rice-cowpea intercrops grown on ferric luvisols soil.

A distinct nature of these studies is that cowpea and inorganic fertilizer treatments were added to aid and measure the upland rice-cowpea intercrop responses to the N and P content of the biochar. Several of the input parameters for simulation, particularly for soil and biochar characteristics, were identified while monitoring the very broad experiments. The data set was used to evaluate the efficacy of APSIM and its new modules, Soil P and Biochar, in simulating the complex connections between climate, soil, and plant growth and yield in rice crops.

A complication, however, is that currently, APSIM rice-cowpea intercrop module is only able to respond to low soil P conditions to simulate P stress on plant growth (Dimes and Revanuru, 2004). However, it was felt that the simulated total biomass response of the APSIM rice-cowpea intercrop could be used as a substitute for the experimental rice responses. Within APSIM, the rice and maize models are based on a common crop template and share the same procedures to act with the soil water and nutrient (N and P) modules to make them available for growing demand. This study validates the performance of APSIM to simulate parts of the experimental rice-cowpea intercrop responses to N and P inputs and the biochar benefits to a successful rice crop.

4.2 Materials and Methods

4.2.1 Study site

Experiments were conducted at the Farming for the Future, University for Development Studies (UDS), Nyankpala in the Northern Region of Ghana (latitude 09.246070N and longitude 000.589920W; altitude 252 m). The area has a unimodal rainfall pattern (April –

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October) with an annual rainfall of 800-1100 mm (Ekekpi and Kombiok 2008). The dry season starts from November to March with day and night temperatures of 33°C - 39°C and 20°C- 26°C respectively (Kombiok et al., 2005; Konlan, 2010). The soil profile has been classified as Nyankpala series (Ferric luvisols and Plinthic acrisols) (FAO-UNESCO, 1988; Imoro et al., 2012).

4.2.2 Biochar preparation

Three different sources of feedstocks were produced from slow and high pyrolysis of groundnut shells, corn cobs, and poultry manure at 400°C - 700°C with a dwelling time of 24 hours under oxygen-limited conditions in a reactor, followed by water and air cooling of charred feedstock to room temperature before grinding. The chemical characteristics of the biochar applied are shown in Table 4.1. Organic carbon was determined by the wet combustion method according to Nelson and Sommers (1996). Total nitrogen was determined by the Kjeldahl method (Bremner, 1965). Available potassium extracted using Bray's no. 1 solution was determined directly using the Gallenkamp flame analyzer. Available phosphorus was determined according to Bray and Kutz (1945).

Table 4.1: Basic biochar properties used for simulations

Feedstock	Pyrolysis	pH 1:5	C.E.C me 100 g^{-1}	N %	P %	K %	C: N ratio (-)	Fraction C (0-1)
Biochar Corn cobs	High	6.67	118.26	0.95	0.21	0.45	11.0	0.129
Biochar Poultry manure	High	9.29	125.63	2.19	0.5	0.47	10.5	0.324
Biochar Groundnut shells	Low	11.13	85.52	1.34	0.13	0.74	12.3	0.243

CEC-cation exchange capacity, N-nitrogen, P-phosphorus, K-potassium, C: N- carbon to nitrogen ratio, C- carbon fraction

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4.2.3 Experimental design and treatments

The experiment was arranged in a randomized complete blocks design (RCBD) with 4 replications. Plot sizes of 1026 m^2 were demarcated into 3x4 m for all treatments. Treatments were applied on June 2017 to experimental plots on a dry weight basis at 5 t ha^{-1}. The test crops were NERICA 14 rice (*Oryza sativa* L.) and Padituya cowpea (*Vigna unguiculata* L.). Treatments comprise of absolute control, sole cowpea, 90N60P60K, biochar poultry manure+45N:30P:30K+cowpea, biochar groundnut shells+45N:30P:30K+cowpea, biochar corn cobs+45N:30P:30K+cowpea, biochar poultry manure+45N:30P:30K, biochar groundnut shells+45N:30P:30K and biochar corn cobs+45N:30P:30K. Then top-dress with nitrogen levels in the form of urea 30 kg ha^{-1} N eight (8) weeks after transplanting. Rice-cowpea intercrop plots were treated with Roundup (Glyphosate) of 300 ml per knapsack as pre-emergence and Gramoxone (paraquat) of 200 mls per knapsack post-emergence herbicides and hand weeded thrice during the season. The nursery seed bed was prepared to a finer tilth to allow uniform crop establishment. One fifty (150) seeds per square meter were drilled at a row spacing of 20 cm and sow seeds 2-4 cm deep. Biochar that preceded the experiments was incorporated in early May 2017 for the nursery. The applied biochar was incorporated into the 20 cm surface soil layer. Short duration (85 days) upland rice (Nerica 14) was transplanted by hand and cowpea (padituya), was sown on the next day. Rice seedlings were transplanted at a spacing of 20 cm by 20 cm at the rate of 75 kg ha^{-1} in the sole crop, Cowpea seeds were planted at the rate of 25 kg ha^{-1} at the spacing of 60 cm by 20 cm in pure stand. The space between any rice row and any of the cowpea rows was 60 cm apart. EmaStar 112 EC (Emamectin benzoate 48 g^{-1} + Acetamipride 64 g^{-l}) 10mls per knapsack was used to treat aphids and spittle bugs on the rice-cowpea intercrop plots. The

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cowpea was harvested at three months, while the rice was harvested at four months after planting.

4.2.4 Simulations

Soil parameters and initial conditions used to simulate experiments on the ferric luvisols soils are set out in Table 4.2. Analysis of the moisture content and water potential determinations taken throughout the rice-cowpea crops provided estimates for the crop lower limit and the drained upper limit water contents in each treatment of the soil. Concentrations of organic carbon (OC), total N, and the amounts of soil water were measured. Bulk density and CEC values were estimated. P sorption characteristics for surface layers were known (Puziy et al., 2002), and data for the other layers were estimated. Higher values (stable soil organic matter not contributing to inorganic nitrogen quantity) have been set using % OC in the 0-30 cm layer as a guide and based on experience in setting this parameter (Verheijen et al., 2010). Carbon in biochar has contributed to the soil crop and has been reported for the guinea savanna environment (Baatuuwie et al., 2020), resulting in abruptly high biomass yields on the N-poor soils. To increase the soil N quantity and include the effects of N additions from the biochar, altered N (from) in the soil 0-30 cm was calibrated aloft until there was a bond between simulated and measured biomass yield for the absolute control treatments. Similarly, altered P values in Table 4.2 were adjusted for the soils, to give a practical prediction of observed yields in the existence of acceptable N.

Table 4.2. Soil profile parameters used in this study

Soil Layer	**1**	**2**	**3**	**4**	**5**
Layer thickness (cm)	0-15	15-30	30-60	60-90	90-120
Soil water parameters					
BD ($g\ cm^{-3}$)	1.58	1.62	1.57	1.59	1.57
SAT (mm^{-1})	0.354	0.358	0.368	0.342	0.339
DUL (mm^{-1})	0.202	0.204	0.201	0.198	0.132
LL15 (mm^{-1})	0.050	0.106	0.153	0.128	0.198
Soil-C parameters					
OC (%)	0.47	0.41	0.33	0.38	0.33
pH (H20)	4.66	4.66	4.66	4.56	4.56
Finerta	0.36	0.36	0.70	0.90	0.90
Fbiomb	0.016	0.02	0.02	0.01	0.01
Soil P parameter					
Labile P ($mg\ kg^{-1}$)	11.6	5.8	5.0	2.0	1.0
P sorption ($mg\ kg^{-1}$)	60	80	150	180	200

Soil parameterization of ferric Luvisols at farming for the future, UDS experimental farm to specify APSIM simulations. LL, lower limit; DUL, drained upper limit; SAT, saturated volumetric water content; BD, bulk density; OC, organic carbon; Fbiom, a non-inert fraction of microbial C; and Finert, an inert fraction of organic C.

4.2.5 Rice-cowpea Intercropping system simulation

An upland rice transplanting and sowing of cowpea were simulated on July 2018 and 2019, with the plant population set to 10 plants m^{-2} (the observed plant stands at harvest). Crop parameters for upland rice Nerica 14 were found to best estimate the duration of the rainy season. Fertilizer was broadcast on August 2018 and 2019 (90N:60P:60K) and 45N:30P:60K) and Sept 2018 and 2019 (30N). To evaluate model predictions, simulated

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upland rice biomass was compared with the observed total biomass of rain-season upland rice.

The APSIM modules were to simulate intercropping systems as part of a project aimed at growth response to biochar application of rice-cowpea intercrops grown under variable biochar and inorganic N and P on a Ferric luvisol soil. Rice-cowpea intercrop for the main cropping seasons was simulated for soil from each treatment using the data in Table 4.3, except in this case it was assumed that there was no P constraint. Simulations began on June 11 and a short-duration cowpea was planted on 22 July, with a population of 33 plants m^{-2}. After grain harvest, the removal of cowpea biomass was simulated on 4 November. Upland rice NERICA 14WAB 880-1-32-1-2-P1-HBWAB 56-50 / CG 14//2*WAB 56-50 was planted on 21 and 29 July 2018 and 2019 respectively with a population of 13.8 plants m^{-2} for the ferric luvisols. Two N fertilizer treatments for the rainy season rice were simulated; 60 and 30 kg N ha^{-1}, with fertilizer applied as per the experimental details described above for the rainy season. To assess model predictions for upland rice, simulated biomass is compared to observed biomass from the 60P treatment (adequate P conditions). To assess the simulation of upland rice response on moisture content following cowpea, simulated biomass is compared to observed biomass for moisture content receiving 30 kg P t ha^{-1}. Inadequate N is a constraint to crop growth is simulated. Atakora et al. (2015); Owusu-Bennoah et al. (1995) found that P is the second most limiting nutrient in soils in the Guinea Savanna agro-ecological zone in the region, which is consistent with findings from earlier studies in the region.

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Table 4.3: Soil fertility treatments used in the short-term experiment at Nyankpala

Treatment	Activity	2017	2018	2019
Absolute Control	None	None	None	None
NPK Fertilizer	Band placement	None	90,60,60 kg ha^{-1}	90,60,60 kg ha^{-1}
Biochar poultry manure	Incorporation	5 t ha^{-1}1y biochar	None	None
Biochar groundnut shells	Incorporation	5 t $ha^{-1}1y^{-1}$ biochar	None	None
Biochar corncobs	Incorporation	5 t ha^{-1} y^{-1} biochar	None	None
Biochar poultry manure +NPK fertilizer	Incorporation & band placement	5 t $ha^{-1}1y^{-1}$ biochar	45,30,30 kg ha^{-1}	45,30,30 kg ha^{-1}
Biochar corncobs +NPK fertilizer	Incorporation & band placement	5 t $ha^{-1}1y^{-1}$ biochar	45,30,30 kg ha-1	45,30,30 kg ha^{-1}
Biochar groundnut shells +NPK fertilizer	Incorporation & band placement	5 t $ha^{-1}1y^{-1}$ biochar	45,30,30 kg ha-1	45,30,30 kg ha^{-1}

Nitrogen (N) 45 Phosphorus (P) 30 Potassium (K) 30

Three different sources of biochar treatments were applied once throughout three years (2017-2019) cropping seasons.

Determination of Organic Carbon,	Determination of Total Nitrogen	Determination of Bulk Density
The Walkley and Black (1935) procedure was used for Soil organic carbon determination	Analysis Total soil nitrogen was assessed using the Kjedahl method by Bremner (1965).	Soil bulk density, pb, the dry density of the soil samples was determined from soil core collected from the field with a core sampler using the Klute (1986). Bulk density was calculated using the formula Blake, (1986) described.

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4.3 Results and discussion

The simulated and observed biomass responses of upland rice crops on ferric luvisols soil are expressed in Figure 4.1. Observed biomass responses on the three different sources of biochar+45N30P30K+cowpea intercrop treatments were significantly ($p < 0.05$) greater than those on the 90N60P60K. The biomass yields for the three different sources of biochar+45N30P30K fertilizer treatments were significantly ($p < 0.05$) higher than the absolute control. In contrast, only the three different biochar+45N30P30K+cowpea intercrop treatments provided statistically significant responses on the ferric luvisols. Results for both biochar and inorganic fertilizer show a stronger response to N fertilizer (N90) than to P fertilizer ($p < 0.05$) and an increased N response ($p < 0.05$) in the presence of P (N and P treatment). The simulated trends in Figure 4.2a, b are less responsive, with almost no change in predicted yields for absolute control. Simulated biomass yields with the addition of biochar+45N30P30K+ intercrop are higher than that simulated for the control on each plot, indicating that the model simulated net immobilization and a reduced N supply for crop growth without the addition of the cowpea intercrop. Simulated responses to the application of inorganic N on both cropping seasons and N+P are close to the observed responses, but there is a large over-prediction for the three different sources of biochar N+P treatment. What the model was able to simulate reasonably well were the differences in biomass yields between the three different sources of biochar.

The observed three different sources of biochar, inorganic fertilizer, and cowpea intercrop varied between RMSE= 315.176 and 460.0358 kg ha^{-1} in 2018 and 2019, respectively, for grain yield. In response to a wider range of applied N+P for upland rice, the model could reasonably simulate the fluctuation of three different biochar, inorganic fertilizer, and

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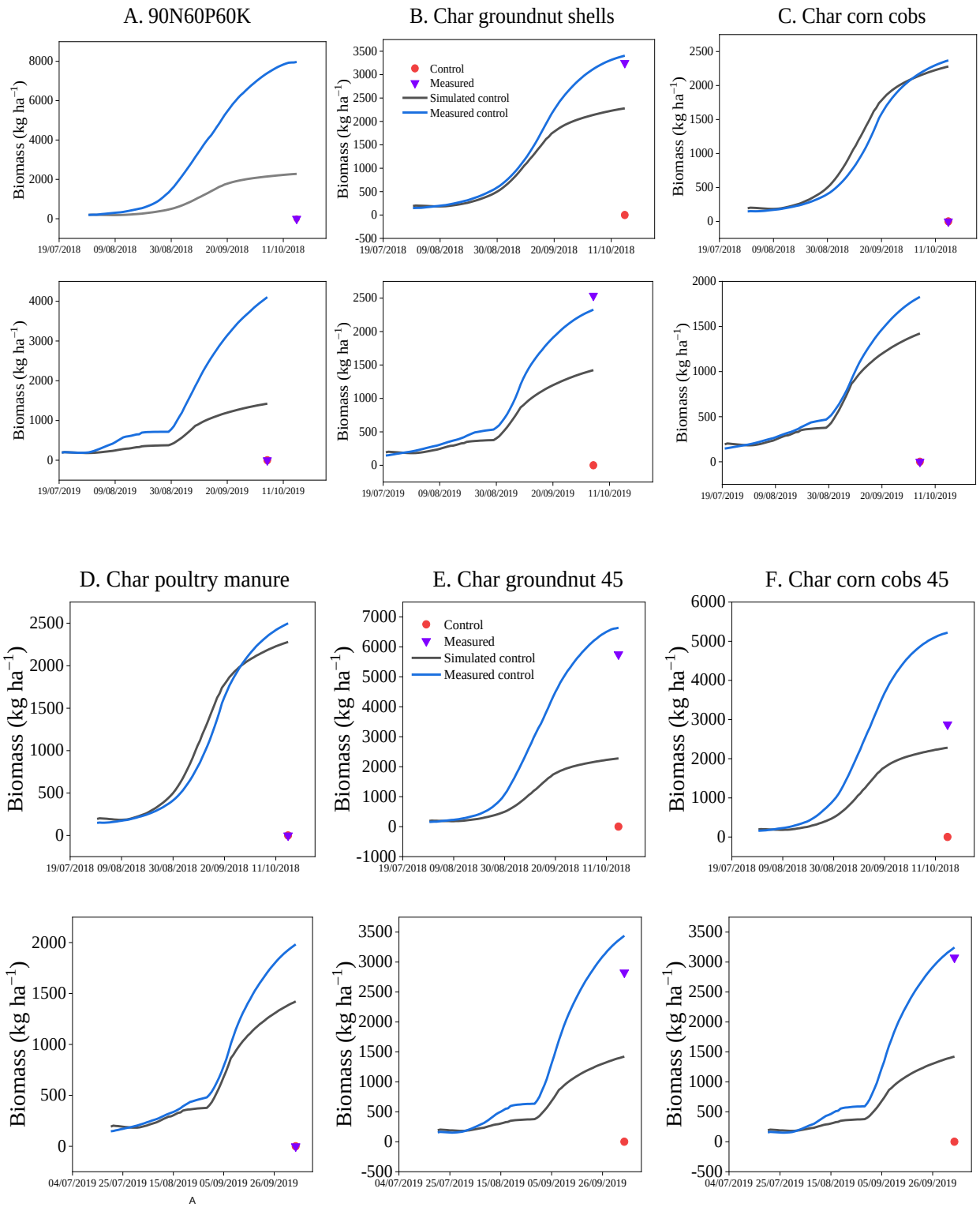
cowpea intercrop sources (Figures 4.1a, e, f and Figure 4.3a, e, f, g). However, as exhibited in Figure 4.3, the model tends to slightly underestimate three different sources of biochar+ 45N30P30K. In figure 4.3 the RMSE of grain yield was 315.18 and 460.04 kg ha^{-1} for 2018 and 2019, respectively. The RMSE of biomass was 1981.669 and 3562.842 kg ha-1 for 2018 and 2019, respectively in figure 5.1.

As shown in Figures 4.1(a, e, f) and 4.3(a, e, f, g), biomass and grain yield (excluding some data points) fit wider one-to-one line with optimum 90N60P60K and three different sources of biochar+45N30P30K+ cowpea intercrop data, but the model overestimated when grain yield data were included. On the contrary, the predicted grain yield at the three different sources of biochar was largely overestimated regardless of the three different sources of biochar, inorganic fertilizer, and cowpea intercrop. There was good fitness between simulated and observed three different sources of biochar+45N30P30K when only optimum grain yield data were used (Figure 4.1b, c, d, and g; Figure 4.3b, c, d). There was good fitness between simulated and observed three different sources of biochar+45N30P30K when only optimum grain yield data were used (Figure 4.3b, c, d, and Figure 4.1b, c, d, and g). However, when 90N60P60K was also included in the validation, model performances were reduced. The RMSE of grain yield was 315.18 and 460.04 kg ha^{-1} for 2018 and 2019, respectively. The RMSE of biomass was 1981.669 and 3562.842 kg ha^{-1} for 2018 and 2019, respectively. The result exhibited that the model performance generally decreased when the data of 90N60P60K conditions were included. The goodness of fitness was reduced and RMSE increased for almost all of the growth parameters concerned in Figures 4.1 and 4.3. In general, the simulation results overestimated the three different sources of

biochar+45N30P30K+ cowpea and 90N60P60K yielded for both treatments, while biochar+45N30P30K was underestimated.



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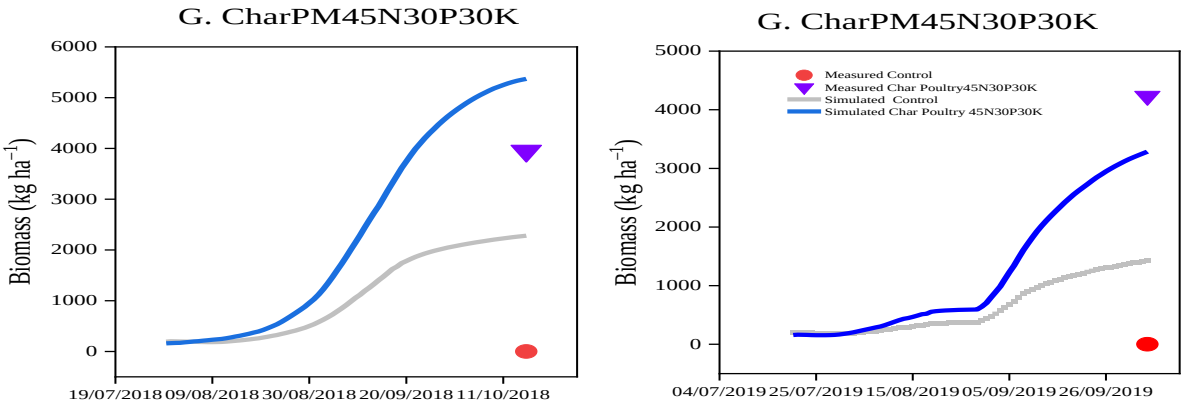

Figure 4.1. Simulated and observed biomass responses of upland rice crops on ferric Luvisols soil

4.4. Upland rice-cowpea intercrop

The observed responses of upland rice to biochar and inorganic fertilizer P in farming for the future, UDS-Nyankpala. In the case of rice, biomass yields are significantly higher ($p < 0.05$) for the luvisols in 2019 than in 2018. There are significant ($p < 0.05$) increases in biomass response of rice to the three nutrient treatments (biochar poultry manure+45N30P30K+cowpea intercrop, biochar corn cobs+45N30P30K+cowpea intercrop, biochar groundnut shells+45N30P30K+cowpea intercrop) compared with the 90N60P60P and absolute control, and between the nutrient treatments, indicating that upland rice responded to the three different sources of biochar and levels of P input (60, 30 kg P t ha^{-1}) and its availability. As APSIM–upland rice is not 'P-aware', simulated biomass can be compared only for the situation where P nutrition can be assumed adequate, in this case, the P30 treatment. In Figure 4.1, the simulated biomass of upland rice for the three different sources of biochar compares well with the observed yield, but for the biochar poultry manure+45N30P30K+cowpea, biochar corncobs+45N30P30K+cowpea, biochar groundnut

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shells+45N30P30K+cowpea, the simulated yield is less than that for the 90N60P60K, and substantially less than the observed.

The upland rice model used here (APSIM Version 7) has routines to simulate water stress on plant growth, and over-prediction of this stress seems to be responsible for the simulation of the lower yield on the upland rice under absolute control treatment. For the three different sources of biochar +45N30P30K+cowpea, 85% of crop days are simulated to have profile water contents indicative of saturation, whereas for the 90N60P60K, it is less than 50% of days. The rice–cowpea intercrop provides an assessment of how well the systems model can simulate the combined effects of organic and inorganic N supply. Figure 4.1 shows the observed and predicted biomass yield of the three different sources of biochar used in upland rice crops in northern Ghana planted (fertilized with P60 and P30) and receiving two rates of N fertilizer. From the observed responses to fertilizer N, it is clear that intercropping cowpea in upland rice was able to supply all of the upland rice crop N requirements on ferric luvisols soil. The model was able to predict very closely the observed biomass responses for the respective different biochar along with the response to N fertilizer inputs on each plot (Figure 4.1). It should be noted that for both the simulated and observed three different sources of biochar and inorganic fertilizer on upland rice, all above-ground biomass from the preceding upland rice was removed, and the carryover of N from the rice grain is via the rice straw material. Hence, results in (Figure 4.1) suggest that the model can simulate these biochar organic N benefits, and interaction with inorganic N, with a high degree of precision.

In these experiments, measured yield responses for cowpea and upland rice were attributed to three different sources of biochar, P, and N-responsive soils. However, the results of the simulation of the observed P responses and interaction with N supply in the upland rice plant

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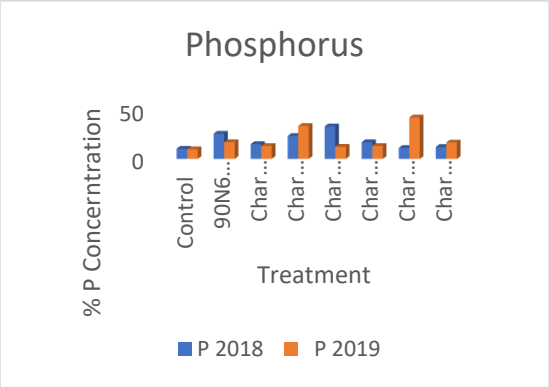
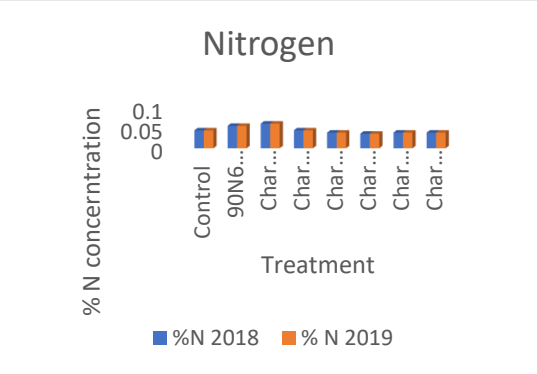
were not disappointing, showing sensitivity to inputs of three different sources of biochar and inorganic P and N levels (i.e., biochar+45N30P30K+cowpea and P60 treatments). The application of APSIM to simulate the northern Ghana data is one of the early experiments at the exploitation of the unique P abilities on an independent data set. Results attained here certainly replicate a measure of naivety by parameterizing this novel model. Probert (2004) has recommended that the impediment in parameterizing the model is mainly related to explicitly the P position in terms of P sorption and labile P in each plot of soil. Additional investigative amendments to input parameters, particularly the percentage factor between measured Olsen P and labile P, are undoubtedly appropriate (Micheni et al., 2004) and how this might differ between soils, and maybe with soil depth. The alternative parameter that may permit consideration in the P uptake aspect that Probert (2004) proposes is crop type and variety. In this study, the P supply aspect was set to 2.

However, the most concern with the model is the insensitivity of upland rice plant response to biochar and P involvement at the low-slung N levels. Part of this challenge may cause the calibration process used for labile P. For the upland rice crop responses used in this experiment, moisture stress, at least owed to deficits, can be reduced. Henceforth, the results recommend further stimulating of the model is obligatory for situations where both N and P are limiting plant growth. The model data set would have crop growth response to each component computed in the appearance of appropriate levels of the biochar, in addition to limiting levels of both N and P. This would help overcome some of the calibration difficulties met in this present study.

The APSIM–upland rice model (Robertson et al., 2001) has also not been extensively evaluated against field-observed growth responses. While the P effects on upland rice crop

growth within the trials cannot be considered at this point, the simulation of the P30 treatment for the sandy soils provided some beneficial sensitivities. Biochar in terms of water deficit practices in upland rice and the soil water retention parameters for the ferric luvisols permits faster attention. The close potential between observed and predicted biomass at absolute control for the cowpea intercrop crop (Figure 4.1) recommends that the model captures very well the main mechanisms beneficial to enhanced soil N supply in upland rice. The earlier, APSIM has been revealed to achieve well in simulating inorganic N supply ensuing biochar+ 45N30P30K inputs (Berghuijs et al., 2021) and crop response to 90N60P60K and biochar+ 45N30P30K+cowpea intercrop (Tsubo et al., 2005; Shamudzarira et al., 2000). Simulation of the upland rice–cowpea intercrop in this experiment has protracted assessment to the northern Ghana, upland rice variety and three different sources of biochar are important to sandy soil in Guinea savanna agricultural systems. The experiment has also emphasized the need to cover the P stress practices to other upland rice and cowpea crops commonly grown by smallholder farmers in northern Ghana.





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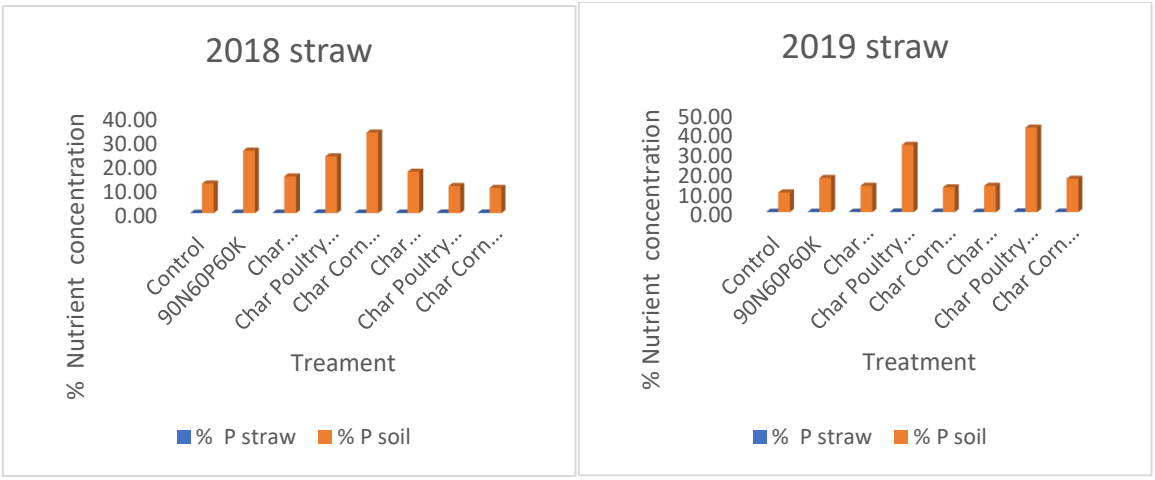

Developmental Stage Developmental stage

Figure 4.2. Comparison of measured P and N concentrations in rice plants under the biochar poultry manure, biochar corncobs, and biochar groundnut shells treatments concentrations of straw and soil defined in APSIM (Developmental stages are: 1 - sowing, 2 – germination, 3 – emergence, 4 – end of the juvenile stage, 5 – floral initiation, 6 – flowering, 7 – start grain filling, 8 – end of grain filling, 9 – maturity)

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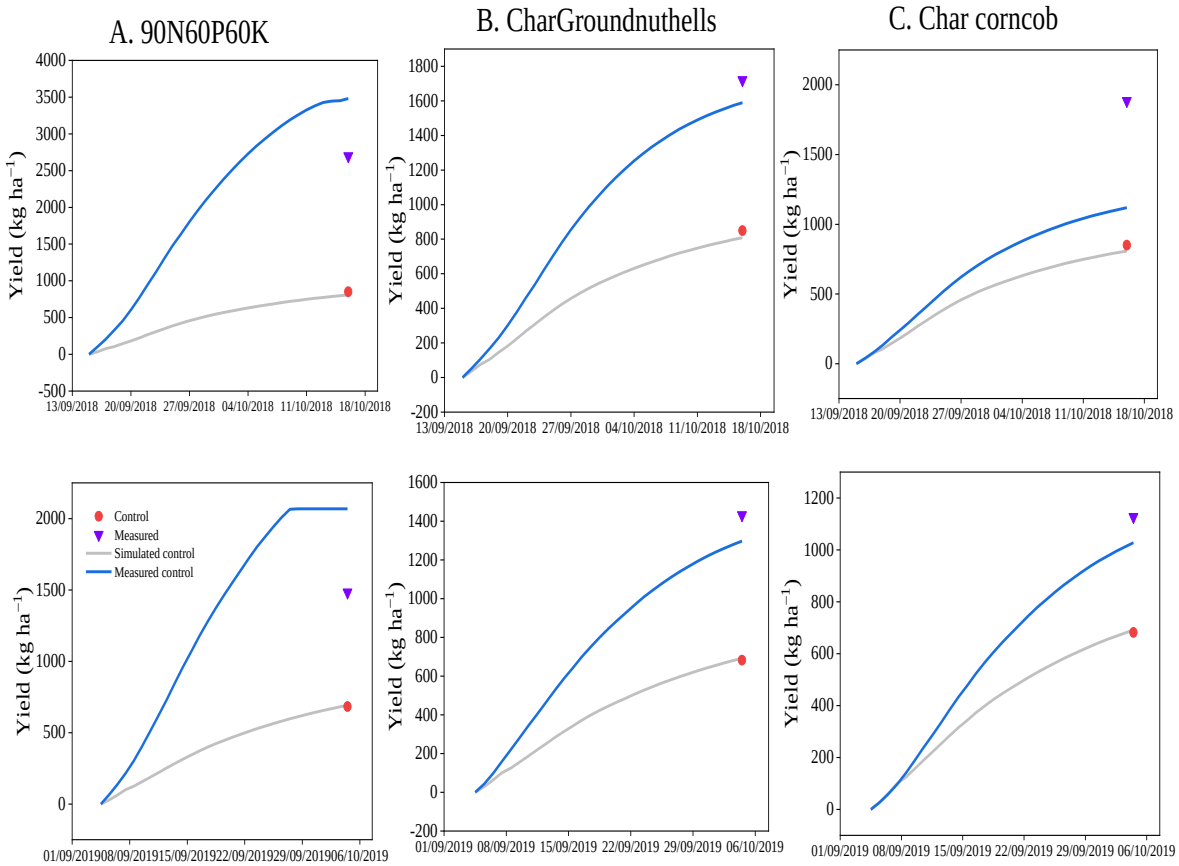

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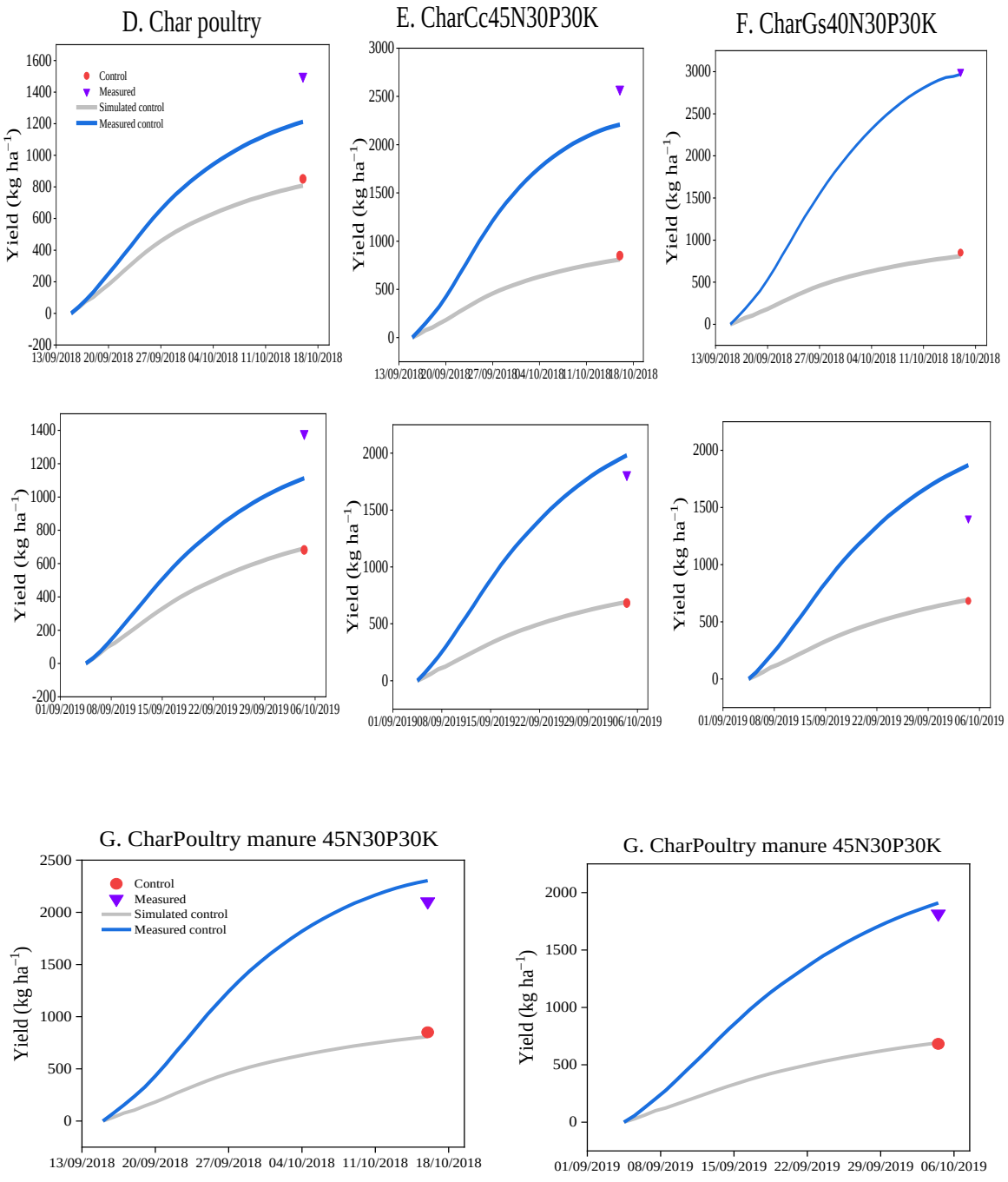

Figure 4.3. Simulated and observed grain yield responses of three different sources of biochar and inorganic fertilizer on ferric Luvisols soil

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4.5 Effects of biochar on upland rice-cowpea intercropping systems on yield and yield components of upland rice on yield and yield components of upland rice

Table 4.2 shows the impact of three different sources of biochar and inorganic fertilizer on the yield and yield components of upland rice-cowpea intercrop. In the intercrop cropping, the number of tillers per square meter of the land of biochar+45N30P30K+cowpea on upland rice was significantly ($P<0.05$) higher than in the 90N60P60K treatment. The number of panicles per square meter was significantly ($P<0.05$) larger in the biochar+45N30P30K+cowpea treatment than in the 90N60P60K treatment when compared to the alternate hills and rows. In terms of the number of panicles, there were significant variations ($P<0.05$) in the cropping systems between the 90N60P60K and biochar+45N30P30K. The biochar+45N30P30K+cowpea cropping system had the longest panicle length per hectare, while the biochar+45N30P30K cropping system had the shortest. In terms of soil moisture content for grain development, however, there were significant variations ($P<0.05$) between the three different sources of biochar+45N30P30K+cowpea cropping systems in terms of the number of spikelets, grain yield, 1000-grain weight, filled grain and unfilled grain than 90N60P60K. Plant height was higher in biochar+45N30P30K+cowpea on upland rice than in the 90N60P60K cropping system, alternate rows, and then alternate hill cropping systems (Table 4.2).

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Table 4.2. Effect of biochar and inorganic fertilizer soil amendments on yield and yield characters of upland rice-cowpea intercrop.

Treatment	Spad leave (m^2)	No. of tillers (m^2)	Panicle length (cm)	Number of panicles (m^2)	Weight of fill grains (kg)	Weight of Unfill grains (kg)	Soil moisture content (kPa)	No. of spikelets per panicle (m^2)	Plant height at maturity (cm)
ChCc+N45P30K30+C	282.24	57.50	35.15	100.5	11.57	3.29	29.66	28.500	74.24
ChGs+N45P30K30+C	276.29	46.69	38.83	98.5	12.76	2.61	27.29	31.500	69.83
ChCc+N45P30K30	237.54	39.94	30.84	38.25	7.932	2.46	19.04	25.250	63.21
ChGs+N45P30K30	226.74	42.94	30.67	33.75	9.72	2.73	19.21	21.000	65.3
ChPM+N45P30K30	247.91	47.94	39.61	42.75	7.99	2.59	20.08	22.750	66.45
ChPM+N45P30K30+C	309.27	66.69	70.92	118.75	16.03	2.88	30.39	33.250	71.78
Absolute Control	208.71	32.69	30.61	22.5	6.102	0.89	17.11	10.000	99.61
N90:P60: K60	288.38	50.13	55.90	31.25	11.23	2.84	17.46	28.250	62.69
Tukeys HSD	**18.87**	**6.41**	**2.30**	**10.24**	**2.19**	**0.84**	**3.00**	**2.91**	**5.01**
CV	**10.56**	**19.33**	**4.57**	**4.57**	**28.84**	**52.01**	**9.29**	**16.19**	**5.91**

Ch-biochar, C-cowpea, N-nitrogen, P-phosphorus, K-potassium, PM-poultry manure, Gs- groundnut shells, Cc-corn cobs

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4.6 Effects of rice-cowpea intercropping systems on yield and yield components of cowpea.

Table 4.3 shows the effects of three distinct sources of biochar and inorganic fertilizer on the yield and yield components of cowpea (CP) in rice-cowpea intercropping systems. Cowpea plant height and grain yield were not significantly different for any of the three different sources of biochar+ C cropping systems. Cowpea plant height was not considerably higher under sole cowpea intercropping than under alternate hills and rows cropping (Table 4.3). Cowpea plant height was also much higher when intercropped with rice than in other cropping systems. Cowpea pod weight was highest when grown as a single crop and lowest when grown in intercropping systems with upland rice. Cowpea pod weight had almost similar values for all the intercropping systems with upland rice.

Table 4.3 Effect of biochar and inorganic fertilizer soil amendments on yield and yield characteristics of cowpea intercrop

Treatment	Plant height (cm)	Pod weight (kg)	Grain weight (kg)
Sole cowpea	79.00	18.27	135.55
ChCc+45N30P30K+C	160.00	5.30	3.87
ChGs+45N30P30K+C	163.25	4.89	3.36
ChPM+45N30P30K+C	167.75	6.64	4.86
Tukeys HSD	**61.45**	**6.69**	**93.60**
CV	**15.94**	**39.58**	**49.03**

Ch-biochar, C-cowpea, N-nitrogen, P-phosphorus, K-potassium, PM-poultry manure, Gs-groundnut shells, Cc-corn cobs.

4.7 Conclusion

The farming for the future experiment was carried out in a very diverse environment and on a very varied soil to those on which the ideas in the APSIM phosphorus procedures were initially developed and verified. Especially, this is a location with intermittent rainfall where the model predicted that moisture stress did not disturb plant growth, and the soil, a ferric

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Luvisol, has increased P-sorption characteristics. The data set used to simulate the behavior of P in the soil and the P concentrations and uptake by upland rice were based on a plant grown on a low P-sorbing soil in a Guinea savannah environment. The model executed well in predicting the growth of upland rice crops from different rates of P treatments. Another factor was that the N and biochar inputs led to different plant growth in the two cropping seasons. The predicted moisture content, and P and N stresses were beneficial in supporting knowing the motives for the variations in response to N and P inputs in the two cropping seasons. This is the initial situation where the P form of the upland rice model was verified under conditions where N stress was also an issue. The result from the model proposes that the simulation of plant growth with two potential restrictive nutrients was feasible. Olsen P data was used for priming the labile P of the model. The soil P data was attained for samples taken after harvest. There was a slightly meager pact between the predicted differences in labile P and the soil P data.

The results showed a positive interaction effect of the incorporation of three different sources of biochar on the upland rice-cowpea intercrop with inorganic fertilizer. In terms of rice yields, the study found that biochar interaction with N and P was generally comparable to the interaction with rice-cowpea intercrop. While the results showed that sole treatment increased rice yields, applications did not. There is no doubt that inorganic fertilizer and intercropping in agroecosystems are beneficial. However, it shows that in areas with insufficient N and P, cowpea intercrop could be used in combination with three different sources of biochar to improve soil productive capacity and crop yields in smallholder agroecosystems. In the presence of a companion crop, cowpea, there were significant

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differences in yields and yield components of the three different sources of biochar on upland rice-cowpea intercrop and N and P. Although not significantly different from the other intercrops, alternate rows of upland rice and cowpea consistently yielded greater numerical cowpea grain yields. Yields of upland rice-cowpea intercrop under biochar plus inorganic fertilizer plus Cowpea intercrop were generally higher than inorganic fertilizer. In conclusion, the improved performance of three different sources of biochar+45N30P30K+cowpea intercrop under diverse N and P regimes demonstrated its advantage, thus recommending it to small-holder farmers with an N application of 30 kg ha^{-1}. Top-dressing of N fertilizers at 8 weeks could be more advantageous than a full dose of N at the time of transplanting, imparting a higher yield. The analysis of the APSIM model results showed the strong dependency of the biochar+45N30P30K+cowpea intercrop system upon plant N and P uptake and growth under ferric Luvisol. The modeling results for N and P under ferric Luvisol showed that they could be utilized as a decision support tool under different sources of biochar+45N30P30K+cowpea intercrop to have good management options.

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CHAPTER FIVE

5.0 EFFECTS OF BIOCHAR ON WATER RETENTION AND LEACHING OF NUTRIENTS IN SANDY LOAM SOIL

Frimpong-Manso J[1] *, Abdul Ganiyu S[2] and Kugbe Xorse J[2]

1CSIR-Soil Research Institute, Academy Post Office, Kwadaso-Kumasi, Ghana
2University for Development Studies, Ghana
**frimpong1977_1@yahoo.co*

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Frimpong-Manso Judith (Candidate)

Conceived and designed the research, analyzed and validated the result, and drafted and revised the manuscript.

Ing. Prof. Abdul Ganiyu Shaibu (Supervisor)

Supervised the work and reviewed the manuscript

Dr. Joseph Xorse Kugbe (Co-Supervisor)

Supervised the work and reviewed the manuscript.

Abstract

Nutrient leaching causes agronomic and environmental problems in intensively cultivated soils. In this study, the effect of biochar on the retension of nutrients in sandy loam soil was evaluated. Upland rice was amended with 3 different sources of biochar in a randomized complete design with 4 replications. The treatment included a control (no input), fertilizer, and upland rice either applied alone or in combination with the three different sources of biochar (poultry manure, corn cobs, and groundnut shell). Biochar levels were 5 t ha^{-1} each and were incorporated into the soil at the same time. Inorganic fertilizer was applied at a rate of 90, 60, 60 and 45, 30, 30 kg ha^{-1} NPK, as straight fertilizer and then top-dress with nitrogen levels in the form of urea 30 kg ha^{-1} N eight (8) weeks after transplanting. Upland rice was planted in each lysimeter. Leachate from each lysimeter was collected at 3 weeks intervals for 24 months. For the 24 months running biochar significantly decreased the volume of water leached. Control and 90N60P60K treatments showed higher concentrations of NO_3-N and K in the leachate. At a depth of 70 cm leaching was significantly reduced with all three different sources of biochar combined with 45N30P30K and 90N60P60K. The application of three different biochar sources to tropical sandy loam soil may give environmental benefits such as carbon sequestration and reduced nitrate and potassium leaching. Our results indicated that biochar and 45N30P30K combination could be appropriate as a sustainable agronomical approach.

Keywords: lysimeter, leaching, nutrient, biochar (poultry manure, groundnut shells, and corn cobs, inorganic fertilizer, moisture retention

5.1 Introduction

Water flowing through the soil is adequate for nominal crop growth as well as conservational management. The amount and action of drainage have consequences for crop water and nutrition management (Chen et al., 2018; Laird et al., 2010). Biochar integration into agricultural soil is a possible way of increasing nutrient bioavailability of phosphorus and reducing nutrient leaching from soil (Chen et al., 2018). Its integration can decrease inorganic N leaching and increase N retention in the soil (Borchard et al., 2019; Oladele et al., 2019; Sun et al., 2017). It has a high cation exchange capacity (Ding et al., 2016; Yang et al., 2017) and affects the soil pH (Novak et al., 2009), with the shortest-way absorption of NO_3^- being the most important process. This can happen very quickly in well-drained clayey soils (Renck and Lehmann, 2004). Adding biochar to soil has been demonstrated to enhance crop yield NH_4^+ (Blackwell et al., 2009; Lehmann and Joseph, 2015; Rondon et al., 2007; Steiner, 2008), but its effect on soil hydrology and nutrient leaching has been less explored. Its addition also improves biomass production, which indicates more plant water uptake. Water may reduce through evapotranspiration when it is amended to the soil. A reduced amount of water would then pass through the soil by unsaturated flow in response to changes in matric potential. Its material is very porous (Downie et al., 2009) and has a low density equated with soil.

It improves negatively charged surfaces as weathering occurs (Sanchez-Monedero et al., 2018; Ventura et al., 2013) and therefore forms relationships with soil minerals (Agegnehu et al., 2017). It has been proven to serve a diversity of molecules in soil, together with pesticides (Khorram et al., 2016; Kookana, 2010), simple hydrophobic organic molecules (Lehmann et al., 2011), and plant leaf extracts (Ding et al., 2016). If applied to soils, it favors

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the development of microorganisms (Gao and DeLuca, 2018; Pietikäinen et al., 2000), which combined with the influences from minerals and other soil organic matter, may lead to greater soil aggregation. These changes may alter the water flow's physical appearance after its application to soil. It can improve the water-holding capacity of the soil and therefore decrease the total volume of leachate (Liu et al., 2017; Ouyang et al., 2013) While its integration io loam soil had no results, its integration into clay soil condensewater-holdingng capacity. All trends improved or reduced linearly with increasing integration rates. Ayodele et al. (2009) testified to augmented infiltration and less runoff in the soils of old charcoal storage sites in Ghana. Major (2009) recommended some hypotheses for mechanisms and concluded that they could reduce and increase nutrient leaching after adding to soil. Leaching, on the other hand, could be helped by improved nutrient conveyance to charcoal particles or improved saturated instability in soil due to greater soil aggregation with biochar.

The comparative importance of these anticipated mechanisms is not distinct. Because it is said to hold more nutrients, their loss due to leaching could be reduced. This procedure for rising nutrient obtainability has been revealed in laboratories (Faloye et al., 2017; Maxfield, 2017; Scholz et al., 2014) and greenhouse experiments with plants (Budai et al., 2013). Partey et al., 2016 demonstrate that "renewed" biochar addition to an Oxisol soil in Sub-Saharan Africa resulted in a 60% reduction in leaching of applied ammonium (NH_4^+) compared to absolute control over 40 days of cropping rice (*Oryza sativa* L.). Early in that trial, calcium (Ca) and magnesium (Mg) leaching decreased as well, but potassium (K) leaching did not, likely because biochar contains a lot of K (Van Zwieten et al., 2010). How the ever, the leaching of K and P usually improved with larger biochar application rates. (Tian et al., 2016) establish more ammonium retention over a longer period, which proposes

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the evolution of cation exchange sites through oxidation. In a field study, ferric luvisols planted to upland rice species preserved a higher proportion of isotopically tagged nitrogen (N) for two years in the Guinea savanna. After biochar was added, it was likened to compost, even though leaching was not restrained directly In literatureLiterature searches no work has directly evaluated the effect of biochar application on soil water and nutrient leaching in a field trial over many cropping seasons.

Process-based models not only assist scientists in improving their understanding of various agroecosystem components, but they also assist policymakers and farmers in determining farm management opportunities. Such models capture the consequences of various practices on soil dynamics and, therefore, the interactions with crop physiological processes (Holzworth et al., 2014). APSIM (Agricultural Production Systems Simulator) may be a model that gives a fully-tested framework with a versatile 69-structure that's capable of simulating interactions among weather, soils, crops, and previously known management systems (Keating et al., 2003). In one of the primary efforts to model the consequences of biochar on soils,(Lychuk et al., 2015) by designing an algorithm that accounted for them, biochar's effects on soil properties were incorporated into the EPIC model (Environmental Policy Integrated Climate). Within that algorithm, biochar directly impacts soil CEC, pH, bulk density, and soil organic carbon, and therefore the dynamic interaction between soil organic carbon and biochar also changes because of the change in soil water dynamics and mineral nitrogen in the soil. Model performance evaluation revealed a suitable end in replicating field trials of biochar impacts on short-term crop yields and soil properties (Lychuk et al., 2015). A biochar sub-model has been developed for the APSIM moto providing a dynamic process-based framework for modeling the effect of biochar on soil and

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crop processes (Archontoulis et al., 2016). This sub-model can simulate carbon decomposition in biochar and assess changes in soil water, bulk density, pH, CEC, and organic and mineral nitrogen robotically. The model's calibration results revealed that it can predict soil (pH, bulk density, total carbon, and water content) and crop-related variables (corn grain yield and corn stover) with a mean relative error ranging from -0.4% to 13.10% (Archontoulis et al., 2016). Following recent trials of the APSIM biochar module in Ghana's guinea savanna zone, a recommendation of implementing it on a larger scale and examining the consistency of biochar effects on upland rice productivity as well as NH_4^+, $N0_3$-N, P, pH, EC, and K leaching for different sources of biochar in the same soils. So far, very little study has been published with focus on bigger scale evaluation of biochar effects on upland rice yield and environmental factors using process-based simulation models. APSIM would help to clarify the involvement of biochar interactions with soil and climate. Over three cropping seasons, this study investigated the effects of three distinct sources of biochar application on poor soils on upland rice yield, soil organic carbon, and NH_4^+, $N0_3$-N, P, pH, EC, and K leaching through saturated sandy soil. The study aims to see if utilizing three distinct sources of biochar as a soil amendment on Guinea savannah agricultural soils improves biomass harvesting sustainability by improving soil quality, sequestering carbon, and boosting nutrient retention and recycling. The specific objective of this study was to see how soil biochar amendments affected nutrient leaching after an inorganic fertilizer application in a typical Guinea-savannah agricultural soil.

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5.2 Materials and methods

5.2.1 Description of the study area

The research site was located at the Farming for the Future, University for Development Studies (UDS), Nyankpala near Tamale in the Northern Region of Ghana (latitude 09.246070N and longitude 000.589920W). The area has a unimodal rainfall pattern with an annual rainfall of 800-1100 mm (Kombiok et al., 2012). The dry season starts from November to March with day temperatures ranging from 33 °C to 39 °C, and night temperatures ranging from 20 °C to 26 °C (Kombiok et al., 2012). The mean annual daytime relative humidity is 54% with an altitude of the area 252 m above sea level. The site is underlain by Upper Voltaian sediments. The area is covered with red and orange-brown drifts partly eroded in places and exposing a layer of shallow ironstone and sandstone (Adu, 1957).

The layer is often separated from the underlying sandstone by a thin stone lime (Adu, 1995). The soil profile has been classified as Nyankpala series (Ferric Luvisol) (ISSS/ISRIC/ FAO, 1998; FAO-UNESCO (1988). They are shallow to very shallow soils overlying in situ developed iron pans within 55.9 cm. It is also moderately shallow to moderately deep concretionary and or gravelly, heavy to medium textured soils overlying mostly highly weathered granite shales (Obeng, 2000). Characteristically the soils are acidic, with low nitrogen and phosphorus content. They are susceptible to moderate erosion and should not, therefore be left bare. They are inherently infertile and will need to be fertilized to obtain the optimum yield (Adu, 1995).

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5.2.2 Biochar preparation

Three different sources of feedstocks were produced from slow and high pyrolysis of groundnut shells, corn cobs, and poultry manure at 400°C - 700°C with a dwelling time of 24 hours in oxygen-limited conditions in a reactor, followed by water and air cooling of charred feedstock to room temperature and grind the biochar. The synthesized biochar was ground. The chemical characteristics of the biochar are shown in Table 5.1. Organic carbon was determined by the wet combustion method according to (Walkley and Black, 1934). Total nitrogen was determined by the Kjeldahl method. Phosphorus and potassium were determined in plant ash using the Gallenkamp flame analyzer method (Bremner, 1996). Available phosphorus was determined according to (Bray and Kurtz, 1945).

Table 5.1: Basic biochar properties used for simulations

Feedstock	Pyrolysis	pH 1:5	C.E.C me100g^{-1}	N %	P %	K %	C: N ratio (-)	Fraction C (0-1)
Biochar Corn cobs	High	6.67	118.26	0.95	0.21	0.45	11.0	0.129
Biochar Poultry manure	High	9.29	125.63	2.19	0.5	0.47	10.5	0.324
Biochar Groundnut shells	Low	11.13	85.52	1.34	0.13	0.74	12.3	0.243

Source: Frimpong-Manso and Ganiyu (2021)
C.EC-cation exchange capacity, P-phosphorus, K-potassium, C: N-carbon nitrogen ratio, C-carbon fraction

5.2.3 Experimental design and treatments

Biochar levels were 5 t ha^{-1} each and were incorporated into the soil in June 2017. The experiment was in a randomized complete blocks design (RCBD) with 4 replications. The crops were Nerica 14 (African upland rice) with 85 days of maturity for the rice (*Oryza sativa* L.). Nerica 14 seeds were soaked in water to separate unfilled grains from filled grains and then dried at room temperature for 24 hours before sowing. The seeds were drilled in

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rice husk biochar at 3 cm below the biochar surface in rows 30 cm apart to maintain moisture for good germination. Weeds were controlled by hand twice before transplanting. Transplanting was done on 28th July 2018 and 21st of July 2019 at a rate of two seedlings per hole. The planting distance was 20 cm x 20 cm for the transplanted rice seedlings. The arrangement of the rice and cowpea was in a 3:1 ratio. A week after transplanting, fertilizer was applied at a rate of 90N:60P:60K and 45N:30P:30K kg ha^{-1} Nitrogen(urea), Phosphorus (triple super phosphates, and Potassium (muriate of potash) respectively, as straight fertilizer and then top-dressed with nitrogen levels in the form of urea at 30 kg ha^{-1} N at tillering and booting stage respectively when it was eight (8) weeks after transplanting. Weeds were controlled by hand on four counts during the season. Weeding was done manually picking and with the use of a hand hoe, two weeks after transplanting and as and when weeds reappeared. Weeding and loosening of the soil surface were done four times in the sole rice plots and two times in the rest of the treatments for both intercrop experiments. The weeds that were found on the plots were the usual weeds associated with rice. Weeds occurrence in sole rice was high (50 % coverage of plot area), while that of intercrop was moderate (30-40 % coverage of plot area), and sole cowpea recorded low occurrence (10-30 coverage of plot area. The common weeds observed were the grasses (*Rottboellia cochichinensis, Oryza barthii,* and *Paspalum orbiculare*); broad leaves (*Ageratum conyzoides, Hibiscus* spp, and *Ipomoea acquatica*) and sedges (*Commelina Africana* and *Cyperus diformis*).

The data used in the current study cover the main crop and soil processes. The soil profile was carried out at the initial stage of the experiment Table 5.2. Soil sampling was done at depth of 0-30 cm for the characterization of both chemical and physical properties. Bulk density and porosity were determined weekly till harvesting Table 5.5. Agronomic data was

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collected every week from 30 days after transplanting to heading. Ten plants were randomly selected on each plot and plant height at maturity, number of panicles, number of tillers, and number of grains per panicle were determined. At maturity, 1 m^2 in each plot was harvested for yield. Data collected at maturity included measurements of plant height for rice, number of panicles, and number of plants within a 1 m^2 area. Five panicles were randomly selected for the number of spikelets, panicle length, number of grains per spikelet on a panicle, weight of unfilled and filled grains, total grain weight, and 1000 grain weight for rice and strawweight. Data were determined by APSIM modules version 7.

5.2.4 Installation of instruments and leachates measurement

Thirty-two (32) lysimeters were installed in thirty-two plots. A 70 cm deep hole was dug to install the lysimeters, and backfilling was carried out in such a way as to provide good soil contact and also prevent excess rainwater from running into the hole of the installed lysimeters. The soil around the lysimeters was filled up to help prevent ponding around them and preferential flow down the backfilled hole. Leachates were sampled from thirty-two (32) plots and measured with a graduated measuring cylinder. Collection of leachate sampling and hydrological monitoring were performed every three weeks until the plants were harvested. The number of sampled leachates for each lysimeter was recorded and transferred into a labeled storage bottle. The sampled leachates were conveyed to the laboratory in an iced chest with some ice cubes for chemical analysis. Figure 5.2 presents the flowchart of constructing lysimeters, collection, and measurement of leachate at the field.

Table 5.2. Soil profile parameters used in this study

Soil Layer	1	2	3	4	5
Layer thickness (cm)	0-15	15-30	30-60	60-90	90-120
Soil water parameters					
BD (g cm^{-3})	1.58	1.62	1.57	1.59	1.57
SAT (mm^{-1})	0.354	0.358	0.368	0.342	0.339
DUL (mm-^{1})	0.202	0.204	0.201	0.198	0.132
LL15 (mm^{-1})	0.050	0.106	0.153	0.128	0.198
Soil-C parameters					
OC (%)	0.47	0.41	0.33	0.38	0.33
pH(H20)	4.66	4.66	4.66	4.56	4.56
Finerta	0.36	0.36	0.70	0.90	0.90
Fbiomb	0.016	0.02	0.02	0.01	0.01
Soil P parameter					
Labile P (Mg kg^{-1})	11.6	5.8	5.0	2.0	1.0
P sorption (mg kg^{-1})	60	80	150	180	200

Source: Frimpong-Manso and Ganiyu (2021)

Soil parameterization of ferric Luvisols at farming for the future, UDS experimental farm to specify APSIM simulations. LL, lower limit; DUL, drained upper limit; SAT, saturated volumetric water content; BD, bulk density; OC, organic carbon; Fbiom, a non-inert fraction of microbial C; and Finert, the inert fraction of organic C.

5.2.5 Weather during the cropping Season 2018-2019

The rainy season's peak happened in July for the current time slice, while a change in the rainfall peak toward August was predicted for the future time slice. The months of August, October, and November are expected to see significant increases in monthly rainfall in the future. The month with the most rainfall was August (Figure 5.1). Since sandy loam soils dry out rapidly due to their low permanent wilting point, accessible water, and water storage

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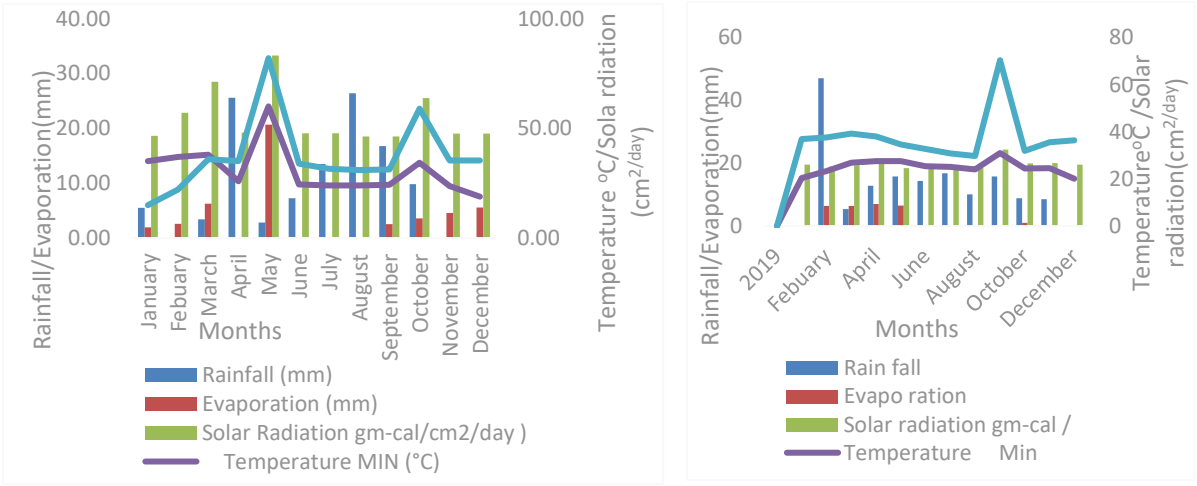
capacity, good crop yields are strongly dependent on a well-distributed rainfall pattern. In the wet season of 2018-2019, Figure 5.1 depicts the study area's seasonal water balance. In 2018-2019, the total rainfall was 133.29 mm, while the total evapotranspiration was 37.10 mm. The upland rice was planted in June of 2018 and 2019 and harvested in November of the same year. From July through October, 61.81 mm of rainfall, while 3.07 mm of evapotranspiration (Figure 5.1). During the rice growth phase, from July to August, the table shows a favorable moisture balance. From July to August, rainfall increased and evapotranspiration decreased dramatically. However, because the September rainfall was lower, there was a slight water deficit after August. During the upland rice growing season, there was drought. As a result, the biochar amended plot had a higher yield than the non-biochar amended. The significant drop in average temperatures during the upland rice's growth phase (Figure 5.1) also contributed to a decrease in evapotranspiration, which favored the rice plant.



Source: Frimpong-Manso and Ganiyu (2021)

1a. climatic weather for 2018 1b. climatic weather for 2019

Figure 5.1. Summary of climatic data observed at the study site from 2018 - 2019 Cropping Season

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5.3 Lysimeters

5.3.1 Flowchart of constructing lysimeters

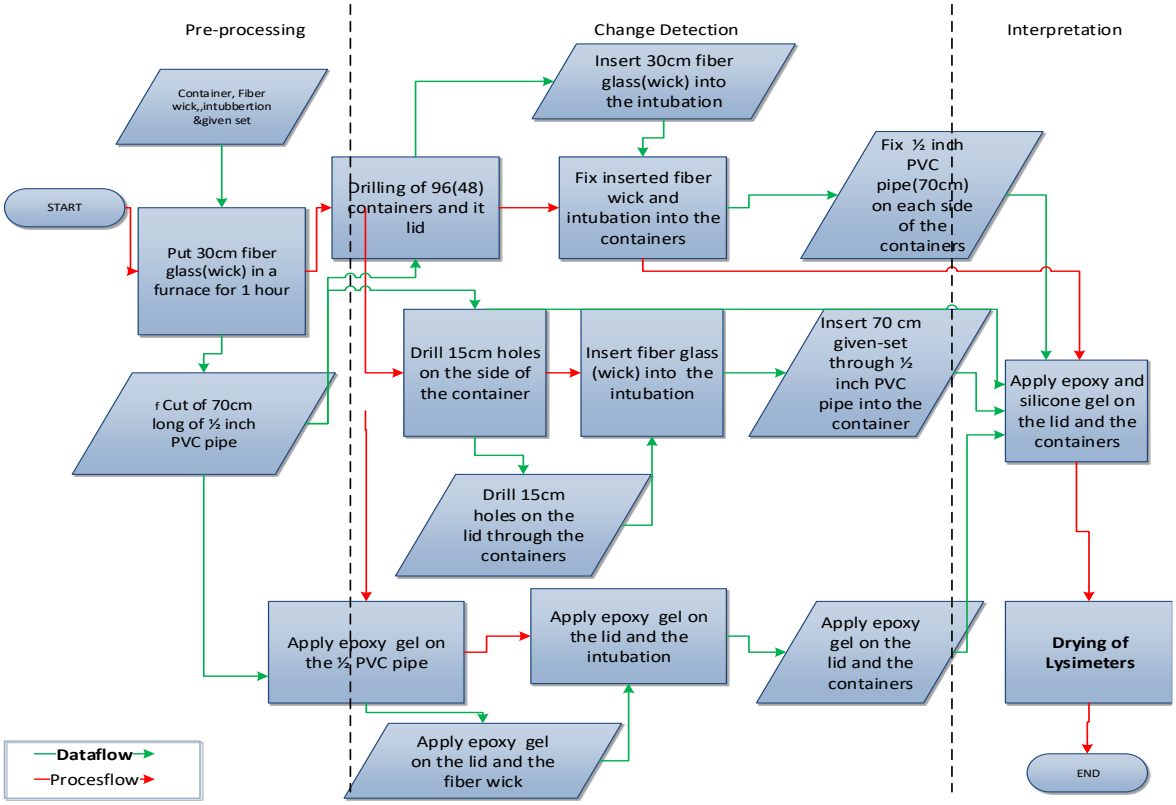

Figure 5.2. The construction process of Lysimeters used for the experiment.

5.3.2 Leachates nutrient analysis

5.3.3 Leachates Sampling

Leachates were collected from thirty-two (32) pots and measured using a graduated measuring cylinder. The number of leachate samples collected for each lysimeter was recorded and transferred to a labeled storage bottle. The sampled leachates were transported to the laboratory in an ice chest containing some ice cubes for chemical analysis. The plants were sampled twice every three weeks until they were harvested.

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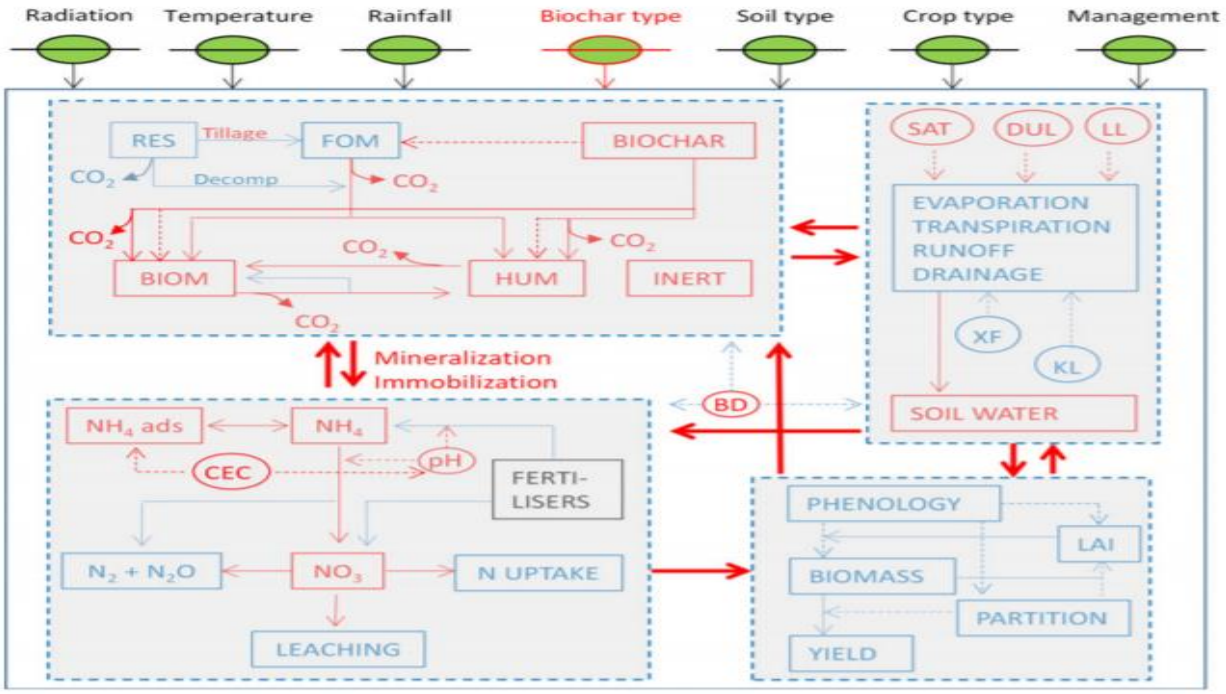

Figure 5.3: Sources: Adapted from John Wiley and Sons (2015)

A basic diagram demonstrating APSIM's soil carbon: (top left windowpane), soil nitrogen (bottom left window pane), soil water (top right windowpane), and crop (bottom right windowpane) modules. Boxes are state variable, solid arrows are rate variables and show material flow (e.g. carbon), broken arrows show information flow (e.g. priming), and circles are intermediate variables. Driving variables for the system (green circles at the top) include weather, soil, crop, and management. Those that are indicated in red are the state, rate, and intermediate variables that we assume to be influenced by biochar amendments. RES, surface residue; FOM, fresh organic matter; BIOM, microbial pool; HUM, humic pool; INERT, inert pool; SAT, saturation point; DUL and LL, drained upper and lower limits; KL, a parameter defining the capability of the roots to take up water; CEC, cation exchange capacity; and BD, soil bulk density.

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5.3.4 Chemical analysis of Leachate

A pH meter was used to measure soil pH in a 1:15 w/v soil with a deionized water mixture that was stirred three times over one hour. Electrical conductivity was measured using the Jenway 4510 Conductivity Meter. It was calculated using the (Rhoades, 1993) method. PO_4 in the leachates was determined using the malachite green technique (Olsen, 1982). The malachite green procedure was used to determine it (Rao et al., 1997). Nitrate was measured using the Cataldo technique (Cataldo et al., 1975). The Indophenol blue method, as stated by (Koroleff, 1983), was used to determine ammonium in leachates.

5.4 Statistical indices for model performance

In SAS, PROC GLM is used (SAS Institute, 2003), and $p<0.05$ was considered significant when calculating statistical differences between treatment means. Time was not included as a predictor in the model for measurements collected repeatedly throughout time because measurement weeks were treated as replicates. The were was log-transformed to conform with the model's equal variance assumption after validating diagnostic residual plots from nutrient transport dominated by saturated instability.

5.5 Results and discussion

5.5.1 Nutrient leaching

The volume of leached water was affected by the interaction of biochar with inorganic fertilizer and the three distinct biochar sources. The rainwater filled the soil pores, and the rest percolated down, and the water leached away. Crops were cultivated with the majority of the water retained by the earth. During the leaching process, 20 liters of water were provided; the collected water discharge ranged from 2.95 to 6.07 liters in 2018 and 2.57 to

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5.04 liters in 2019 Table 5.3a, b. Higher water absorption by rice plants with more vigorous growth induced changes in altered cumulative water percolation at the end of the trial. Except for the control, the cumulative amount of water leached from the soil was connected with yield output rather than soil amendments.

The biochar treatments of poultry manure+45N30P30K and control produced the most leached water. Application of biochar groundnut shells+45N30P30K, biochar groundnut shells, and biochar corncobs+45N30P30K, biochar corncob (5 t ha^{-1}) resulted in the lowest volume of leached water. This indicates that the water was absorbed by the plant and kept by the soil, resulting in less water being leached Table 5.3a, b. Yield vs. tillers, spikelets per panicle, and grain per panicle production were calculated using water and nutrients ingested by plants (Figure 5.5a, b, 5.6a, b, and 5.7a, b). Because most of the water was leached from the ground, the absolute control treatments yielded the lowest yields. The results presented in Tables 5.3a, and b demonstrate that biochar+45N30P30K was added to the volume of leached water. Biochar reduced drainage water volume by two folds. On days 1–15 after planting, there was no interaction between biochar material and biochar rate on NH_4^+, NO_3-N, P, and K leaching, while on days 15–30 after planting, there was an interaction (Table 5.3a, b). According to the findings, a similar pattern was observed in EC and pH leaching. Although the levels of pH, NH_4^+, NO_3-N, P, K, and eC were high in the soil, the kind of biochar rate used resulted in less leaching of pH, NH_4^+, NO_3-N, P, K, and eC (Table 3a, b). Biochar groundnut shells, biochar groundnut shells+45N30P30K, and biochar corncobs+45N30P30K treatments had the lowest pH, NH_4^+, NO_3-N, P, K, and eC leaching during rice growth (day 15–30), while biochar poultry manure and biochar poultry manure+45N30P30K treatments had the highest. Mineral fertilizer caused intensive leaching

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of pH, NH_4^+, NO_3-N, P, K, and eC. However, with increased biochar poultry manure+45N30P30K, pH NH_4^+, NO_3-N, P, K, and eC leaching increased by two folds, and biochar poultry manure was substantially higher in 2019 than in 2018. The increase in pH, NH_4^+, NO_3-N, P, K, and it appears to be connected to the type of biochar used in the soil. The soil amendments had minimal effect on the proportions of N and P uptake, while pH and EC showed a clear response (Figure 5.4a, b and e and Table 5.3a, b). Biochar+45N30P30K with K was highly effective, increasing SO_4-S and K absorption in a proportional manner (Figure 5.4c and f). The amount of K uptake from biochar soil reduced as the concentration of NO_3-N increased. Applied N and K were mobile in the soil, and the amount of leaching increased in mineral fertilizer treatments. The absolute control showed high ratios of uptake-to-leaching for all studied nutrients. After the amendment application, however, leaching increased more than uptake, and the proportions decreased. For all nutrients, the proportions of nutrient uptake to leaching increased when biochar was applied to the soil.

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Table 5.3a: Effects of biochar materials and volume of water and Nutrient leached for 2018

	Nutrient leached (mg l^{-1})												
Treatment	**NO_3^-N mg l^{-1}**		**NH_4^+N mg l^{-1}**		**K^+**		**P**		**eCuS/ cm**		**pH**		**The volume of Water leached (ml)**
	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	30 Day
Control	5.81	4.49	0.76	1.02	4.1	2.5	0.18	0.18	153	161.1	6.56	6.78	5.42
90N60P60K	7.35	6.22	0.51	0.76	3.3	2.7	0.41	0.47	176.2	106	6.76	6.69	6.07
ChGs+45N30P30K+C	4.77	3.38	1.02	1.02	3.4	1.49	0.30	0.79	124.4	80	6.68	6.81	2.95
ChPM+45N30P30K+C	6.29	6.01	0.76	1.27	6.2	6.7	1.04	1.60	139.1	129.7	6.72	6.63	4.58
ChCc+45N30P30K+C	6.74	2.16	0.25	0.76	8	3.3	0.20	0.24	157.4	72.4	6.85	6.66	3.06
ChGs+45N30P30K	3.65	3.79	0.76	1.02	2.7	2.3	0.24	0.16	117.7	91.9	6.81	6.67	4.07
ChPM+45N30P30K	5.42	4.13	0.51	0.51	5.2	3.5	0.16	0.12	155.9	104.6	6.72	6.59	3.81
ChCc+45N30P30K	4.02	3.00	0.25	0.51	5.3	1.59	0.30	0.18	137	54	6.63	6.74	4.12

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Char-biochar, Gs-groundnut shells, PM-poultry manure, Cc-corn cobs, NPK-nitrogen, phosphorus, potassium, NO_3^-N-nitrate, NH_4^+-N-ammonium, eC-electrical conductivity, P-phosphorus, K^+-potassium

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Table 5.3b: Effects of biochar materials and volume of water and Nutrient leached for 2019

	Nutrient leached (mg l^{-1})												
Treatment		**NO_3^-N mg l^{-1}**		**NH_4^+N mg l^{-1}**		**K^+**			**P**	**eCuS/ cm**		**pH**	**The volume of Water leached (ml)**
	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	15 Days	30 Days	30 Day
Control	5.81	4.49	1.78	3.06	4.1	2.5	0.18	0.18	153	161.1	6.56	6.78	5.04
90N60P60K	7.35	6.22	2.04	2.04	3.3	2.7	0.41	0.47	176.2	106	6.76	6.69	4.04
ChGs+45N30P30K+C	4.77	3.38	1.27	2.04	3.4	1.49	0.30	0.79	124.4	80.0	6.68	6.81	2.57
ChPM+45N30P30K+C	6.29	6.01	1.53	2.29	6.2	6.7	1.04	1.60	139.1	129.7	6.72	6.63	4.06
ChCc+45N30P30K+C	6.74	2.16	0.76	3.31	8.0	3.3	0.20	0.24	157.4	72.4	6.85	6.66	4.34
ChGs+45N30P30K	3.65	3.79	1.78	3.82	2.7	2.3	0.24	0.16	117.7	91.9	6.81	6.67	3.83
ChPM+45N30P30K	5.42	4.13	1.02	2.29	5.2	3.5	0.16	0.12	155.9	104.6	6.72	6.59	3.30
ChCc+45N30P30K	4.02	3.00	0.51	1.02	5.3	1.59	0.30	0.18	137	54	6.63	6.74	3.86

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Ch-biochar, Gs-groundnut shells, PM-poultry manure, Cc-corn cobs, NPK-nitrogen, phosphorus, potassium, NO_3^-N-nitrate, NH_4^+N-ammonium, eC-electrical conductivity, P-phosphorus, K^+-potassium

5.5.2 Nitrate (NO3-N) and potassium (K^+) lost as leachate from biochar

Variations in cumulative water percolation and extent of nutrient leaching among treatments were caused by variations in plant water uptake and efficiency of nutrient retention. As expected, the leaching of nutrients was significantly lower among the three different sources of biochar amendment compared with the control mineral-fertilizedized soil. The groundnut shells biochar treatment cumulatively had lower leaching of nutrients than biochar groundnut shells + 45N30P30K, biochar corncobs, and biochar corncobs + 45N30P30K. This could be because more pore spaces within the sole biochar, and increased sorption capacity through oxidative reactions on the biochar surfaces over time (Figure 5.8a-d). The experiment exhibited the reduction of leaching of NO_3-N by 3.65–4.77 mg l^{-1} per 15 days, while K^+ was 2.7–3.4 mg l^{-1} from the applications of biochar groundnut shells and biochar groundnut shells+45N30K30P on the same soil type (Figure 5.8a-d) 45% of the applied N fertilizer (Meisinger and Delgado, 2002). A similar study exhibited that charcoal application reduced the proportion of leached N and Ca on Ferralsols (Lehmann et al., 2003). Although N and K proved very mobile in soil (Figure 5.8a-d)the, application of sole biochar and their combination with mineral fertilizer the reduced leaching of NO_3-N 5.42 and 6.29 mg l^{-1} and K- 5.2 and 6.2 mg l^{-1}, respectively, compared with soil applied with mineral fertilizer only. For example, biochar poultry manure+45N30P30K reduced leaching. The retention of N and K should be specifically targeted with additions of slow-releasing nutrients and soil amendments. Leaching happens at a more moderate rate when most of the ions are extant in exchangeable form (Troeh and Thompson, 2005), or when uptake by plants rises (Lehmann

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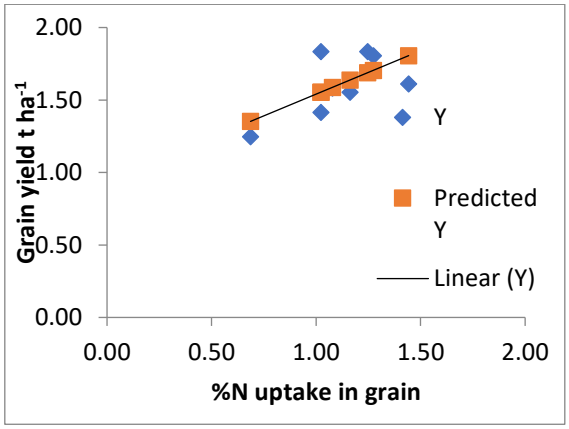
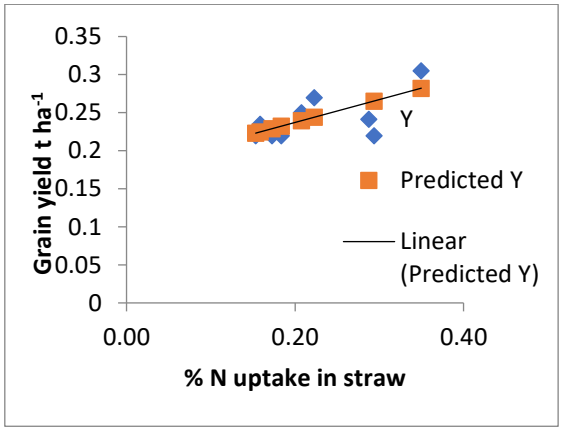
et al., 2003). Low leaching at high nutrient availability promotes sustainable soil fertility, which agrees with the findings of (Lehmann et al., 2003). Soils that have been strongly weathered and leached often have low levels of NO_3-N and K^+ and plant grow nutrient-limited limited (Glaser *et al*., 2002). According to Sika (2012), biochar significantly the decreased leaching of NO_3-N (26–95%), NH_4-N (12–86%), basic cations, P, and certain micronutrients. By difference, (Novak et al., 2009) specified higher EC and K concentrations of leachates but lower concentrations of P. Although the initial soil K status was sufficient for plant growth, the ratio of K uptake to initial soil K was the lowest for the control, because K uptake might be limited by the low availability of other nutrients, such as N and P.



A



B

Figure 5.4a, b. Relationship between grain yield kg ha^{-1} and %N uptake in grain and straw

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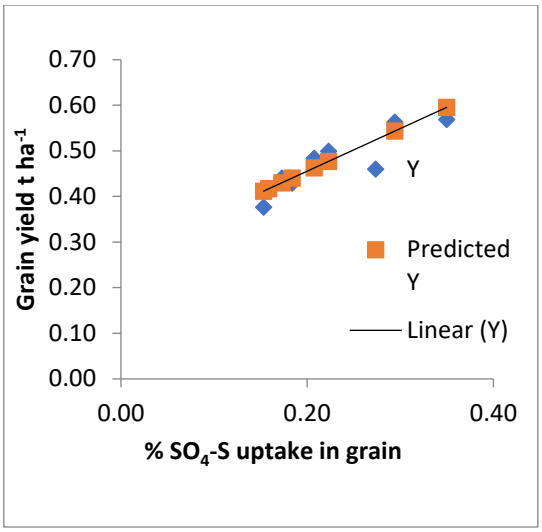
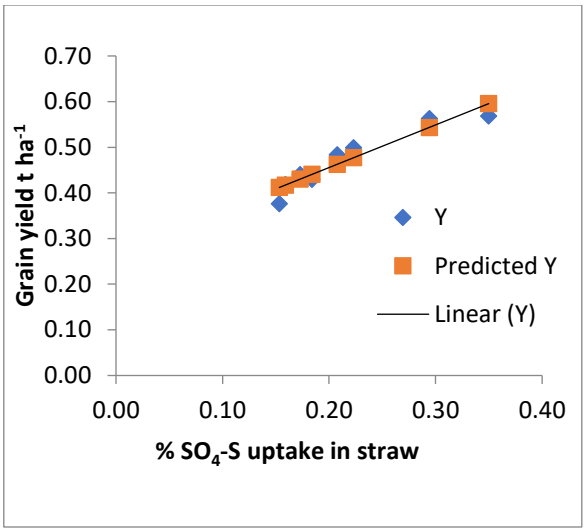
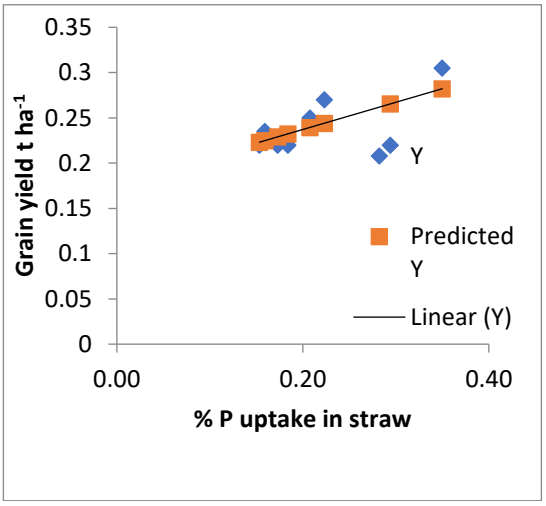
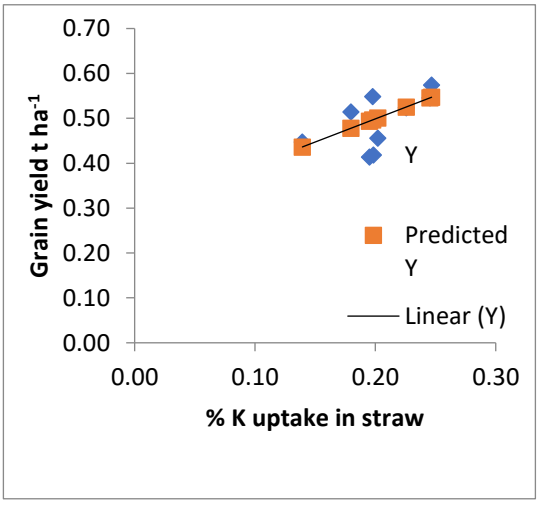




C **D**

Figure 5.4c, d. Relationship between grain yield kg ha^{-1} and % SO4-S uptake in grain and straw





E **F**

Figure 5.4e, f. Relationship between grain yield kg ha^{-1} and % P and %K uptake in straw

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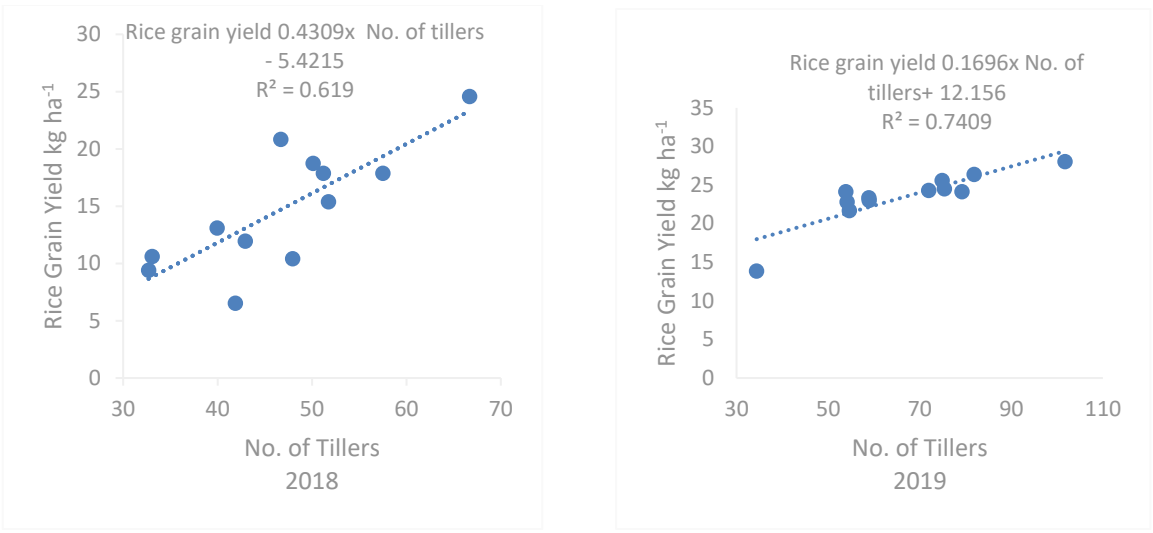
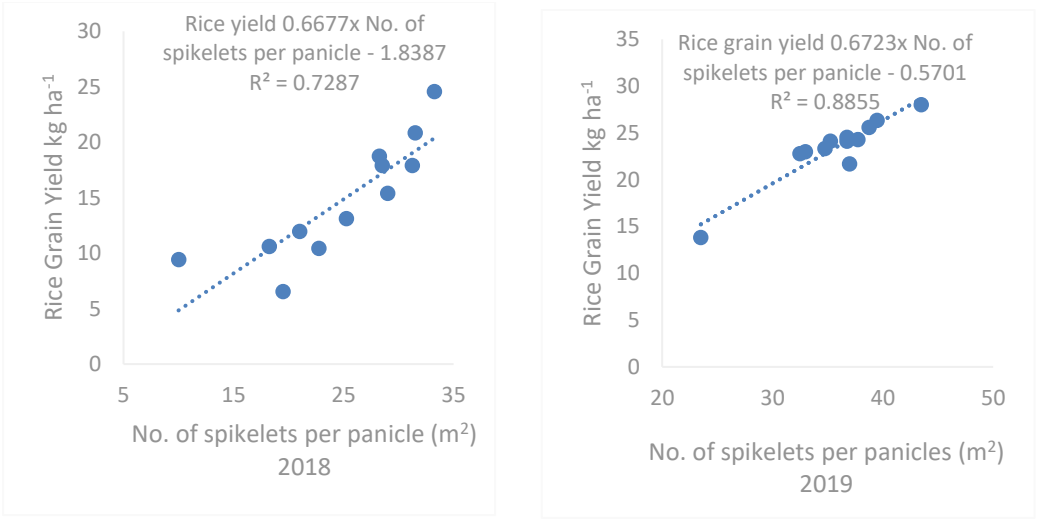


A **B**

Figure 5.5. Relationship between the number of rice grains yield kg ha^{-1} and tillers (2018 and 2019)



A **B**

Figure 5.6. Relationship between grain yield and number of spikelets per panicle (2018 and 2019)

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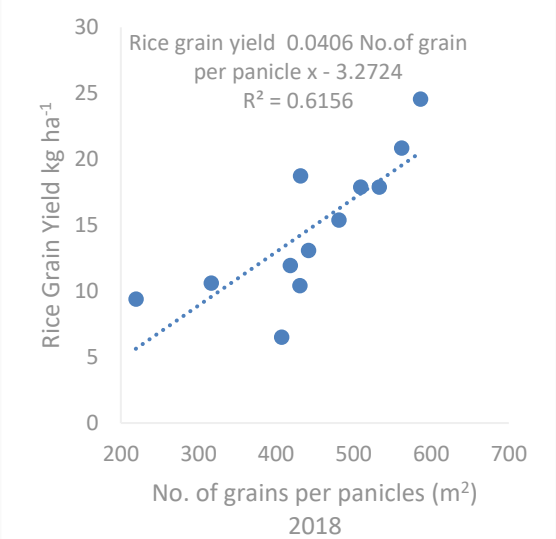

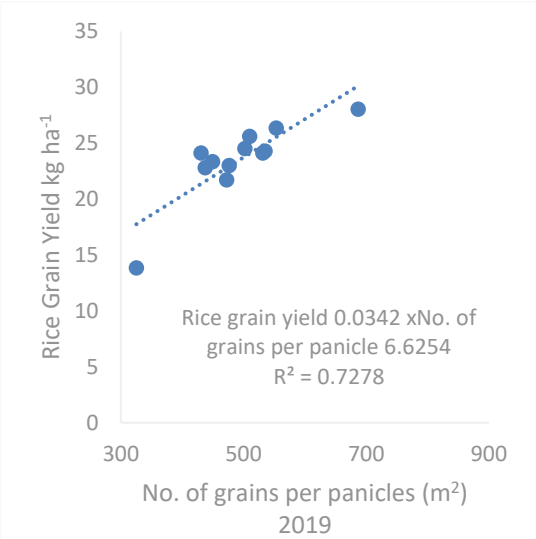

A **B**

Figure 5.7. Relationship between grain yield and number of grains per panicle (2018 and 2019)

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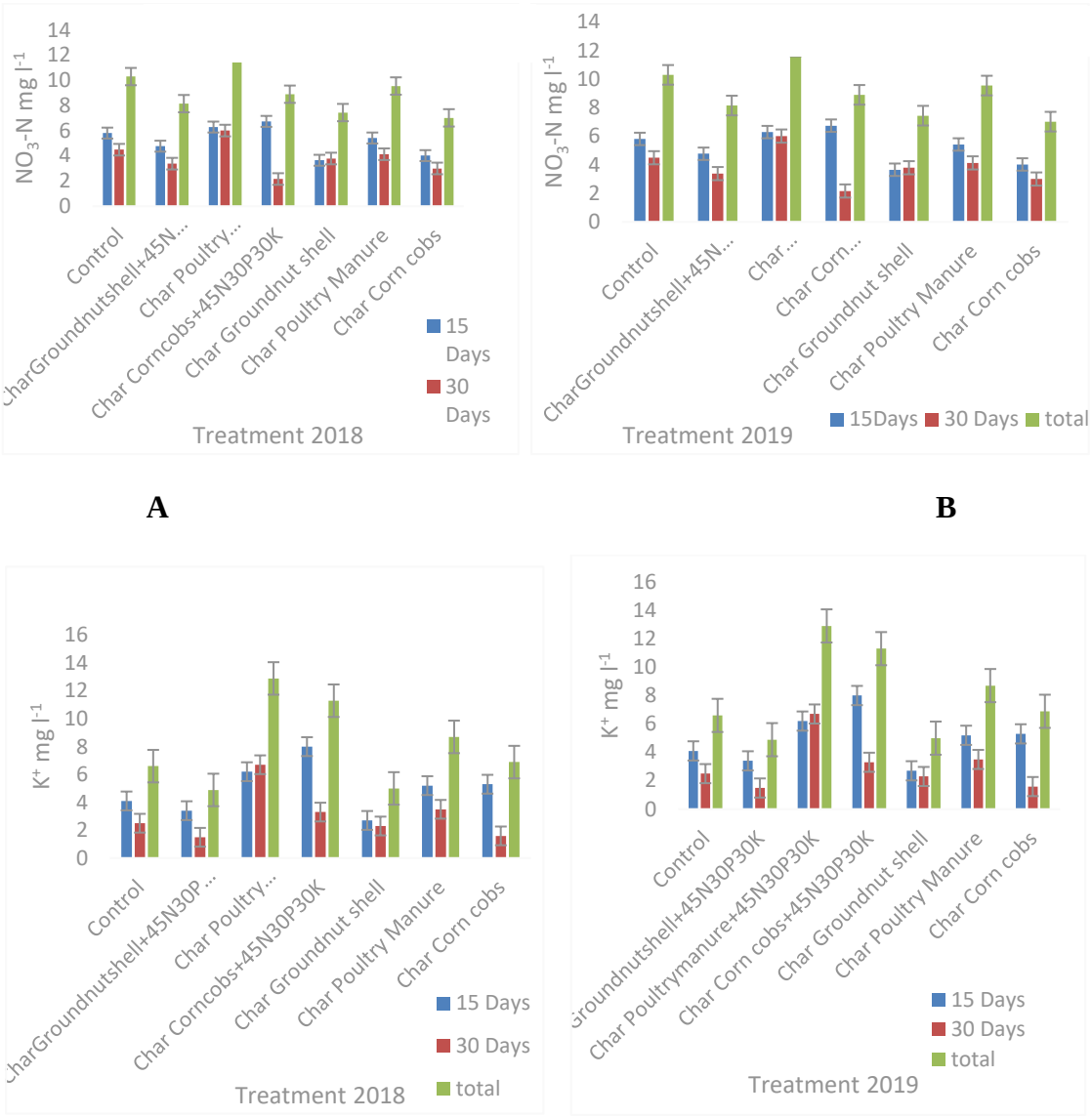

Figure 5.8. Days total of nitrate (NO3-N) and potassium (K^+) lost as leachate from soil amended from lysimeter on three different sources of biochar

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5.3 Mineral fertilizer and biochar effects on plant production

Mineral fertilizers and biochar, as well as three distinct sources of biochar from poultry manure, groundnut shells, and corn cobs, increased plant production based on recommendations. The amounts applied were conventional for plant growth. The longer biochar stays in the soil, the higher the yield (Ali et al., 2020). Experiments have shown that biochar combined with mineral fertilizer may primarily sustain agricultural production (Figure 4a to f). Higher P levels and micronutrient additions are likely to have improved crop performance. The P was applied at a rate that was revealed to be a bit low to meet rice plant demands nutrients in the soil. In a recent field experiment, large yield increases of 5.5 times of fertilized rice could be found with an application of 60P kg ha^{-1} of inorganic fertilizer (Ahmed, 2018; Musah, 2019), and similar outcomes were presented for biochar and inorganic fertilizer application in a lysimeter experiment (Lehmann et al., 2003; Major, 2009).

Nitrogen nutrition has been critical for improving crop growth as straw N levels were lower in the crops grown on the ferric Luvisols (Dogbe et al., 2015), while at the same time, biomass production was higher. However, plant development was aided by P and K additions, which is consistent with prior research on the rice-cowpea intercrop in the same area (Baba et al., 2013; Inusah et al., 2013; Musah et al., 2013). Similar work was done by Oroka and Omoregie (2007) K was very mobile in soil, with considerable amounts of up to 30% of the quantity present in improved soil being rapidly leached.

5.4 Nutrient retention in the soil after application

The increased P availability in biochar compared to inorganic fertilizer was mostly responsible for the higher crop growth. Higher levels of soil SO_4 and micronutrients,

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particularly Zn and S, may have further aided plant performance. Different phases of the crop require higher levels of P and S (Buri et al., 2012; Dobermann et al., 2002; Krishna, 2013). Various ferric Luvisol of primitive origin has been reported regularly on the Guinea savanna. The total N contents were higher in the mineral fertilizer than the biochar +45N30P30K, but N availability was low due to a high C-to-N ratio. However, the low N availability did not seem to reduce crop growth. In contrast to the potential cation exchange capacity (Lehmann et al., 2003; Steiner, 2008), the effective cation exchange capacity was higher in the mineral fertilizer than in the biochar+45N30P30K, which caused low retention of applied nutrients and high leaching. The primordial ferric luvisols' low fertility may have been due to nitrogen release from sequentially available soil pools rather than high ion levels at exchange locations. In comparison to the mineral fertilizer, the leachate in the biochar experiment showed extremely low nutrient concentrations despite having high nutritional availability. Soil fertility is maintained via low leaching and high nutrient availability. These findings are consistent with those of (Obodai (2018) and Yeboah et al. (2009), who discovered biochar in Ghana after 40 years of continuous cultivation without fertilization. The features of relict human-caused soils have crucial implications for ferric luvisols soil management, indicating that solo biochar poultry manure applications can be used for sustained crop production in semi-arid environments. These findings, on the other hand, suggest that biochar corncobs and biochar groundnut shell+45N30P30K applications should continue.

5.5 Biochar amendments for increasing soil fertility

Biochar application resulted in decreased N availability due to high C-to-N ratios, similar to ferric Luvisols soil. Direct nutrient additions with the addition of three different sources of

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biochar, especially of K^+, but also of P, NH_4-N, and NO_3-N, result in improved biomass production and nutrient uptake. Nutrient losses were modest at the same time. The soil K content increased by an order of magnitude, surpassing that of inorganic fertilizer soils, whereas leaching losses in biochar-augmented soils were less than half of those in inorganic fertilizer soils. Furthermore, biochar and biochar+45N30P30K condensed the leaching of applied inorganic fertilizers NH_4-N and NO_3-N, as well as NH_4-N, NO_3-N, P, K, pH, and is in the first 15 days, and the ratio of uptake to leaching increased for all nutrients after biochar+45N30P30K application, demonstrating a high efficiency of nutrients applied with biochar+45N30P30K. Biochar+45N30P30K amendments have not been proven to help with nutrient retention. There are numerous possibilities, including (a) establishing places for electrostatic adsorption; (b) retaining soil water and nutrients. Biochar and biochar+45N30P30K additions did not reduce water percolation, and nutrient retention was then activated by adsorption to an exchange complex generated by biochar+45N30P30K additions. The study found that biochar made from poultry manure, corn cobs, and groundnut shells boosted high cation exchange capacity by as much as 125.63, 118.26, and 85.52 m g^{-1}, respectively Table 5.1. It is important to remember that the surface properties of biochar vary a lot depending on the organic matter used to make it and the charring environment, such as temperature and oxygen supply (Budai et al., 2014; Kammann et al., 2017; Lehmann, 2007).

5.6 Particle size of biochar

The size of the biochar pieces amended to soil had only minor effects on nutrient uptake and biomass production of upland rice. This could indicate that either the surface area or the number of nutrients provided by the three distinct biochar sources (poultry manure,

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groundnut shells, and corn cobs) were sufficient with larger pieces, or that neither of the two factors was significant in increasing crop growth in the studied soil. We can accept that nutrient retention was a significant reason for the rise in nutrient uptake and growth of upland rice, since nutrient leaching was insignificant from the lysimeter and the contents of those nutrients that could be supplied by the three distinct biochar were high. This may change after some cropping seasons and more intense leaching and should be tested in long-term field experiments. Furthermore, the number of nutrients supplied by three distinct sources of biochar pieces may have been sufficient for plant growth, either because the total amount of three distinct biochar pieces already exceeded plant demands or because nutrients were contained inside the three distinct biochar pieces. Plant roots were found to be huddled around the three distinct biochar pieces, or even grow into the three distinct biochar pieces, demonstrating nutrient availability in the three distinct biochar pieces. Nutrients may have been leached or diffused into the rhizosphere from the inside of the three distinct biochar pieces.

5.7 Effect of the amount of biochar on soil fertility

The amounts of the three distinct sources of biochar from poultry manure, groundnut shells, and corn cob additions were critical for the effects on crop growth and nutrition. Plant growth was significantly improved with the addition of 5 t ha^{-1} of three distinct sources of biochar, and higher quantities added further increased biomass production. This quantity corresponds to a CEC contribution of 126.63 m g^{-1} by biochar poultry manure, 85.52 m g^{-1} by biochar groundnut shells, and 118.26 m g^{-1} by corncobs, which falls within the larger range of possible biochar yields (0.324 kg ha^{-1} C) estimated by the aboveground biomass in (Table 5.1). Additional inorganic fertilizer nutrients must be used to ensure consistent and long-

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term development and yields. The land use approach of producing and applying three distinct sources of biochar to soil is only feasible if the three distinct sources of biochar are formed from charred agricultural waste materials. Lysimeter trials were conducted to test the positive results of this field experiment for plant nutrition and growth. Furthermore, as a result of human-caused or natural fires in our forest, biochar can be found in many soils of the refuse dump and farmlands. As a result, biochar is abundant in such large quantities in farmland soils that we can expect an effect on plant development and nutrition. Biochar does not only exist as large pieces in soil but also as fine particles of less than 20 m (Glaser et al., 2000; Glaser et al., 2001), providing indicating portion of the stable carbon pool in the soil is present as supposed black carbon and may have derived from charred organic matter. According to Liang et al. (2008); Czimczik and Masiello (2007) and Glaser et al., 2002), there is a lot of stable black carbon in grassland soil that has been burned a lot. Because of its potential importance in the global biogeochemical C cycle (Schulze *et al*., 2001), black carbon has become a major research topic (Glaser et al., 2002; Nguyen et al., 2004; Schmidt et al., 2011). Long-term research on the effects of biochar treatments on soil fertility and nutrient dynamics is required.

5.8 Effects of treatments on soil properties

The differential impacts of inorganic fertilizer and three different sources of biochar on soil parameters and agronomic characteristics of the rice-cowpea intercrop were evident in the results of this study, as expected, and reflected their apparent chemical composition disparities. The results of the analysis revealed that the treatments had a substantial impact on the soil parameters that were measured. The use of the three different sources of biochar in combination considerably improved the pH of the soil used, in contrast to fertilizer

application (Table 5.4a and b). The liming impact of biochar on soils has been widely reported (Wang et al., 2021), and the findings of our study are consistent. While the mechanism underlying biochar's lime effects is unknown, the liming effect has been explored in the literature as one of the most plausible reasons for increasing plant production following biochar application (Nguyen et al., 2018). When the three different sources of biochar and inorganic fertilizer were combined with cowpea intercrop, the pH dramatically improved compared to when inorganic fertilizer was applied alone. It is practical to accept that biochars with higher liming potential can help to lime required arable soils more by being applied more frequently at lower rates or in combination with cowpea intercrop (Xiao et al., 2018).

Furthermore, in all treatments, mineral N levels increased, except for the control. Mineral N was comparable between inorganic fertilizer treatments either applied alone or in combination with three different sources of biochar and inorganic fertilizer (Table 5.4a and b). These findings reveal that in areas where inorganic nitrogen fertilizers are scarce, high-quality cowpea could be planted alongside three different biochar sources. Except in control soils, biochar amended treatment application improved phosphorus availability. The soils that received biochar poultry manure plus inorganic fertilizer treatments, either alone or in combination with inorganic fertilizer and biochar groundnut shells, had the highest phosphorus availability. Meanwhile, inorganic fertilizer had similar impacts on available P when used alone or in combination with the three biochar sources. High-quality organic residues, such as those found in rice straw diversifolia, have been proven to be comparable to inorganic fertilizers in terms of nutrient supply (Chimouriya et al., 2018; Kiboi et al., 2019). The effects of biochar on mineral N and P availability were either comparable or

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significantly higher than inorganic fertilizers, as established in this study. This finding backs up previous research that found high-quality plant wastes to be feasible alternatives to inorganic fertilizers (Mahmud et al., 2018; Reyes-Cabrera et al., 2019). The quantities of extractable C recorded were found to be strongly associated (Table 5.1) with nitrogen availability in soil (Figure 5.4), confirming soil nitrogen contributions from N released during the decomposition of the plant materials employed in the experiment (Table 5.4a and b). Because of the slow decomposition and mineralization patterns of the three different sources of biochar, the nutrient supply contributions from the three different sources of biochar when applied with inorganic fertilizers may only be apparent in the long term (Farhangi-Abriz et al., 2021; Stagnari et al., 2017). With its high carbon content, applying biochar to soil is likely to raise the soil's C: N ratio, potentially resulting in initial net N immobilization by microorganisms (Table 5.1). Although higher mineral N levels were observed in biochar-amended soils (Figure 5.3a to e), this finding could only be explained by a hypothetical priming effect of the biochar on N mineralization from already existing organic matter in the soil. Chang et al., 2020 from already existing organic matter in the soil. Several experimental studies (Fischer et al., 2018; Whitman et al., 2015) have verified the priming effect of biochar in triggering C and N mineralization. The results were attributed to the conditioning effect of the biochar in limiting nutrient losses, mainly through leaching, rather than N mineralization from the biochar itself, in some cases where biochar application had a significant effect on nutrient availability (Antonangelo et al., 2021; Gao and DeLuca, 2016; Major, 2009). Furthermore, enhanced nutrient availability in soils treated with a combination of biochar and inorganic fertilizer or biochar and green manure could have been attributed to the conditioning effects of biochar in enhancing soil structural and chemical

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properties. Sohi et al. (2010) wrote a review that explains these mechanisms. CEC rose as a result of treatment, having the greatest influence in soils treated with biochar (Table 5.1). The effect of biochar treatment on CEC is well recognized (Ren et al., 2020; Yadav et al., 2019; Šimanský et al., 2018), but the mechanism behind it is still being researched. It's important to note, however, that improving CEC with biochar is critical in many semi-arid areas dominated by low- cation-exchange-capacity soils, such as high-acidity sandy soils, which can quickly lose their fertility if fallow periods, or something similar to fallow conditions, aren't imposed (Ren et al., 2020). The application of 5 t ha^{-1} of three different sources of biochar did not change the particle size distribution in the top 0–30 cm of the soil ($p > 0.05$). Only at 1.0-0.97g cm^3, where the density of absolute control soil (1.05 g cm^3) was greater than three different sources of biochar-altered soil (1.01-0.96 g cm^3), were significant changes in bulk density ($p<0.05$) detected (Table 5.5).

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Table 5.4a: Soil properties as affected by biochar and inorganic fertilizer for the 2018 cropping season

Treatment	pH	O.C	TN	OM	Ca	Mg	K
			%		cmol (+) kg^{-1}		
Absolute Control	4.94±0.01	0.46±0.00	0.03±0.01	0.79±0.01	1.37±0.01	0.74±0.00	0.13±0.01
90N60P60K	5.54±0.01	0.50±0.01	0.05±0.00	0.87±0.00	1.69±0.01	1.06±0.00	0.50±0.03
ChGs+45N30P30K+C	5.14±0.01	0.41±0.01	0.05±0.01	0.72±0.01	1.27±0.01	1.27±0.01	0.13±0.01
ChPM+45N30P30K+C	5.32±0.01	5.32±0.01	0.03±0.01	0.79±0.01	1.27±0.01	1.06±0.00	0.16±0.01
ChCc+45N30P30K+C	5.32±0.01	0.46±0.00	0.03±0.01	0.79±0.01	1.69±0.01	1.06±0.00	0.19±0.01
ChGs+45N30P30K	5.06±0.01	0.33±0.01	0.03±0.00	0.57±0.01	1.27±0.01	0.84±0.01	0.13±0.01
ChPM+45N30P30K	5.27±0.01	0.50±0.01	0.03±0.01	0.87±0.00	1.48±0.01	1.06±0.00	0.16±0.01
ChCc+45N30P30K	5.11±0.01	0.37±0.01	0.03±0.01	0.65±0.01	1.16±0.01	0.95±0.01	0.14±0.01

Treatment	Na	T.E. B	EX. acidity	ECEC	BS	Av. P
			cmol (+) kg^{-1}			Mg kg^{-1}
Absolute control	0.02±0.01	2.29±0.01	1.1±0.01	3.49±0.01	65.70±0.00	12.21±0.01
90N60P60K	0.01±0.01	2.98±0.01	0.7±0.01	3.77±0.01	78.90±0.01	25.81±0.01
ChGs+45N30P30K+C	0.02±0.01	2.72±0.00	0.94±0.01	3.67±0.00	74.14±0.01	15.17±0.01
ChPM+45N30P30K+C	0.00±0.00	2.51±0.01	0.84±0.01	3.36±0.01	74.77±0.01	23.45±0.01
ChCc+45N30P30K+C	0.00±0.00	2.65±0.01	0.84±0.01	3.82±0.01	77.77±0.01	33.30±0.01
ChGs+45N30P30K	0.01±0.01	2.28±0.01	0.33±0.01	3.28±0.01	69.59±0.00	17.14±0.01
ChPM+45N30P30K	0.01±0.01	2.73±0.01	0.8±0.01	3.63±0.01	75.29±0.01	11.23±0.00
ChCc+45N30P30K	0.02±0.01	2.30±0.01	0.94±0.01	3.25±0.01	70.82±0.01	10.44±0.01

Values in (mean± SE) are not significantly different at ($p< 0.05$) Ch-biochar, Gs-groundnut shells, Cc-corn cobs, PM-poultry manure, C-cowpea, Nitrogen (N), Phosphorus (P), Potassium (K) and Cowpea (C)

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Table 5.4b: Soil properties as affected by biochar and inorganic fertilizer for the 2019 cropping season

Treatment	pH	O.C	TN	OM	Ca	Mg	K
		%			cmol (+) kg^{-1}		Mg kg^{-1}
Absolute Control	4.91±0.01	0.46±0.00	0.03±0.01	0.79±0.01	1.27±0.01	0.74±0.00	0.06±0.01
90N60P60K	4.85±0.01	0.46±0.00	0.04±0.01	0.79±0.01	1.27±0.01	0.84±0.01	0.13±0.01
ChGs+45N30P30K+C	5.05±0.01	0.50±0.01	0.05±0.00	0.87±0.00	1.48±0.01	0.74±0.00	0.18±0.01
ChPM+45N30P30K+C	5.31±0.01	0.54±0.01	0.05±0.00	0.94±0.01	2.12±0.01	0.42±0.00	0.14±0.01
ChCs+45N30P30K+C	5.3±0.06	0.58±0.01	0.04±0.01	1.01±0.01	1.91±0.00	1.06±0.00	0.27±0.01
ChGs+45N30P30K	4.74±0.01	0.46±0.00	0.04±0.01	0.79±0.01	1.06±0.00	0.74±0.00	0.17±0.00
ChPM+45N30P30K	4.97±0.04	0.46±0.00	0.04±0.00	0.79±0.01	1.48±0.01	0.74±0.00	0.06±0.01
ChCc+45N30P30K	4.62±0.01	0.41±0.01	0.02±0.01	0.72±0.01	1.48±0.01	0.42±0.00	0.15±0.03

Treatment	Na	T.E. B	EX. acidity	ECEC	BS	Av. P
			Cmol (+) kg^{-1}			mg kg^{-1}
Absolute control	0.00±0.00	2.60±0.01	1±0.01	3.19±0.01	65.66±0.01	9.85±0.00
90N60P60K	0.00±0.00	2.27±0.01	1.1±0.01	3.47±0.01	65.48±0.01	17.14±0.01
ChGs+45N30P30K+C	0.04±0.00	2.46±0.01	0.33±0.01	3.46±0.01	71.19±0.01	13.19±0.01
ChPM+45N30P30K+C	0.02±0.01	2.73±0.01	0.84±0.01	3.58±0.01	76.31±0.01	33.70±0.01
ChCc+45N30P30K+C	0.02±0.01	3.29±0.01	0.7±0.01	4.60±0.25	80.47±0.00	12.41±0.01
ChGs+45N30P30K	0.03±0.01	2.02±0.00	1.24±0.01	3.27±0.00	61.84±0.01	13.20±0.01
ChPM+45N30P30K	0.00±0.0	2.31±0.01	0.33±0.01	3.31±0.01	69.88±0.01	42.37±0.01
ChCc+45N30P30K	0.01±0.01	2.12±0.01	1.2±0.01	3.42±0.01	62.07±0.01	16.75±0.00

Values in (mean ± SE) are not significantly different at ($p< 0.05$) Ch-biochar, Gs-groundnut shells, Cc-corn cobs, PM-poultry manure, C-cowpea, Nitrogen (N), Phosphorus (P), Potassium (K) and Cowpea (C)

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Table 5.5a. Model Parameters and measured bulk density, porosity, and particle size distribution in the top 0-30cm of the soil for all treatments for 2018

	2018					
Treatment	**Sand**	**Silt**	**Clay**	**Texture**	**Bulk Density**	**Porosity**
		%			**gcm^{-3}**	**%**
Absolute Control	77±0.01	17±0.01	3±0.01	LS	0.97	60.63
90N60P60K	81±0.01	13±0.01	3±0.01	LS	1.01	60.00
ChGs+45N30P30K+C	83±0.01	11±0.01	3±0.01	LS	1.00	63.13
ChPM+45N30P30K+C	81±0.01	13±0.01	3±0.01	LS	1.05	63.00
ChCc+45N30P30K+C	79±0.01	15±0.01	3±0.01	LS	1.01	63.25
ChGs+45N30P30K	81±0.01	13±0.01	3±0.01	LS	1.27	67.88
ChPM+45N30P30K	79±0.01	15±0.01	3±0.01	LS	1.08	61.38
ChCc+45N30P30K	79±0.01	15±0.01	3±0.01	LS	1.07	64.25

Values were significant changes in bulk density ($p<0.05$) Ch-biochar, Gs-groundnut shells, Cc-corn cobs, PM-poultry manure, C-cowpea Nitrogen (N), Phosphorus (P), Potassium (K)

Table 5.5b. Model Parameters and measured bulk density, porosity, and particle size distribution in the top 0-30cm of the soil for all treatments for 2019

	2019					
Treatment	**Sand**	**Silt**	**Clay**	**Texture**	**Bulk Density**	**Porosity**
		%			**gcm^{-3}**	**%**
Absolute control	81±0.01	13±0.01	3±0.01	LS	0.93	61.13
90N60P60K	81±0.01	13±0.01	3±0.01	LS	1.08	61.25
ChGs+45N30P30K+C	71±0.01	16.33±0.01	9±0.01	LS	1.01	62.88
ChPM+45N30P30K+C	75±0.01	19±0.01	3±0.01	LS	1.02	62.50
ChCc+45N30P30K+C	71±0.01	17±0.01	9±0.01	LS	1.03	61.13
ChGs+45N30P30K	81±0.01	13±0.01	3±0.01	LS	1.07	59.63
ChPM+45N30P30K	83±0.01	11±0.01	3±0.01	LS	1.06	63.63
ChCc+45N30P30K	81±0.01	13±0.01	3±0.01	LS	1.04	63.50

Values were significant changes in bulk density ($p<0.05$) Ch-biochar, Gs-groundnut shells, Cc-corn cobs, PM-poultry manure, C-cowpea, Nitrogen (N), Phosphorus (P), Potassium (K)

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5.9 Upland rice yield

Short-term rice yields are difficult to model. The seasonal yield differences in both treatments were difficult to predict. Short-term environmental events, such as high temperatures and moisture stress during key periods, flood damage, high winds, and occurrences of pests, diseases, or birds in the field, can be used to induce measured yields that the model cannot deliberate. A comparable study on short-term rain-fed upland rice simulation also found that extreme short-duration weather events not considered by the model are the reason behind imprecise short-term upland rice simulation (Reynolds et al., 2018). The planting date is known to influence rice yield (Jalota et al., 2012; Karim et al., 2012; Yao et al., 2007), and in this simulation, the planting dates over the years were not known but only based on a managing regulation that originated planting in a pre-defined planting. Other considerations, like the availability of planting materials and labor, can influence the planting date more than the weather. For the 90N60P60K treatment, yield overrating between 1990 and 2019 may be an effect of varieties cultivated in those years not being as vigorous as calibrated Nerica 14, which was used for the entire simulation. Another explanation for the control's erroneous yield estimate could be the model's mention of N and insufficient moisture yields. Other factors not well thought-out by the model have previously influenced the measured yields. Previously, yield quantities were calculated by multiple people, which could be another source of error in yield measurements. All of these considerations showed that, in the vast majority of situations, poor statistical outcomes may be attributed to the incorporation of poor model performance and possible inconsistencies in measured data when secondary data is employed.

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5.10 Soil organic matter

The amount of soil organic matter (SOM) was generally adequately approximated by APSIM, which had previously demonstrated its usefulness by being able to estimate comparable patterns with observed data. The slow, steady waning of modeling capacity from the start could indicate that the decomposition of SOM on the barren ground is undervalued. According to popular belief Fageria (2012); Kekeli (2015) and Lemenih (2004), tilling of land causes SOM loss in cropping systems, with considerable initial soil organic matter loss when virgin vegetation is replaced by cropping systems. Organic inputs and the degree of decomposition, which is heavily influenced by management techniques, influence variations in SOM content. SOM is normally stable in natural vegetation when humus is generated and degraded at the same rate. This steadiness is then bothered by human actions like tilling and bush burning, which create favorable environments for oxidation that result in SOM waning and the ultimate decline in plant nutrient reserves like N, P, and S, which are essential parts of organic matter. Higher SOM in biochar+45N30P30K than in the control treatment is attributed to a higher stable C pool in the biochar input (Table 5.2) as an effect of the amendment raising biomass production in the mineral fertilizer treatment. Soil tilling and low C inputs from residues reduce control. However, soil tilling and N treatment can lead to significant mineralization of organic inputs despite low C inputs for mineral fertilizer. Clough et al. (2013) stated that the higher mineralization rate of biochar inputs in mineral fertilizer treatments was due to N fertilization improving the decay process by raising the availability of essential microbes. Biochar integration has been shown in several studies to reduce inorganic nitrogen leaching and increase soil N retention (Borchard et al., 2019; Major et al., 2012; Oladele et al., 2019; Sun et al., 2017; Yao et al., 2012). The mechanisms underlying biochar's impacts on soil N retention are not completely understood, but some

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potential advancements have been suggested; in Table 5.1, biochar has a high cation exchange capacity (Ding et al., 2016; Nelissen et al., 2014; Yang et al., 2017) and changes the soil pH (Novak et al., 2009), foremost by the shortest way of absorption of NH_4^+ and NO_3-N. As crop yields were not precisely simulated at all times, likely, biomass was not precisely simulated at all times, and this capacity persuaded the SOM-level assessments.

6. Conclusion

The experiment shows that the soil in the lysimeters was not deficient in plant-available nutrients, consistent with control treatments in the general observation that Luvisols are nutrient-depleted and suboptimal for plant growth without additions of organic and inorganic amendments. Applications of the three different sources of biochar+45N30P30K were more efficient in improving soil organic carbon, soil water storage capacity, nutrient-retention capacity, and nutrient-use efficiency than mineral fertilizer alone. The use of three different sources of biochar as soil amendments reduced the loss of some nutrients through leaching, with nutrient leaching of NO_3-N, P and exchangeable bases significantly decreasing as the growth of plants progressed. Application of 5 t ha^{-1} of the three different sources of biochar resulted in the highest yield production, number of grains per panicle, number of grains per spikelets, and number of tillers. Although the sole application of the three different sources of biochar did not perform in terms of biomass yield and nutrient uptake, the combined application of biochar+45N30P30K improved and sustained soil biophysical and chemical properties, because most of the mineral fertilizer will dwindle over time through decomposition, whereas the biochar will stay in the soil for years.

The findings of this study strongly suggest that adding three different sources of biochar to Guinean savannah agricultural soils will increase the soil's ability to retain nutrients and thus

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reduce nutrient leaching. Increased nutrient retention in the soil profile should increase the likelihood of nutrients being taken up by plant roots, reducing the risk of them being leached and transported to surface or groundwater reservoirs. The net effect of these processes should be improved nutrient use efficiency, reducing the need for fertilizer and lime amendments in production agriculture while also improving water quality. The use of three different sources of biochar and one soil for a short period was a limitation of the current study. Biochar properties vary greatly depending on the properties of the pyrolyzed biomass, the conditions under which it is pyrolyzed, and the degree of aging of the biochar. Biochar surfaces are expected to oxidize as they age in the soil, forming carboxylate groups and thus active sites for the adsorption of various compounds. The longer biochar remains in soils, however, the more likely its surfaces will become saturated with metals, oxyanions, and organic compounds. As a result, biochar's function in soils will almost certainly change over time. However, the Terra Preta soils' high fertility and capacity to retain nutrients today, more than 500 years after the practices that led to their development, suggest that biochar's beneficial effects on soils are long-lasting

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CHAPTER SIX

6.0 INFLUENCE OF BIOCHAR AND INORGANIC FERTILIZER ON UPLAND RICE-COWPEA INTERCROP COMPETITIVE INDICES

Frimpong-Manso J[1] *, Abdul Ganiyu S[2] and Kugbe Xorse J[2]

1CSIR-Soil Research Institute, Academy Post Office, Kwadaso-Kumasi, Ghana
2University for Development Studies, Ghana
**frimpong1977_1@yahoo.co*

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Frimpong-Manso Judith (Candidate)

Conceived and designed the research, analyzed and validated the result, and drafted and revised the manuscript.

Ing. Prof. Abdul Ganiyu Shaibu (Supervisor)

Supervised the work and reviewed the manuscript

Dr. Joseph Xorse Kugbe (Co-Supervisor)

Supervised the work and reviewed the manuscript

Abstract

A trial was conducted to evaluate the competitive indices of upland rice-cowpea intercrop. Sole cropping of the two crops was also done. The experiment was a randomized complete block with 4 replications. The treatment included a control (no input), fertilizer, rice, and cowpea intercrop either applied alone or in combination with three different sources of biochar (poultry manure, corn cobs, and groundnut shell). At the same time, 5 t ha^{-1} of biochar level each was incorporated into the soil. Inorganic fertilizer was applied at the rate of 90, 60, 60, and 45 kg ha^{-1} NPK, as straight fertilizer, and then top-dressed with nitrogen levels in the form of urea at 30 kg ha^{-1} N eight (8) weeks after transplanting. The crops were arranged in a 3:1 rice-cowpea ratio. In this study, the intercropping system gave higher land equivalent ratio (LER). Biochar of poultry manure+45N30P30K exhibited higher rice aggressivity (2.43), relative crowding coefficient (1.74), and competitive ratio (4.11). Rice performed better in terms of competitive ratio when grown in combination with cowpea. In terms of nutrient use efficiency nitrogen was high with intercrops, but was very low in the sole crops. Intercropping of rice with cowpea gave higher economic advantage (9544.5), income equivalent ratio (403.1), and production and cost-benefit ratio for biochar poultry manure+45N30P30K (2.68) than 90N60P60K (2.52) respectively. For economic crop yield in upland rice-based ecosystems, small-holder farmers, therefore, should intercrop rice and cowpea and apply biochar +45N30P30K and nitrogen (30 kg N ha^{-1}).

Keywords: Land equivalent ratio, intercropping, nutrient use efficiency, biochar, inorganic fertilizer

6.1 Introduction

The main benefit of intercropping is an increase in yield per unit area of land. Several research studies have been reported on intercropping. According to Lizarazo et al. (2020) concluded that in most of the experiments on mixed cropping in the tropics, more than one acre of the sole stand was required to produce the yield of one acre of mixed crop, and concluded that for the tropical small-scale farmer, there was no advantage to be gained by replacing the traditional practice of mixed cropping. Research by Iderawumi and Friday (2013) reported that intercropping maize is one of the most popular mixed cropping combinations in rain-fed agriculture in the tropics. Cultivation of maize in combination with other crops is, therefore, a widespread practice in northern Ghana, especially in the Northern Region. It is not uncommon to see crops like legumes, okra, melon, peppers, and cassava being intercropped with maize. Systems that intercrop maize with cowpea can reduce the number of nutrients taken from the soil as compared to maize as a sole crop (Ananthi et al., 2017; Zhang and Li, 2003). Production increased due to reduced competition between species compared with competition within species. Eskandari (2011); Maitra et al. (2021) and Maitra et al., 2019 also consider intercropping as an economic method for higher production with lower levels of external inputs. This improved resource use efficiency is critical, particularly for small-scale farmers and in areas where the growing season is short (Altieri, 2002; Daryanto et al., 2020). More production in intercropping can be attributed to the higher growth rate, reduction of weeds, reducing pests and diseases, and more effective use of resources due to differences in resource consumption (Eskandari, 2011; Maitra et al., 2020; Stomph et al., 2020). In addition, if there are "complementary effects" between the

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components of intercropping, production increases due to reducing the competition between them (Dwivedi et al., 2015; Maitra et al., 2019; Mousavi and Eskandari, 2011).

Increased diversity of the physical structure such as leaves and roots of plants in an intercropping system also produces many benefits. Increased leaf cover in intercropping systems helps to reduce weed populations once the crops are established (Belel et al., 2014). Having a variety of root systems in the soil reduces water loss, and increases water uptake and transpiration. The increased transpiration may make the micro-climate cooler, which, along with increased leaf cover, helps to cool the soil and reduce evaporation (Ai et al., 2021; Gebregergis, 2016; Workayehu, 2014). This is important during drought or water stress, as intercropped plants use a larger percentage of available water from the field than mono-cropped plants. Seran and Brintha, 2010 also reported that rows of maize in a field with a shorter crop will reduce the wind speed (above the shorter crops) and thus reduce desiccation. Increased plant diversity in intercropped fields may reduce the impact of pest and disease outbreaks by providing more habitats for predatory insects and increasing the distance between plants of the same crop (He et al., 2019; Smith and McSorley, 2000). Intercropping has environmental benefits such as requiring less land for crop production, reducing the use of inorganic fertilizers, pesticides, and herbicides, and reducing soil erosion. Intercropping also has several benefits to the farmer, including a reduction in farm inputs, the addition of cash crops and diversification of diet, increased labor utilization efficiency, and a reduced risk of crop failure due to uncertainties in the weather. The quantity of time to plant the multiple varieties of seeds is reduced to increase labour utilization efficiency. Peak labour requirements during the harvest become easy when two or more crops are harvested at different times, allowing the smallholder to finish the harvest with family labour

(Maitra et al., 2021). Intercropping presents a large level of risk reduction for smallholders in northern Ghana. If one crop is entirely lost to pest or drought damage, the farmer may still harvest the other crop in the field. Given the unpredictable rainy season and the different water requirements of each crop, planting many varieties of the same crop in an intercropped field gives the farmer a better chance that some crops will survive (Maitra et al., 2021). One important advantage of intercropping is its ability to reduce pest and disease damage. In general, strategies involved in reducing pest infestation and damage in intercropping can be divided into three groups (Mousavi and Eskandari, 2011). The first is the delimiter crop hypothesis, in which the second specie breaks down the ability of a pest to attack its host and is used more in proprietary pests. Second, for pests and pathogenic agents, the trap crop hypothesis, in which the second species attracts pests or pathogens that normally cause damage to the main species, is used more broadly. The natural enemy's hypothesis asserts that predators and parasites prefer intercropping to monocropping, which reduces parasitized and preyed populations.

Although intercropping does not always reduce pest or pathogen populations, most reports have pointed to reduced populations of pests and diseases in intercropping (Lopes et al., 2015). In a review by Mousavi and Eskandari (2011) on intercropping, in 53% of the experiments, intercropping reduced the pest, and in 18% it increased the pest more than pure cropping. Increasing pests can be due to several reasons, like the second crop may be a host for pests in intercropping, or increasing the shade in the canopy provides favorable conditions for pests and pathogen activity. In addition, plant residues are often used as a source for pathogens inoculated, as also reported by Imathiu et al. (2014). More species diversity in agricultural ecosystems can limit the spread of plant pathogenic bacteria.

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Intercropping systems increase biodiversity just like natural ecosystems. This increase in diversity reduces pest damage and diseases, (Imathiu et al., 2014). Recent advances in organic agriculture have reemphasized the use of conservation agricultural practices such as crop intercropping with leguminous species and green manuring as cost-effective mechanisms for improving and maintaining soil fertility (Sarkar et al., 2021). In addition to biological nitrogen fixation, biochar sources play an important role in plant nutrient recycling, soil temperature improvement, soil structure enhancement, and microbial activity promotion, as well as maintaining high soil nutrient status (Das and Ghosh, 2020; Palansooriya et al., 2019). Despite this, the long-term beneficial impacts of biochar and fertilizers on farmlands may be limited by weak soil structure and weathering, which makes them more vulnerable to erosion and nutrient leaching (Ding et al., 2016). According to reviews by (Guo et al., 2016; Mulabagal et al., 2017; Rawat et al., 2019), amending soils with biochar (a by-product of the pyrolysis of plant biomass in a low-oxygen environment) reduces nutrient leaching and improves soil cation exchange capacity, soil organic matter, microbial biomass, pH, and soil moisture retention. Smallholder farmers in Northern Ghana use legume–cereal intercrop systems with organic residue inputs, although yield responses are generally limited by the aforementioned soil issues. Biochar's incorporation into these cropping systems is thus predicted to enhance the long-term benefits of crop rotation systems by increasing nutrient availability, nitrogen recovery efficiency, and crop performance (Bashagaluke et al., 2020; Kalu et al., 2021; Oladele et al., 2019). Biochar's use could ensure a long-term advantage for soil fertility improvement and crop output because it can persist in soils for decades without degrading (Agegnehu et al., 2017; Kalu et al., 2021). Currently, only a few research studies in African agroecosystems have looked into the viability of

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applying biochar in legume–cereal intercropping systems. The effects of biochar on soil nutrient availability and the agronomic performance of upland rice within a legume–rice intercropping system in Northern Ghana were thus the focus of this study. It is expected that biochar application will increase upland rice agronomic performance in the legume–rice intercropping system by increasing soil nutrient availability, and nutrient uptake. Also serving as carbon sinks and makes them effective in the ecosystems for storing carbon in the soil. The study aims to decrease yield losses and sustain a level of cropping competition indices that improves resource use as well as impacts on high crop yields within the rice-cowpea intercrop.

6.2 Material and methods

6.2.1 Study area

The research site was located at the Farming for the Future, University for Development Studies (UDS), Nyankpala near Tamale in the Northern Region of Ghana (latitude 09.246070N and longitude 000.589920W). The area has a unimodal rainfall pattern with an annual rainfall of 800-1100 mm (Abdul-Ganiyu et al., 2018; SARI, 2013). The dry season starts from November to March with day temperatures ranging from 33 °C to 39 °C, and night temperatures ranging from 20 °C to 26 °C (Abdul-Ganiyu et al., 2015; Dogbe et al., 2016). The mean annual daytime relative humidity is 54% with the altitude of the area 252 m above sea level. The site is underlain by Upper Voltaian sediments. The area is covered with red and orange-brown drifts partly eroded in places and exposing a layer of shallow ironstone and sandstone (Adjei-Gyapong and Asiamah, 2002; Adu, 1957; Imoro et al., 2012).

This layer is often separated from the underlying sandstone by a thin stone-lime (Adjei-Gyapong and Asiamah, 2002; Adu, 1957; Imoro et al., 2012). The soil profile has been classified as Nyankpala series (Ferric Luvisols) (Adjei-Gyapong and Asiamah, 2002; Imoro et al., 2012; FAO, 1988; ISSS/ISRIC/ FAO, 1998). They are shallow to very shallow soils overlying in situ developed iron pans within 55.9 cm. It is also moderately shallow to moderately deep concretionary and or gravelly, heavy to medium textured soils overlying mostly highly weathered granites shales (Asiamah and Dwomo, 2009). Characteristically the soils are acidic, with low nitrogen and phosphorus content. They are susceptible to moderate erosion and should not, therefore be left bare. They are inherently infertile and will need to be fertilized to obtain optimum yield (Adjei-Gyapong and Asiamah, 2002; Adu, 1957; Imoro et al., 2012).

6.2.2 Biochar preparation

Three different sources of feedstocks were produced from slow and high pyrolysis of groundnut shells, corn cobs, and poultry manure at 400°C - 700°C with a dwelling time of 24 hours in oxygen-limited conditions in a reactor, followed by water and air cooling of charred feedstock to room temperature and grind the biochar. The synthesized biochar was ground and analyzed for a few selected parameters (Table 6.1). Organic carbon was determined by the wet combustion method according to (Walkley and Black, 1934). Total nitrogen was determined by the Kjeldahl method. Phosphorus and potassium were determined in plant ash using the Gallenkamp flame analyzer method (Bremner, 1965). Available phosphorus was determined by (Bray and Kurtz, 1945).

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6.2.3 Biochar Types

Table 6.1: Basic biochar properties used for simulations

Feedstock	Pyrolysis	pH 1:5	CEC me100g^{-1}	N %	P %	K %	C: N ratio (-)	Fraction C (0 -1)
Biochar Corn cobs	High	6.67	118.26	0.95	0.21	0.45	11.0	0.129
Biochar Poultry manure	High	9.29	125.63	2.19	0.50	0.47	10.5	0.324
Biochar Groundnut shells	Low	11.13	85.52	1.34	0.13	0.74	12.3	0.243

Source: Frimpong-Manso and Ganiyu (2021)

CEC-cation exchange capacity, C: N- carbon-nitrogen ratio, C-carbon fraction

Table 6.2: Initial Chemical and Physical Properties of Soil

Soil parameter	0-30 cm
pH 1:2.5	6.01±0.02
O.C	0.72±0.06
%TN	0.08±0.01
%OM	1.25±0.01
Ca (cmol kg^{-1})	1.00±0.10
Mg (cmol kg^{-1})	0.08±0.07
K (cmol kg^{-1})	0.02±0.01
Na (cmol kg^{-1})	2.61±0.15
T.E.B (cmol kg^{-1})	0.180±0.03
EX. acidity (cmol kg^{-1})	2.79±0.18
ECEC (cmol kg^{-1})	93.51±0.76
Base saturation (cmol kg^{-1})	3.30±0.05
P (mg kg^{-1})	62.67±0.67
% Sand	29.33±0.67
% Silt	8±0.00
% Clay	0
Texture class	sandy loam
% WHC	12.67±0.84
%PWHC	0.29±0.03
% A. W	5.43±0.58
HDY COND mm/Hr	102.05±0.02
eC uS/cm 1:5	16.66±0.01

Values are (mean± SE) within 0 to 30 cm soil depth are significantly different at P<0.05

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The data used in the current study cover the main crop and soil processes. Initial soil sampling was done at a depth of 0-30 cm for the characterization of both chemical and physical properties (Table 6.2). Ten plants were randomly selected on each plot and plant height at maturity, the number of panicles, the number of tillers, and number of grains per panicle were determined. Data was collected every week from 30 days after transplanting to heading. Data were collected on maturity indices, namely measurements of plant height for both cowpea and rice, number of panicles, and number of plants within a 1m area.

Five panicles were randomly selected for the number of spikelets, panicle length, number of grains per spikelet on a panicle, weight of unfilled and filled grains, total grain weight, and 1000 grain weight for both rice and cowpea and strawweight. The combination of the rice and cowpea was in a 3:1 ratio (three rows of rice and one row of cowpea). Varieties of the crops were Nerica 14 (85 days) for the rice (*Oryza sativa* L.) and erect cowpea (padituya) type (*Vigna unguiculata* L. W), respectively. Data on yield components were collected at the field while data on yield was obtained from a net plot area of 12 m^2 (3 m × 4 m). Grain parts were analyzed for nutrient uptake and total nitrogen concentration using the micro Kjedahl method (Chukwuka and Omotayo, 2008). Nutrient use in the interplant competition was evaluated using the nitrogen, phosphorus, and potassium utilization efficiency-NUE concept (Baligar et al., 2001; Baumann et al., 2001; Fixen et al., 2015).

NUE= YF -Yo/ Uf- Uo

where YF and YO = Yield in kg ha^{-1} at corresponding fertilizer rates; Uf and UO = Uptake of nitrogen, phosphorus, and potassium in kg ha-1 at corresponding fertilizer rates. The intra- and interspecific competition in the rice–cowpea intercropping system was assessed using

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the land equivalent ratio-LER (Mead and Willey, 1980), the relative crowding coefficient-K (Willey and Rao, 1980), and the aggressivity index-A (Taha and El-Mahdy, 2014)

LER= Yij /Yii + Yij /Yjj

where Y = Yield per unit area; Yii = Sole crop yield of crop I (rice); Yjj = Sole crop yield of crop j (cowpea); Yij and Yji = yield per unit area of I intercropped with j and j intercropped with i. When LER is 1, there is no advantage in intercropping as compared to sole cropping, whereas if LER > 1, a larger area of land is needed to produce the same yield of both sole crops of each component, concerning the intercropped mixture. An LER < 1.0 shows a disadvantage of intercropping. If a species i is in mixture with a species j in a 3:1 mixture of I and j, then an individual coefficient, termed the relative crowding coefficient k can be expressed as

Kij = Yij/Yii-Yjj

Kij =Yji/Yjj –Yii

where Kij and Kji = relative crowding coefficients of crop i intercropped with crop j and crop j intercropped with i; Yij and Yji = yields per unit area of i intercropped with j and j intercropped with i; Yii and Yjj = yields per unit area of sole crop i and sole crop j. The crop component that had a higher coefficient was said to be dominant. If the coefficient of a particular crop species is less than, equal to, or greater than 1, then that species has produced less yield, the same yield, or more than "expected", respectively (Willey and Rao, 1980). Aggressivity (Taha and El-Mahdy, 2014) is a measure of how much the relative yield in species i is greater than that for species j. This can be expressed as follows:

Aij = Yij/Yii * Zji – Yji/ Yjj * Zji

Aij = Aggressivity index of crop i intercropped with j; Yij = Yield per unit of crop i intercropped with j; Y-ii and Yjj = yield per unit area of sole crop i and j; Zji = Proportion of intercropped area initially allocated to crop i; Zji = Proportion of intercropped area initially allocated to crop j. If A = O, the component species are equally competitive, for situations where A ≠ O, both species will have the same numerical values, only that the value of the dominated species will be negative. If the numerical absolute value of A is large, there is a large difference in the competitive abilities of the two species and a larger difference between measured and expected yields. Values of yield, yield components, and total nitrogen of both rice and cowpea were presented as the average of two cropping seasons and were subjected to the appropriate analysis of variance (ANOVA) for factorial and randomized complete block designs statistically using statistix10.0 (Analytical Software, Tallahassee FL) techniques for analyzing intercropping trials (Akter Suhi et al., 2022; Pereira[1] et al., 2021 and Degaga and Angasu (2017). Comparisons of means of the cropping systems were made by the Honest significant difference.

Increasing nitrogen rates increased ($P < 0.05$) yield and yield components of rice in sole rice arrangement competition indices (Tables 6.3, 6.4, and 6.5), but in the mixtures, only the number of panicles significantly increased (Table 4). However, for cowpea, higher nitrogen rates did not increase yield and yield components in sole and mixed competition indices, respectively. The number of panicles per rice plant was reduced ($P< 0.01$) by higher arrangement competition indices in mixed populations (Tables 6.5 and 6.6). The number of panicles per plant decreased with planting competition in sole and mixture stands of rice, although the sole rice crops had a higher number of panicles per plant on average. Increasing

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planting row arrangement competition decreased panicle number by 26%, 38%, 47%, and 59% at biochar poultry manure+45N30P30K+cowpea, biochar groundnut shells+45N30P30K+ cowpea, biochar corncobs+45N30P30K +cowpea, biochar saw dust+45N30P30K+cowpea, biochar rice husk+45N30P30K+cowpea, respectively, for rice mixtures. This trend did not occur in the sole rice stands. High-density competition indices decreased ($P < 0.05$) the number of grains per panicle in mixed rice populations (Table 6.7). The weight of pods per plant and grain yield of cowpea in mixed populations did not result in any increase with increasing plant density (Tables 6.5, 6.6.and 6.7). The grain yield of cowpea in the sole crop increased ($P < 0.05$) with cropping density (Table 6). With exception to the number of grains per panicle of rice (Table 6.7) that decreased in biochar rice husk+45N30P30K by intercropping with cowpea, other yield and yield components of rice and cowpea had no effect when intercropped (cropping systems). Interactions ($P < 0.05$) were observed between Nutrient use efficiency on rice grain (NPK) × row arrangement density, treatment on Nutrient use efficiency × cropping system, and row arrangement density× cropping system in yield and yield components of rice (Table 6.5). The weight of pods per plant showed no significant interactions with cowpea. Cowpea grain yield indicated ($P < 0.05$) row arrangement density x system interactions. However, the grain yield of rice presented significant interactions with N x row arrangement density ($P < 0.05$), P × cropping system, and K x cropping system ($P < 0.01$) but the percentage phosphorus in grain showed negative (Tables 5.5, 6.6, and 6.7). Yield advantage of intercropping was observed at all levels of nitrogen, phosphorus, potassium, and row arrangement density on the treatments for the rice-cowpea intercrop. This is shown by the (LER) values in Table 6.9. The low biochar rice husk+45N30P30K and biochar corn cobs+45N30P30K in density recorded

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yield advantages ranging from LER 1.236 and LER 1.259, respectively. A lower LER of 1.236 was observed for the high density at biochar rice husk+45N30P30K. Yield advantage due to NPK was more pronounced at biochar poultry manure+45N30P30K (LER 1.552) and biochar groundnut shell+45N30P30K (LER 1.324) at the lowest density. High nitrogen levels of biochar saw dust+45N30P30K and biochar rice husk +45N30P30K with high density gave lower intercrop yield advantage of LER 1.289 and 1.236, respectively. Values of the aggressivity indices (A) indicated that cowpea is the dominant crop (Table 6.5). The values of A are high at biochar poultry manure+45N30P30KNPK and high in density. At all levels of NPK with low row arrangement in density at biochar rice husk+45N30P30K, rice was more aggressive on the dominant crop. The relative crowding coefficient values also indicate that cowpea was dominant in the rice-cowpea intercropping system in the experiment (Table 6.5). The dominant attribute of the cowpea was expressed more at high densities. However, rice was more dominant at all levels of nitrogen with low-density biochar rice husk+45N30P30K. Both rice and cowpea yield in the intercrop at all nitrogen in rice grain levels were high than expected in plots with low density. Compared to their sole crop absolute control, NUE was generally higher in all intercrops (Table 6.3). In rice, NUE was higher with sole crops 90N60P60K and high densities. Negative NUE values in phosphorus were obtained for most of the biochar+45N30P30K combination with cowpea as well as biochar sole rice plots, except 90N60P60K and absolute control. At the low NPK in absolute control, high values of NUE were obtained for biochar+45N30P30K combination with cowpea intercrop and sole rice crop 90N60P60K and biochar at medium and high densities. Therefore, the results of nutrient uptake (kg ha^{-1}) of rice straw grown at various treatment levels in the 2018 and 2019 cropping seasons previously performed on UDS-

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farming for the future experimental plots (Table 6.3) were integrated into the newly developed.

Table 6.3. The efficiency of utilization (kg ha^{-1}) of rice grain absorbed nutrients on biochar and inorganic fertilizer in the seasons 2018 and 2019

Treatment	NUE (% N) 2018	NUE (%N) 2019	NUE (% P) 2018	NUE (%P) 2019	NUE (%K) 2018	NUE (%K) 2019
Absolute Control	1.25	1.28	0.46	0.38	0.22	0.23
90N60P60K	16.63	20.96	16.65	21.10	16.65	23.60
ChGS+45N30P30K+C	20.39	22.32	-71.46	22.44	20.42	27.92
ChPM+45N30P30K+C	27.04	25.31	39.81	25.38	27.07	26.32
ChCc+ 45N30P30K+C	15.11	18.63	-1.57	18.69	15.14	20.98
ChGs+45N30P30K	4.55	16.35	0.49	16.48	4.55	17.38
ChPM+45N30P30K	1.81	16.93	-0.81	16.98	1.81	18.84
ChCc+45N30P30K	6.59	14.02	-2.69	14.07	6.59	12.76

(Source: Frimpong-Manso and Ganiyu, 2021)
Ch-biochar, Nitrogen (N), Phosphorus (P), Potassium (K) and Cowpea (C), NUE-nutrient use efficiency, PM-poultry manure, Gs-groundnut shells, Cc-corn cobs

6.4 Nutrient uptake of rice straw

Among the treatments, the highest N% uptake was logged under the biochar+45N30P30K combination with cowpea, followed by biochar compared to 90N60P60P for both the 2018 and 2019 seasons at maturity phase (Table 6.4a&b). The last N uptake was recorded under absolute control, which did not incorporate biochar and inorganic nutrients as well as cowpea intercrop. At maturity, there was a similar trend in P, K, and S uptake. Nutrient uptake is a product of nutrient concentration and straw accumulation. The combination of biochar plus inorganic fertilizer with cowpea intercrop helped nutrient use by analyzing for healthier NPKS uptake and NPKS yield of rice. The improved uptake capacity owing to the higher

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availability of nutrients from the soil pool and also from the add-on sources of biochar resulted in a similarity to (Lehmann et al., 2006). The effect of biochar plus inorganic fertilizer combination with cowpea intercrop treatment on the macronutrient (N, P, S, and K) uptake of rice plants was analyzed in both seasons (Table 6.4a&b). The results of nutrient concentrations in rice straw and grain from various treatments were recorded in terms of percentages. In both cropping seasons on sandy loam soils, biochar+45N30P30K in combination with cowpea treatment aided higher N uptake in rice plants for both straw and grain. Both cropping seasons, 90N60P60K, caused higher N intake. However, the biochar+45N30P30K treatment had high N uptake in plants. Dong et al. (2018) also testified to the higher retention of N in the paddy fields through successive growing seasons after biochar incorporation. The combined use of biochar plus inorganic fertilizers and cowpea intercrop performed significantly better than inorganic fertilizers alone for N uptake. Biochar+45N30P30K in combination with cowpea intercrop help to sustain higher absorption of soil nitrate (NO_3-N) and ammonium (NH_4^+) retention for a longer period of time, as well as restoring carbon in the soil environment to grasp its fertility and yield, thus grasping higher N uptake of rice.

Phosphorus moves very little in mineral soil, diffusing over a distance as small as a one-quarter inch. While P uptake in plants was best in moist soils, substantial differences were seen in the sandy loam soils among the 32 plots. Among the eight treatments, the biochar+45N30P30K combination with cowpea intercrop was the best in well-drained soil, improved phosphorus uptake, and translated into the grain. Biochar treatments had a greater effect on total nitrogen balance than straw (Table 6.3). An experiment by Liu et al. (2019), exhibited an increase in the availability of soil P after rice straw biochar application. In

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contrast, the application of biochar+45N30P30K in combination with cowpea intercrop improves the activity of microorganism that place phosphorus in solution and improves diffusion to roots for phosphorus uptake by plants in sandy loam soil, which might be due to the inherent P content of biochar+45N30P30K combination with cowpea intercrop. The absolute control treatment resulted in relatively low soil compaction or poorly drained soil, which reduced the percentage of P uptake in rice plants' straw and grain (0.15 and 0.30%) in both seasons.

Steiner et al. (2007) also uttered similar views. Improved P uptake with careful application of biochar+45N30P30K combination with cowpea intercrop blended factors that improve P availability in soils. These consist of the production of organic acids through the decomposition of organic matter and ensuing releases of phosphate ions, the development of phospho-humic complexes, isomorphic restoration of phosphate ions by humate ions, and also synergistic results existing between N and P due to the application of biochar as carbon. Such properties in soil P and rice straw uptake were also attested to by Liang et al. (2006).

Potassium uptake in rice was high in plants to transpire less and make better use of water supplies in biochar+45N30P30K combination with cowpea intercrop treatment. Shin et al., 2020 testified to increased K in the soil after rice straw biochar incorporation. The K uptake in rice plants increases hardiness or toughness. In general, plants well stocked with potassium have strong stems that are less prone to lodging both rice straws and grains of rice in sandy loam soils compared to absolute control. The outcomes of rice plant growth and nitrogen uptake in this study conform with those exhibited by Kang et al. (2021), who testified to improved rice yield and N retention after the incorporation of biochar with inorganic fertilizer. Percentage (%) N and potassium content act to balance the effects of

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nitrogen and a particular nitrogen-potassium ratio in rice plants. The percentage of P, K, and S uptake by rice-cowpea plants varied significantly across three different biochar incorporation sources. Higher uptake of K capacity may be owing to the readying result of biochar on decay-linked the release of organic acids that solubilize innate K. In addition, the advanced greatness of rises in K uptake by conjunctive use of biochar plus inorganic fertilizers in combination with cowpea intercrop exhibited that biochar takes advantage of biochar in improving the use efficiency of practical nourishment as well as inherent nutrient availability in the soil. Gul and Whalen (2016) also produced a similar report. Biochar as well as 90N60P60K treatment were significantly effective in improving rice % S content in both cropping season plants. In both cropping seasons, treatments triggered the lowest S uptake in rice (Table 6.4a&b). The biochar+45N30P30K combination with cowpea intercrop was shown to aid in the highest sulfur uptake for straw (0.13 and 0.16%) in both the 2018 and 2019 seasons. Absolute control treatments had a relatively very low percentage of S uptake in straw during the cropping seasons.

Biochar+45N30P30K in combination with cowpea intercrop treatment of % sulfur aids rice plants in making chlorophyll and also aids cowpea nodulation and seed production of all plants more than the absolute control. Biochar+45N30P30K combination with cowpea intercrop treatment showed that sulphur uptake in rice and cowpea plants improves protein and chlorophyll content, stress tolerance, and also pungent flavors more than absolute control. Sulphur uptake by straw was significantly influenced by the application of three different sources of biochar in a combination of inorganic fertilizer with cowpea intercrop (Table 6.4a&b). The S uptake by straw ranged from 0.16 to 0.04% biochar poultry manure+45N30P30K to absolute control. In grain N uptake was 0.38% to 0.12% biochar

poultry manure to absolute control for 2018 but in 2019 N uptake was 0.48% to 0.05 biochar groundnut shells+45N30P30K to absolute control respectively (Table 6.4a&b). The highest S uptake by straw (0.16%) was observed in the biochar poultry manure+45N30P30K treatment and the lowest S uptake by straw (0.04%) was observed in the absolute control treatment (Table 6.4a). Bhuvaneswari and Sriramachandrasekharan, 2006 detected that the incorporation of biochar and inorganic fertilizers improved the sulfur uptake significantly by rice. Azmi et al. (2004) established that increasing fertility levels significantly improved the upland rice yield and S uptake. In general, the combination of biochar + 45N30P30K with cowpea intercrop is recommended for the production of upland rice-cowpea intercrop.

Table 6.4a. Effect of biochar (5 t ha^{-1}) and inorganic fertilizer (kg ha^{-1}) on the nutrient uptake in rice straw

	Rice Straw – 2018				Rice Straw – 2019			
Treatment	**N**	**SO_4**	**P**	**K**	**N**	**SO_4**	**P**	**K**
				%				
Absolute Control	0.06	0.04	0.01	0.12	0.13	0.07	0.02	0.31
90N60P60K	0.27	0.08	0.04	0.33	0.36	0.12	0.05	0.45
ChGroundnutshell+45N30P30K+C	0.22	0.11	0.04	0.38	0.31	0.15	0.05	0.59
ChPoultry manure+45N30P30K+C	0.29	0.13	0.06	0.32	0.30	0.16	0.08	0.65
ChCorn cobs+45N30P30K+C	0.18	0.08	0.04	0.33	0.20	0.12	0.05	0.49
ChGroundnut shell+45N30P30K	0.15	0.06	0.02	0.22	0.26	0.11	0.04	0.48
ChPoultry Manure+45N30P30K	0.11	0.05	0.02	0.17	0.31	0.10	0.08	0.57
ChCorn cobs+45N30P30K	0.17	0.08	0.03	0.24	0.23	0.10	0.05	0.44

Ch-biochar, Gs-groundnut shells, PM-poultry manure, Cc-corn cobs, C-cowpea, NPK-nitrogen, phosphorus, potassium, SO4-sulfur

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Table 6.4b. Effect of biochar (5 t ha^{-1}) and inorganic fertilizer (kg ha^{-1}) on the nutrient uptake in rice grain

	Rice Grain – 2018			Rice Grain – 2019		
Treatment	**N**	**P**	**K**	**N**	**P**	**K**
			%			
Absolute Control	0.12	0.04	0.02	0.18	0.05	0.03
90N60P60K	0.30	0.10	0.06	0.43	0.11	0.06
ChGroundnutshell+45N30P30K+C	0.33	0.10	0.06	0.45	0.12	0.06
ChPoultry manure+45N30P30K+C	0.38	0.11	0.06	0.43	0.16	0.06
ChCorn cobs+45N30P30K+C	0.25	0.07	0.04	0.42	0.12	0.05
ChGroundnut shell+45N30P30K	0.22	0.04	0.03	0.41	0.10	0.05
ChPoultry Manure+45N30P30K	0.19	0.04	0.02	0.36	0.13	0.05
ChCorn cobs+45N30P30K	0.24	0.05	0.02	0.36	0.10	0.05

Ch-biochar, Gs-groundnut shells, PM-poultry manure, Cc-corn cobs, C-cowpea, NPK-nitrogen, phosphorus, potassium

6.5 Competitive roles of rice and component crop

When different crops are put on an effective, similar basis by employing some relative metrics, the extensive effects of intercropping were often recognized by comparing intercropping with sole cropping. The competitive ratio (CR), relative crowding (K), and aggressivity (A) are roles that evaluate intercrop competition by correlating yield changes (Dhima et al., 2007). Rice appeared to be substantially overridden in this experiment's intercropping systems (Table 6.5), as it had greater relative crowding coefficient (K) values than the component crop in all row layouts. For both cropping seasons, the following treatments were used: biochar poultry manure+45N30P30K combinations + cowpea,

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biochar groundnut shells+45N30P30K combinations + cowpea, biochar corncobs+45N30P30K combination with cowpea intercrop. Biochar poultry manure+45N30P30K combinations + cowpea gave the highest K value. According to the K Value, one rice plant was comparable to 15.5 percent of cowpea plants. In the biochar poultry manure+45N30P30K combo + cowpea (3:1) row arrangement of rice and cowpea, cowpea most likely had a competitive edge over the component crop, therefore receiving the bulk of growing resources for better grain output. The implication is that the intercropping systems had yield advantages because the product of the relatively high crowding coefficient (K) of component crops in the biochar poultry manure + 45N30P30K combination + cowpea (3:1 rice-cowpea) and biochar groundnut shells + 45N30P30K combinations + cowpea (3:1 rice-cowpea) row arrangements were greater than one. During the 2018 and 2019 seasons (Table 6.5), K values for rice were consistently higher than K values for component crops in all intercrop row combinations, implying that rice had absolute dominance. Biochar poultry manure+45N30P30K combinations + cowpea and biochar groundnut shells+45N30P30K combinations + cowpea gave the K value (1.76 and 1.56) for rice in the two seasons. In both experiments, the rice crowding coefficient (K) was consistently greater than one. Rice, on the other hand, had total K values larger than one, except rice-cowpea row arrangements in the 2019 season, which had total K values less than one. In most cases, three different sources of biochar plus inorganic fertilizer combinations with cowpea under rice-cowpea intercrop where they captured more resources were possibly better than 90N60P60K and absolute control under sole crop (Table 6.5).

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6.6 Aggressivity

Under all row arrangements, treatments for both cropping seasons were biochar poultry manure+45N30P30K combination+cowpea, biochar groundnut shells+45N30P30K combination with cowpea intercrop, biochar corncobs+45N30P30K combination+cowpea. An aggressivity value of zero shows that the component crop is in every way competitive. In any other circumstance, both crops will have the same value, but the sign of the dominant varieties will be positive and that of the dominant varieties negative. Chhetri and Sinha, 2019 stated similar outcomes for maize gaining positive aggressivity value when intercropped with legumes. The greater the value, the bigger the difference between actual and expected yields. The data exhibited in Table 6.5 revealed that the component crops did not compete correspondingly. In the three different sources of biochar plus inorganic fertilizer combinations with cowpea under rice-cowpea intercrop systems, rice was dominated by cowpea in the biochar poultry manure+45N30P30K combinations + cowpea under 3:1 row arrangement in both seasons. In the biochar groundnut shells+45N30P30K combination+ cowpea 3:1 row arrangement, on the other hand, the results showed that rice and cowpea were equally competitive. In both cropping seasons, cowpea seemed to be more dominant in their respective row arrangements, whereas rice dominated the cowpea significantly in the 3:1 row arrangement. Cowpea had the lowest aggressiveness value in the biochar corn cobs+45N30P30K combination + cowpea row arrangement, implying that cowpea was less competitive against rice. Khan and Khaliq (2004) also reported similar results of positive aggressivity value in maize-cotton intercropping.

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6.7 Competitive ratio (CR)

During the 2018 and 2019 cropping seasons, the competitive ratios were biochar poultry manure+45N30P30K combination+cowpea, biochar groundnut shells+45N30P30K combination +cowpea, biochar corncobs+45N30P30K combination+cowpea. It's a useful technique for determining how closely one crop competes with another. In all combinations, there were higher CR values for rice than for cowpea, except for the biochar rice husk+45N30P30K combinations + cowpea row arrangements of rice and cowpea at both cropping seasons. The experiment exhibited that in rice-cowpea row arrangements, rice was more competitive than cowpea (Table 6.5). Rice was found to be a superior competitor to cowpea when cultivated in combination. According to Dhima et al. (2007), competitive ratio (CR) is a better indication of a crop's competitive potential in a polyculture and can show a better index than the relative crowding coefficient (K) and aggressively. Khan, 2009 has highlighted the benefits of rice-cowpea intercropping. Rice was the most dominant type in a crop combination, according to the relative crowding coefficient and competitive ratio in terms of aggressiveness. Rice has been shown to have a higher competitive ability regarding resources when grown alongside cowpea (Ogola et al., 2013). The advantages gained from intercropping systems were attributable to better growth resources under the cowpea intercropping system, which was evident through competitive roles (Kermah et al., 2017). In these conditions, the major aim of intercropping is to get a full yield of the staple crop and an extra yield from the alternative crop, so that the combination gives the alternative crop the highest output without lowering the main crop production.

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6.8 Land equivalent ratio (LER)

The land equivalent ratio (LER) imitates the increased benefit of intercropping systems above single-cropping systems. For both cropping seasons, the LER values are listed in Table 6.5. Both cropping seasons of the intercropping advantage experiment are on biochar poultry manure+45N30P30K with cowpea intercrop, biochar groundnutshells+45N30P30K with cowpea intercrop, biocharcorncobs+45N30P30K with cowpea intercrop, which is under rice-cowpea intercrop in 3:1 row arrangement. Both time-based and spatial harmonization, according to (Negash and Mulualem, 2014), resulted in a yield benefit. When the LER value of the biochar poultry manure+45N30P30K combination +cowpea was more than one (1), it showed that intercropping outperformed sole cropping in terms of conservational resource consumption for plant growth. The LER values for rice were more than 0.5 in all intercropping row combinations, indicating a yield benefit for intercropping rice over biochar corn cobs+45N30P30K + cowpea intercrop, 90N60P60K, and absolute control in single cropping systems.

The LER value for biochar corn cobs+45N30P30K combination + cowpea (0.95) was less than (0.5) biochar poultry manure+45N30P30K combination +cowpea. When three different sources of biochar plus inorganic fertilizer were combined with cowpea under three rows of rice, one row of cowpea was to one row of rice, implying that the intercropping utilized resources more efficiently than 90N60P60K and absolute control. Workayehu (2014) found that under a maize-based intercropping system, the LERs for cowpea, soybean, and groundnut were less than half of one (LER<0.05). Rice is more competitive than cowpea in the intercrop context, as evidenced by the yield advantage of intercropping systems (total LERs). Studies showed that such competition led to decreased survival, growth, or

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reproduction of at least one species (Malézieux et al., 2009). Rice had LER values of 5.07 in both seasons, indicating yield advantages for rice intercrop over sole crop under 90N60P60K. In the rice-cowpea row arrangements, the biochar poultry manure+45N30P30K combination +cowpea 1.19 had the highest LER value. The overall LER achieved with biochar corn cobs+45N30P30K combination+cowpea 3:1 row arrangement was 0.95, indicating a yield disadvantage for intercropping systems compared to 90N60P60K and absolute control solo cropping.

Cowpeas had a lower LER value than 0.5 in the 3:1 row arrangement, according to the report. The biochar poultry manure+45N30P30K combination+cowpea total LER (LER for rice+LER for cowpea) was 1.55 in comparison to 90N60P60K and absolute control of sole cropping, the system of intercropping rice with cowpea was highly productive in terms of conservational resource use between row arrangements, indicating that the system of intercropping rice with cowpea was highly productive in terms of conservational resource use. The LER values obtained in this experiment can be compared to those obtained in rice-cowpea intercropping systems (Mbah and Ogidi, 2012). The higher LER values could be attributed to a higher combined intercropped yield as well as a time-based difference between the crops. Rice's short season and early maturity crop growth rate are expected to enable it to rebound from competitive consequences (Amanullah, Somasundaram, et al., 2007; Amanullah, Vanathi, et al., 2007).

6.9 Economic advantage index

Significant agronomic advantages from intercropping do not always ensure an economic advantage, and there is a need for some economic evolution and absolute yield comparisons of intercropping systems (Tana and Mulatu, 2000). Thus, a more satisfactory use of cost-

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benefit ratio values would probably be to calculate the absolute value of the unaffected yield advantage (Hayder et al., 2003). Consequently, the cost-benefit ratio was calculated by multiplying the respective yields of the component crops by their lowest market prices during the trial and dividing them by their respective LER. Intercropping advantage values show the disadvantage of the system as the economic values were negative. On the other hand, cost-benefit ratio values were positive, which presented a definite yield advantage in intercropping compared to sole cropping (Khan, 2009). It is an indicator of the economic viability of intercropping systems as compared to 90N60P60K and absolute control of sole cropping. The experimental data presented in Table 6 exhibited that economic advantage was significantly influenced by intercropping arrangements. The economic values in terms of net income were positive under five different sources of biochar in the 3:1 row arrangement in the experiment: biochar poultry manure+45N30P30Kcombination with cowpea intercrop (6699.5), biochar groundnut shells+45N30P30K combination with cowpea intercrop (5251.85) and biochar corncobs+45N30P30K combination with cowpea intercrop (4274.8) intercropping row arrangements (Table 6.6), which demonstrates a definite yield advantage compared with sole cropping systems and other intercrops tested in this experiment. Cost-benefit ratio values in biochar poultry manure+45N30P30K intercropping arrangements with cowpea (2.92) and biochar corncobs+45N30P30K intercropping arrangements with cowpea (2.68) was found to be highly positive when compared to 90N60P60K and absolute control due to very low LER caused a decrease in cowpea yield.

The outcome was in substantiation with (Dhima et al. (2007), who stated that vetch-barely intercropping in different seeding ratios gave a positive cost-benefit ratio as compared to

sole cropping. In the same way, cost-benefit ratio values in rice-barley combinations were found highly positive among the treatments due to the high LER-caused increase in rice yield (Ghosh, 2004). The maximum positive value in the biochar adsorbs more moisture and cowpea for the intercropping arrangements, implying that the compatibility arrangement showed an economic advantage. The combined maximum positive cost-benefit ratio values in both experimental intercropping arrangements showed that the 3:1 intercropping arrangement was high in terms of economic advantage and implies the suitability of intercropping arrangements. A probable explanation for the moisture content and increased soil organic carbon content was the better use of resources between the rice-cowpea intercropping arrangements. In the same way, (Ghosh, 2004) found that when the LER is high, there is also a significant economic benefit expressed with a higher cost benefit.

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Table 6.5. Effect of biochar and inorganic fertilizer influenced by row arrangements

Treatment	LER			Rice Grain N	Rice Grain P	Rice Grain K	RCC K			A		CR	
	LER Rice	LER Cowpea	Total	%	%	%	K Rice	K Cowpea	Total	A Rice	A Cowpea	CR Rice	CR Cowpea
ChGs+45N30P30K+C	1.06	0.26	1.32	21.36	-24.51	24.17	1.56	-0.99	-1.55	2.33	0.41	3.25	0.24
ChPM+45N30P30K+C	1.19	0.37	1.55	26.17	32.61	26.69	1.74	-1.41	-2.44	2.43	0.43	4.14	0.31
ChCc+45N30P30K+C	0.95	0.31	1.26	16.87	8.56	18.06	1.39	-1.19	-1.65	2.26	0.46	3.22	0.34

Ch-biochar, PM-poultry manure. Cc-corn cobs, cowpea Land equivalent ratio (LER), relative crowding coefficient (K) and Aggressivity index (A), Competitive Ratio (CR), Area Time equivalent (ATER) (A), Nitrogen (N), Phosphorus (P) and Potassium (K)

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Table 6.6. An economic evaluation of three different sources of biochar and inorganic fertilizer Intercropping combinations.

Treatment	LER		Cowpea grain t ha^{-1}	Rice grain t ha^{-1}	Total variable cost GH₵ t ha^{-1}	Total variable cost GH₵ t ha^{-1}	RYE Revenue (rice yield equivalent) GH₵ t ha^{-1}	RYE Revenue (rice yield equivalent) GH₵ t ha^{-1}	Net income GH₵ t ha^{-1}	Net income GH₵ t ha^{-1}	Benefit-cost ratio BCR	Benefit-cost ratio BCR
	LER Rice	LER Cowpea			Rice	Cowpea	Rice	Cowpea	Rice	Cowpea	Rice	Cowpea
ChGs+45N30P30K+C	1.06	0.26	181.75	286.40	2895	200	8146.85	355.45	5251.85	155.45	2.20	1.78
ChPM+45N30P30+C	1.19	0.37	256.08	403.05	2845	200	9544.5	299.85	6699.5	99.85	2.68	2.11
ChCc+45N30P30K+C	0.95	0.31	205.33	373.07	2945	200	11159.5	422.5	8214.5	222.5	2.92	1.94
Control	-	-	-	139.11	1475	-	1866.6	-	391.6	-	1.435	-
90N60P60K	-	-	-	301.87	2530	-	8534.4	-	6004	-	2.52	-

Ch-biochar, PM-poultry manure. Cc-corn cobs, Gs- groundnut shells, C-cowpea, N-nitrogen, P-phosphorus, K-potassium, LER-land equivalent ratio

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Table 6.7. Number of spikelets on a panicle of rice planted solely with cowpea and intercropped with it at different treatment levels and cropping densities

Treatment	No of Tillers (m^2) 2018	No of Tillers (m^2) 2019	No of spikelets per panicles (m^2) 2018	No of spikelet panicles (m^2) 2019	No Of grains per panicles (m^2) 2018	No grains per panicle (m^2) 2019	Weight of full grains (g) 2018	Weight of full grains (g) 2019	Weight Unfill grains (g) 2018	Weight of Unfill grains (g) 2019
ChCc+45N30P30K+C	57.50	72.00	28.50	37.75	508.75	534.75	11.57	12.41	3.29	4.13
ChGs+45N30P30K+C	46.69	81.88	31.50	39.50	561.50	553.25	12.76	13.60	2.61	3.45
ChCc+45N30P30K	39.94	54.63	25.25	37.00	441.75	472.00	8.00	8.77	2.46	3.30
ChGs+45N30P30K	42.94	59.00	21.00	33.00	418.00	476.25	9.72	10.56	2.73	3.57
ChPM+45N30P30K	47.94	58.88	22.75	34.75	430.50	449.00	8.00	8.84	2.59	3.44
ChPM+45N30P30K+C	66.69	101.75	33.25	43.500	586.00	686.75	16.03	16.87	2.88	3.72
Control	32.69	34.38	10.00	23.500	219.25	325.25	6.10	6.94	0.89	1.73

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90N60P60K	50.13	74.88	28.25	38.750	431.25	510.00	11.233	12.073	2.8375	3.68
Turkeys HSD	22.35	28.49	10.10	7.71	194.87	151.04	7.64	7.64	2.92	3.01
CV	19.33	17.32	16.19	9.35	17.77	12.44	28.84	26.75	2.01	39.30

Ch-biochar, PM-poultry manure. Cc-corn cobs, Gs-groundnut shells, C-cowpea, N-nitrogen, P-phosphorus, K-potassium

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6.10 Discussion

The reduction in yield components of rice-cowpea intercrops with high densities, despite high NPK rates, may be ascribed to excessive density ensuing in intra and inter-competition for sunlight, moisture, volatilization, and mineralization of nutrients. Low availability in vegetative and reproductive development showed that there was a possible increase in soil organic carbon concerning biochar accumulation, leading to soil N immobilization (Lehmann et al., 2011) and, consequently, reduced N uptake by the rice plants. However, the upsurge in grain yield of sole rice and cowpea with cumulative plant density was an effect of the rise in yield components per unit area. This was buttressed by (Inthapanya et al., 2001), who testified to improved yields by 13–31% when the stand density improved from 16 stands per m^{-2} of plants (25x25 cm) to 25 and 44 stands per m^{-2} of plants, respectively, as an effect of improved panicle density. The non-significance of N on most yields and yield components of rice and cowpea may be due to the high rainfall that occurred during the period of the experiment, which may be linked to nitrogen mineralization and resulting leaching losses. Poor growth of rice and cowpea in Guinea savanna was due to the leached acid soils (ferric Luvisol soils found in low rainfall areas; the top soil tends to be droughty while the subsoil had moderate to poor moisture holding capacity because of many concretions and gravel. Results attained for the intercropping ratios gave land equivalent ratios above unity, demonstrating an intercrop benefit and hence an apparent upsurge in resource usage efficiency by the crop combination (Table 6.5 and 6.6). The yield benefit of the rice-cowpea combination may be an inherent characteristic of the more effective use of sunlight in combination with tall rice and erect cowpea. The differences in growth cycles between rice and cowpea allowed for more efficient use of available water and nutrients (Table 6.5). Consequently, the crop combination enhanced the resource utilization through higher yield, which was ascribed to a

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density outcome, though lower LER was detected at high density. A similar investigation was conducted in a rice-cassava intercrop in Sierra Leone and was testified by (Dahniya et al., 1991), who distinguished the highest LER with low density (1.85 and 1.73) and high intercrop density, which gave lower LER (1.54 and 1.13).

Competition effects were observed on biochar corn cobs+45N30P30K densities were low, hence K values too were low. This might have triggered insufficient use of resources (Baumann et al., 2000). In terms of crowding coefficient values and aggressivity indices, cowpea seems to be the overriding crop, and rice is the dominating crop. The dominance of cowpea in the intercrop could be owing to their phenological traits and branching during the growth period (Abayomi et al., 2001). This is buttressed by (Sullivan, 2001), who stated that in a cereal–legume intercropping system, an aggressive creeping bean could destroy rice, maize, or sorghum intercrop, which could decrease yield. The effect could be serious for smaller cereals such as rice. Due to the dominant nature of the cowpea, which results in its ability to trap light, interception, and integrate soil fertility, Cowpea, with its trifoliate leaves, has the ability to seizure lighter than rice, with its thin leaves. This study was also supported by (Baumann et al., 2000). Under nutrient use efficiency on rice grain, the biochar+45N30P30K combination with cowpea intercrop had high nitrogen usage (Table 6.3). The high interspecific competition of biochar rice husk+45N30P30K of the rice-cowpea intercrop led to low NUE, while absolute control resulted in very low NUE. The biochar+45N30P30K combination with cowpea N and water interrelates sturdily to control crop yield and water availability, and the strictness of drought can affect NUE. Drought tolerance hybrid (NERICA 14) results showed larger NUE since they increased biomass production over a lengthy range of soil moisture availability and meteorological conditions

(Beringer et al., 2011; Harrigan et al., 2009). Plant P uptake was negative when the nutrient was dissolving. There is some proof that changing plant phenology influences nutrient attainment (Nord and Lynch, 2009).

Accelerated growth limits P uptake; plants that flower swiftly and have a short vegetative stage have small biomass production and P uptake. The disruption in growth that is characteristic of P deficiency is thought to be a changing condition for low P because it allowed for a longer period of P uptake (Postma and Lynch, 2012). High temperatures could speed growth and decrease the uptake of P, leading to a decrease in PUE. However, this prediction saw the result of the intensification of soil temperatures on P uptake. This study found that high nitrogen rates can compensate for interspecies competition. Intercrops provided increased benefits, as did complementarity among component crops and decreased intercrop competition (Oroka and Omoregie, 2007). Biochar+45N30P30K cowpea combination could improve time-based and spatial complementarity, as well as the compatibility of hybrids used as combination components. For instance, time-based changes in resource use by the crops may involve planting at any of the various alternating times of planting the crops. Other studies have revealed increased yield benefits as a result of the arrangement of various treatments to the component crops (Oroka and Omoregie, 2007). The interplanetary assigned to the component crops is correlated directly to the resources accessible for both crops. Nevertheless, (Hauggaard-Nielsen et al., 2001) observed that row arrangement trials within some particular range of plant densities yielded no decline. The biochar +45N30P30K combination with cowpea exhibited that there was a response in rice yield to intercrop density. It was vital that the biochar+45N30P30K combination with cowpea

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was vital that the population of the rice crop and the density of the cowpea ought not to be so high as to significantly reduce grain yield.

6.11 Grain yield, nutrient uptake, and efficiency utilization

The values for N and K were near maximum and that of P was near minimum on the biochar+45N30P30K combination with cowpea intercrop of both seasons, indicating that P was the least available of these four nutrients. Biochar releases nutrients that are absorbed by the crops cultivated. In Table 6.3 the results of nutrient use efficiency show a decrease in P total plants in and after harvest (85 days) and the effect has disappeared. Due to the improved P status, plant growth was stimulated, apparently to such an extent that the absorbed N was diluted. This explains the higher mass portions of N in plants on biochar+45N30P30K combination with cowpea intercrop than in plants on 90N60P60K combination with 85 days. In both seasons, the biochar+45N30P30K combination with cowpea intercrop increased K availability to the point where K mass fractions of straw remained higher on the biochar+45N30P30K combination with cowpea intercrop than on the absolute control.

In both seasons' biochar+45N30P30K combination with cowpea intercrop and 90N60K60P, some of the P was negative. This can be clarified by soil water tension stress through the panicle stage. At this stage, rice is extremely sensitive to water deficits (Ndjiondjop et al., 2012). If there was adequate moisture in the soil, the soil absorption of P would have been utilized more efficiently. Yields would have amounted to 301.87 t ha^{-1} for rice. On both the 90N60P60K and to over for rice, 403.05 t ha^{-1} and cowpea, 256.08 t ha^{-1} on the biochar+45N30P30K combination with cowpea intercrop for both seasons, if the P value for 90N60P60K in 2018 (16.65%) and 2019 is 22.10%), biochar+45N30P30K combination with cowpea intercrop for 2018 (39.81%) and 2018, in 2019, the absolute amount of nutrients

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absorbed by rice had decreased, except for sole cowpea. In 2019, moisture sources were sufficient for more efficient use of the absorbed nutrients, resulting in higher N, S, and K than in 2018. The biochar+45N30P30K combination with cowpea intercrop values of P for rice in 2018 and 2019 indicated that the absorbed nutrients were efficiently used, although yields were very high in both seasons. The biochar+45N30P30K combination with cowpea of K was probably not overrated. The Biochar+45N30P30K combination with cowpea intercrop considerably increased both seasons' yields of rice and cowpea.

Efficiency utilization for four nutrients for rice, but not for cowpea. This could be because cowpea was more sensitive to acidity than upland rice. Incorporating biochar into the soil resulted in a pH increase. Table 6.2 showed the relationship between pH 5.66 at the initial stage of the growing season and biochar+45N30P30K combination with cowpea of P, for cowpea in 2018 and cowpea in 2019. For rice, the absolute control of P was not influenced by pH, but it was for cowpea. For rice, the positive effect of the biochar+45N30P30K combination with cowpea intercrop consisted of a pH effect and a P effect, and for rice of a P effect only. In Table 6.4, the differences in uptake of nutrients from the Biochar+45N30P30K combination with cowpea intercrop and 90N60P60K studies were obtained in kg ha^{-1} as well as in percentages of the amounts of nutrients added. After harvest chemical analysis differences decreased in P from 2018 to 2019. In both seasons, the trends were regular. In both seasons, extra N was absorbed more than P. Biochar+45N30P30 K combination with cowpea intercrop stimulated the uptake of soil-N. The increase in pH due to biochar + 45N30P30K combination with cowpea intercrop improved the mineralization rate of organic matter. Another reason, more important, was the combination of biochar+45N30P30K with cowpea intercrop and cowpea intercrop that stimulated crop

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growth and increased the essential N. It is possible that with 90N60P60K, more N was available than perhaps used by the plant because of growth being limited by a P deficit. This was emulated in the high biochar+45N30P30K combination with cowpea of N and the low biochar+45N30P30K combination with cowpea of P in the plant.

6.12 Conclusion

From the standpoint of climate change, this study reveals the good impacts of biochar obtained from local resources as an organic soil additive. Biochar improved rice soil fertility by enhancing its chemical, physical, and biological qualities. Biological nitrogen fixation, and cowpea play an important role in plant nutrient recycling. The studies also suggested that biochar can be used as a lime substitute in Nyankpala acidic soils, increasing the yield of acid-sensitive crops. Rice growth was improved by improving soil properties using organic soil amendment applications, as evidenced by increasing plant height, number of tillers, number of spikelets, grain per panicle, and grain yield. In general, the experiment demonstrated that intercropping systems perform better than sole cropping. They specify better growth resources for rice under rice-cowpea intercropping systems, as evidenced by competitive functions. The intercropping systems exploited resources more competitively, as evidenced by the crowding coefficient, especially when three rows of rice to one row of cowpea were present. Rice, on the other hand, looked to be the dominating crop, as demonstrated by higher relative crowding coefficients, competitive ratios, and positive aggressivity indicators. Cowpeas utilized resources more aggressively in the 3:1-row arrangement, indicating their eligibility as prospective intercropping crops in a rice-based system. Carbon sequestration in soils and vegetation can extract carbon from the atmosphere, lowering carbon dioxide levels in the atmosphere. The use of biochar affects the C sink

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capacity of upland rice soils, as evidenced by increasing CEC and soil organic carbon in biochar studies. Higher macroaggregate formation was reported in rice-cowpea intercrop soil with biochar, which encourages the storage of significant amounts of CEC and soil organic carbon in the soil. Importantly, a positive link between CEC and soil organic carbon and aggregate stability was discovered. The study demonstrates that adding biochar to the soil and biomass increases carbon level, indicating that it can act as a carbon sink. Biochar application to soil could be a significant step in reducing the detrimental impact of upland rice cultivation on global warming. Biochar has the extra benefit of reducing CO_2 emissions when used instead of lime in Nyankpala soils. Biochar additions can significantly reduce total direct N_2O emissions and indirect CO_2 emissions in rice production by reducing N fertilizer consumption and increasing agronomic NPK-use efficiency and nutrient uptake. As a result, biochar can significantly reduce the total global warming potential of rice soil, making it a viable tool for combating global warming without jeopardizing productivity or food security. Because nutrient losses and contamination of the soil and water systems of the rice cultivation tract is a key managerial issue, the potential of biochar to hold applied fertilizer against leaching and also boost fertilizer use efficiency is very desirable for the soils of Nyankpala. Biochar addition into upland rice soils may help to minimize the toxicity and transport of common agro-based pollutants by increasing the overall sorption capacity of soils towards anthropogenic organic contaminants. Although organic composts and chemical fertilizers provided positive outcomes in some areas, they were unable to have a significant impact on rice soil from the viewpoints of climate change and yield optimization. The research highlights the importance of transitioning from high-input agriculture to a low-cost, long-term system. Biochar application along with conversion to organic agriculture techniques can

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help restore system resilience without compromising crop yield. Hence it is vital to favor sustainable agriculture approaches in upland rice cultivation areas like Nyankpala, towards reaching maximum yield without harming our climate system.

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CHAPTER SEVEN

7.0 EFFECT OF BIOCHAR USED IN A RICE-COWPEA INTERCROP SYSTEM ON SOIL HYDROLOGICAL PROPERTIES

Frimpong-Manso J[1] *, Abdul Ganiyu S[2] and Kugbe Xorse J[2]

1CSIR-Soil Research Institute, Academy Post Office, Kwadaso-Kumasi, Ghana
2University for Development Studies, Ghana
frimpong1977_1@yahoo.co

(Draft manuscript to be submitted)

Frimpong-Manso Judith (Candidate)

Conceived and designed the research, analyzed and validated the result, and drafted and revised the manuscript.

Ing. Prof. Abdul Ganiyu Shaibu (Supervisor)

Supervised the work and reviewed the manuscript

Dr. Joseph Xorse Kugbe (Co-Supervisor)

Supervised the work and reviewed the manuscript

Abstract

Biochar's physical properties, such as its small particle size, make it very porous, allowing it to change soil properties and improve soil water dynamics. However, no long-term measurements of changes in soil physical attributes due to biochar application under real field settings have been made. The study incorporated the model with soil water content measurements in two cropping seasons to assess the impact of biochar use in a rice-cowpea intercrop system on soil hydraulic properties. In four replications, the amount of water in the soil was monitored weekly at the same depths. The hydrologic parameters of the soil utilized for the experiment were expected to be affected by the biochar. Inverse modeling was used to determine the physical properties of biochar on the hydrologic properties of the soils using the Agricultural Production Systems Simulator (APSIM) model, a process-oriented crop model. The most sensitive input for the APSIM model for soil water simulation was determined through a sensitivity analysis. Using soil moisture measurements, a time series was utilized to inversely estimate the APSIM soil input properties. The drainage upper limit (DUL) was shown to be the most sensitive soil attribute, followed by saturated hydraulic conductivity (KS), saturated water content (SAT), maximum rate of plant water uptake (KL), lower limit moisture water content (LL15), and lower limit plant water uptake (LL). The difference in DUL between the biochar+45N30P30K and 90N60P60K distributions showed a 15% increase in DUL. It was discovered that biochar+45N30P30K improved soil hydraulic characteristics. The parameters for the soil's physical attributes in the APSIM model were approximated via inverse modeling. The most sensitive soil property was DUL, which was followed by KS. In the three distinct sources of biochar, there was a 15% rise in DUL, and a significant shift in KS as compared to inorganic fertilizer. In three different sources of biochar+45N30P30K plus cowpea intercrop, three different sources of biochar+45N30P30K, respectively, compared to 90N60P60K and absolute control, a significant change was observed in LL15 and KS, whereas SAT and LL showed a slight increase and decrease in three different sources of biochar+45N30P30K+cowpea intercrop and three different sources of biochar+45N30P30K. It is recommended that farmers in the Guinea Savannah zone adopt an integrated soil management approach to improve soil physical properties in a continuous rice-cowpea intercrop under rain-fed conditions.

Keywords: Sensitivity, Biochar, Time series, Soil moisture content

7.1 Introduction

Biochar has recently gotten a lot of attention due to its potential for carbon sequestration and agronomic benefits. It has a large surface area, which is one of its numerous advantages (Mohammadi, 2021) particle size is small (Basso et al., 2013; Mohammadi, 2021; Sakhiya et al., 2020), bulk density is low (Kamali et al., 2022; Pathy et al., 2020) contains a significant proportion of organic carbon (Guo et al., 2020; Rashid et al., 2020). It can reduce soil bulk density, boost porosity, and aid coarse-texture soils by increasing their water-holding capacity (Igalavithana et al., 2017; Liu et al., 2016; Verheijen et al., 2019). Despite the increased interest, no consensus on the impact of biochar on soil hydraulic properties has yet been reached (Liu et al., 2016). Numerous laboratory and field experiments have revealed short-term changes in the physical and hydrological properties of treated soils using biochar (Ibrahimi and Alghamdi, 2022; Xiao et al., 2016). Laboratory-scale observations of soil physical properties, on the other hand, are mostly based on the static steady-flow assumption (Dokoohaki et al., 2018a) this may result in significant inaccuracies (Dokoohaki et al., 2018b). Furthermore, Are et al. (2017); Ibrahim and Horton (2021) varied lab approaches may yield different estimations for soil physical properties, according to the findings. Dissimilar measurements of soil physical properties have been recorded due to sensitivity to flow geometry, sample size, and sample collection process, to name a few factors. (Are et al., 2017; Dokoohaki et al., 2018b; Khodaverdiloo et al., 2017). The dynamic interactions of soil properties with crop and management approaches are missing from these investigations, despite the ease of implementation and measurements. Increased porosity and water-holding capacity of altered soils with biochar, for example, may encourage root penetration and aeration, as well as increased water and nutrient uptake. However, a dynamic approach capable of directly and indirectly capturing the interaction between soil, biochar, and crop is

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required to comprehensively study increases in crop water and nutrient uptake. The use of inverse modeling is one method for indirectly assessing field-relevant soil physical properties of biochar-amended soils. Inverse modeling looks through a model's input parameter space for the most plausible set of inputs that results in the best fit between the model and the data.

Observations and projections from the model Inverse methods have been used in several research to estimate soil physical parameters, model verification, and uncertainty analysis (Lievens et al., 2015; Wesseling et al., 2020) and Wu and Zeng, 2013). As an example, Cichota et al. (2018); Vogeler et al. (2019 and Wöhling and Vrugt (2008), Inverse modeling of process-oriented crop models, such as APSIM, has been recommended as a viable technique for determining “effective” hydraulic properties of soils. When compared to lab measurements, this technique compensates for greater dynamic interactions of soil properties when estimating hydrological parameters. The APSIM model was employed in this study for two years, as well as a unique dataset of continuous soil water content measurements in two cropping systems (three different sources of biochar plus inorganic fertilizer treatment). To inversely estimate hydraulic parameters in the APSIM model, we presented an optimization approach. As input data, two years of soil moisture measurements were used to optimize the system. We believed that using a process-oriented crop model to analyze this dataset will allow us to generate realistic estimations of biochar's effect on soil hydrological parameters. The main objective of this research is to determine the effect of biochar on the hydrological properties of the soils using the Agricultural Production Systems Simulator (APSIM) model. The use of the APSIM model is to generate subsequent distributions for soil physical properties for three different biochar and inorganic fertilizer treatments. The three different

sources of biochar and inorganic fertilizer are expected to demonstrate the effect of biochar on soil physical properties in the field.

7.2 Materials and methods

7.2.1 Field Plot Establishment

The experiment was conducted at the University for Development Studies (UDS), Nyankpala, Tamale in Ghana's Northern Region. It is on a ferric Luvisols and Plinthic Lixisols) sandy soil FAO-UNESCO (1988), (Latitude 09.246070N and longitude 000.589920W). The soils are slightly acidic with a pH of 5.4, and CEC is between 1 and 15 cmol (+)/kg. The altitude is 252 meters above sea level. It has a unimodal rainfall pattern with an annual rainfall of 800-1100mm (Jasaw et al., 2014; Kah, 2021). The rainy season begins in late April with minimal rainfall and rises to a peak in July-August before an abrupt decline and ending in October-November. The dry season starts from November to March with day temperatures ranging from 33°C-39°C, whereas mean night temperatures range from 20°C to 26°C (Kah, 2021).

7.2.2 Experimental design and treatments

The experiment was a Split Plot in factorial design arranged in randomized complete blocks (RCBD) with 4 replications. The test crop was the upland rice NERICA 14. Treatments comprised of 90N60P60K, poultry manure biochar +45N30P30K, groundnut shells biochar +45N30P30K, corn cobs biochar +45N30P30K, absolute control, biochar corn cobs, biochar poultry manure, and biochar groundnut shell. Slow and high pyrolysis of groundnut shells, corn cobs, and poultry manure at 400°C - 700°C with a dwell time of 24 hours in oxygen-

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limited conditions in a reactor, followed by water and air cooling of charred feedstock to room temperature and grinding the biochar was used to produce three distinct feedstocks. Dry weights and chemical characteristics of the biochar applied are shown in Table 7.1. Methods for three distinct sources of biochar, chemical analysis, and analytical results are shown in Table 7.1 (Frimpong-Manso 2021). 5 t kg^{-1} biochar was incorporated on a 12 m^2 plot. From June 2018 to 2019 October, a bowl of upland rice (Nerica 14) (*Oryza sativa*) was grown on the same plots for each replication. Row spacing was 1 m and between replication was 2 m where upland rice was planted. At transplanting, two seedlings per hill and 200 kg of NPK were banded using cutlasses. At panicle initiation urea of 30 kg was side-dressed at the surface after crop establishment. The insecticide Emaster (Acetamiprid and Emamectin benzoate) was sprayed on the crop against ants and spittlebugs whenever appropriate. Yield, plant uptake, soil moisture, soil temperature, and five soil layers were measured in the 2018 and 2019 cropping seasons (Frimpong-Manso, 2021).

Soil water status was monitored by tensiometers and hydro-senses moisture meters (Gardner et al. (1951); Willard Gardner and Lorenzo A, Richards 1919). Random installation of tension meters was installed at a depth of 20 cm and were measured every 5 days. Hydro-sense moisture meter was fixed 20 cm below the soil surface, and data was recorded at weekly intervals. Soil sampling at 30 cm depth for both chemical and physical analysis (bulk density and porosity were determined weekly till harvesting. The Root Mean Square Error (RMSE) was employed as the statistic merit, and soil water content was simulated using acceptable samples and compared to the matching observed soil moisture.

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$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{N}} \quad 3.18$$

where Oi denotes the observed soil moisture and Si denotes the simulated soil moisture

7.2.2 Weather Data

In simulations, the model used daily rainfall, daily solar radiation, minimum and maximum daily temperatures, and evaporation. Chapter 3 shows a summary of weather conditions for the growing season.

7.3 Soil and water dynamics

The APSIM model has been created in a modular approach, allowing users to execute their simulations utilizing multiple soils, crops, climate, and management components (Holzworth et al., 2006; Holzworth et al., 2014). It can simulate soil water content, soil temperature, and nutrient cycling as well as their interaction with different crops and management practices (fertilization) on a daily time step (Archontoulis et al., 2014; Böldt et al., 2021; Gaydon et al., 2017). Specifically, the Guinea Savannah zone, it has been used as a way to examine the indirect effect of new management practices on different soil and crop properties (Archontoulis et al., 2014; Basche et al., 2016). The SOILWAT module in APSIM (Archontoulis et al., 2014; Chimonyo et al., 2016; Gaydon, 2014; Smith et al., 2019) estimates daily variations in soil water content for distinct soil layers as a result of rainfall penetration, vertical drainage, unsaturated and saturated flow, soil evaporation, and root water absorption mechanisms. Soil samples were taken from profile pits from the experimental sites at different horizons and analyzed for organic carbon, pH, bulk density, and particle size distribution

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Table 7.4ab and 7.5. The model uses a tipping bucket approach for computing soil water drainage (Shelia et al., 2018; Soldevilla-Martinez et al., 2014). Evapotranspiration was simulated using the Priestley-Taylor-Ritchie method (Araghi et al., 2022; Ran et al., 2020; Vashisht et al., 2013). Excess water exceeding a layer's field capacity is directed to the layer below in this manner. Upward unsaturated flow is also calculated using a conservative estimate of the soil water diffusivity and volumetric soil water content variations between neighboring strata. The following are some of the parameters that were utilized to run the model in Table 7.1.

7.4 Sensitivity analysis and optimization

To inversely estimate soil hydrological parameters, the following framework was designed and used: (Table 7.1) in the APSIM model.

1. DUL, LL15, and SAT were subjected to sensitivity testing. For this work, the soil water content is the major output variable of importance. Sensitivity analysis was used as a screening procedure to rule out non-influential variables and pinpoint those to be optimized.
2. To ensure that samples created by hydrological parameters are genuine the soil water content parameters must be between the 0 - 1 range and have meaningful relationships (LL15 should be smaller than DUL and DUL should be smaller than SAT).
3. The uncertainty range of soil water contents during the simulation period was visualized using soil water content simulated from acceptable samples.

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7.5 Sensitivity analysis

The current study used the analysis of variance approach. We decomposed the variability of the result (soil water content) and calculated the contribution of each input component using this method (Guse et al., 2014; Wallach et al., 2018). This approach calculated the main effect as well as linear interactions for each parameter. Sums of squares (SSQ) were used to calculate the main effects and total sensitivity indices, as shown below (Wallach et al., 2018):

- Main effect sensitivity indices: $S_1 = \frac{SS1}{SST}$; $S2_{=} \frac{SS2}{SST}$ 3.19
- Interaction sensitivity indices: $S_{12} = \frac{SS12}{SST}$
- Total sensitivity indices: $TS1 = \frac{SS1+SS12}{SST}$; $TS_2 = \frac{SS2+SS12}{SST}$ 3.20

Where SS1 is the SSQ for the first parameter, SS_{12} is the SSQ of the interaction between the first and second parameters, and SS_T is the total SSQ.

Soil hydrological inputs were measured using a set of 14 parameters. The APSIM model was run 12,000 times using random samples from a recommended distribution for each parameter, and the mean soil water content was recorded after each simulation. The contribution of each factor with its first interactions was then analyzed using an analysis of variance. Even though 153 SWC measurements were taken, autocorrelation (time correlation between measurements) reduces the total number of independent measurements to roughly 14. We opted to employ no more than 10 parameters (half the data) because of the large number of independent measurements, and we discovered that 8 was the most optimal number of parameters through trial and error. As a result, optimization was limited to the top eight most critical parameters. The sensitivity analysis-derived parameter rankings are solely valid for this study; no inferences should be drawn from them for other soils, crops, or weather

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conditions. However, any simulation involving soil water content, for example, is likely to discover DUL to be a particularly sensitive parameter.

7.6 Optimization

The Bayesian approach not only allowed us to leverage previous knowledge and data from many sources to estimate parameters, but it also allowed us to quantify the model output uncertainty (Wallach et al., 2018). The marginal posterior distribution of selected parameters, as well as the uncertainty of the simulated soil moisture due to parameter uncertainty, were both evaluated utilizing the optimization procedure in this work. Model input uncertainty can be caused by a variety of factors, including temporal and spatial variability like the process, measurement inaccuracy, and model flaws. The posterior densities must be carefully understood because marginal densities do not indicate parameter correlations and make the uncertainty appear higher when compared to joint distributions. All parameters in this study had low to moderate uncertainty (approximately 5–40%) around their medians, indicating that they all contributed to the model fit.

7.7 Results and discussion

In 2018 the average yield for all plots was RMSE 478.62 kg ha^{-1} while the 2019 value was 605.33 kg ha^{-1}. Measured daily means of soil moisture for the three different sources of biochar treatment was 23.95 to 27.85 and 119.69 to 122.4 cm^3 cm^{-3} in 2018 and 2019 respectively which is greater compared to the 90N60P60K treatment with a mean of 22.7 to 19.6 and 108.3 to 112.3 cm^3 cm^{-3} for the same years. Interestingly, in both years, the three different sources of biochar+45N30P30K treatment hit a lower (minimum and maximum)

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soil water content of (23.95 and 27.85 cm^3 cm^{-3}) compared to 90N60P60K treatment with the lower (maximum and minimum) soil water content of (22.7 and 19.6 cm^3 cm^{-3}) signifying the crop is absorbing more water in the earlier. It also showed that SWC variability in these two metrics was the most sensitive. However, with the two cropping season experiments DUL1, SAT1, KL2, and LL15-2 were demonstrated to be highly sensitive. The most sensitive parameters above explained the different patterns of the soil water cycle. These capacities (DUL, LL15, and SAT. LL15-2, LL, and KL2) of SWC simulation in APSIM directly control crop water uptake (transpiration) and indirectly affect soil evaporation of which KS is the principal driver of saturated water flow and soil seepage. The residual interactions were greater than second other interactions among all the parameters and accounted for less than 10% of the overall variance (Figure 7.1).

7.8 Optimization

In both treatments, there was some degree of connection between KS1 and SAT1 resulting in greater variability than other measures. The DUL2 and DUL1 medians for the three different sources of biochar+45N30P30K treatment were 15.3 and 16.2 m^3 m^{-3}, respectively, whereas the 90N60P60K and control values were 12.3 and 13.3 (Table 7.1). This suggests that three different sources of biochar treatment resulted in a 15% increase in water-holding capacity in the current investigation, assuming no change in the lower limit (PWP) for water intake. This study's predicted improvement in water retaining capacity is less than the 30 to 35 percent indicated by (Abel et al., 2013) and the 20 to 50% increase stated by (Haider et al., 2017; Karer et al., 2013; Liu et al., 2012; Sánchez-Monedero et al., 2019). The combination of two distinct soil types with three different biochar sources increased water retention capacity by

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5–38 percent for both years. The increase in water retention could be attributed to changes in the total number of pores, the pore size distribution (PSD), or soil surface area (Dokoohaki et al., 2017). SAT1 was a little higher in the three different sources of biochar treatment (0.42 m^3 m^3) than in the 90N60P60K treatment (0.39 m^3 m^3). The lower SAT in the 90N60P60K treatment could be attributed to settlement after a long series of intensive wetting and drying cycles (Dokoohaki et al., 2017; Yao et al., 2011). The three different sources of biochar treatment reduced the number of macro pores and increased aggregate stability due to higher organic carbon content, resulting in less soil settling and compaction as well as less total porosity loss and hence higher SAT. We can assume that the three different sources of biochar application resulted in a minor increase in porosity, which could lead to considerable gains in root growth and water uptake because the saturated water content is highly related to soil porosity and given the higher SAT of the three different sources of biochar treatment.

The greatest rate of water uptake by plants (KL) occurs when there is a maximum demand from the atmosphere (high Vapor Pressure Deficit), but it is also restricted by the soil's capacity to meet this demand in Figure 7.1. As a result, both KL and LL use plant and soil parameters in the APSIM model to determine water uptake capacity. In comparison to the controls, the KL and LL values of the treatments in the three different sources of biochar signified better capacity for water uptake. Higher KL and lower LL for the three different sources of biochar treatments were consistent with an improvement in soil water-holding capacity and predictions of increased total porosity and root growth. The APSIM model was able to predict yield for both years within a reasonable range of observed values (315.18 kg ha^{-1} in 2018 and 460.04 kg ha^{-1} in 2019) due to total porosity and root growth. APSIM's technique resulted in tightly related yield, biomass, and transpiration simulated values, as we

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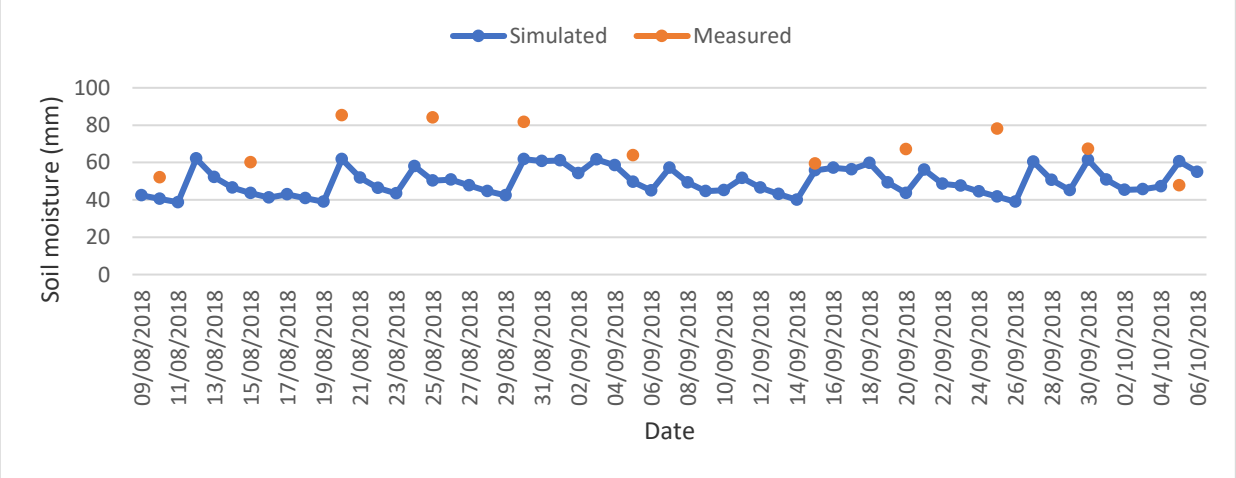
expected transpiration/water uptake by the crop to be estimated (rather than observed) in a tolerable range. The soil moisture uncertainty band estimated using the subsequent distribution of KL and LL for biochar+45N30P30K and 90N60P60K treatments fall within the observed error ranges. This demonstrates that the samples derived from subsequent distributions yielded plausible soil moisture readings. For the 90N60P60K and the different sources of biochar treatments, the RMSE between simulated and observed soil moisture was 21.751 cm^3 and 19.021 cm^3 respectively. An RMSE of 21.751 cm^3 cm^{-3} and 19.021 cm^{-3} was found in simulations of soil moisture in bare soil. Overall, the parameter estimation results for both years demonstrated trends that were consistent with the predicted impacts of the three different sources of biochar application on soil physical attributes chapter 3. In the altered soil layer, the three different sources of biochar had higher DUL and SAT than the 90N60P60K treatments. Furthermore, the greater KL and lower LL values for the three different sources of biochar treatment compared to the control reflected the higher water uptake capacity found in soil moisture measurements (Table 7.1 and figure 7.1).



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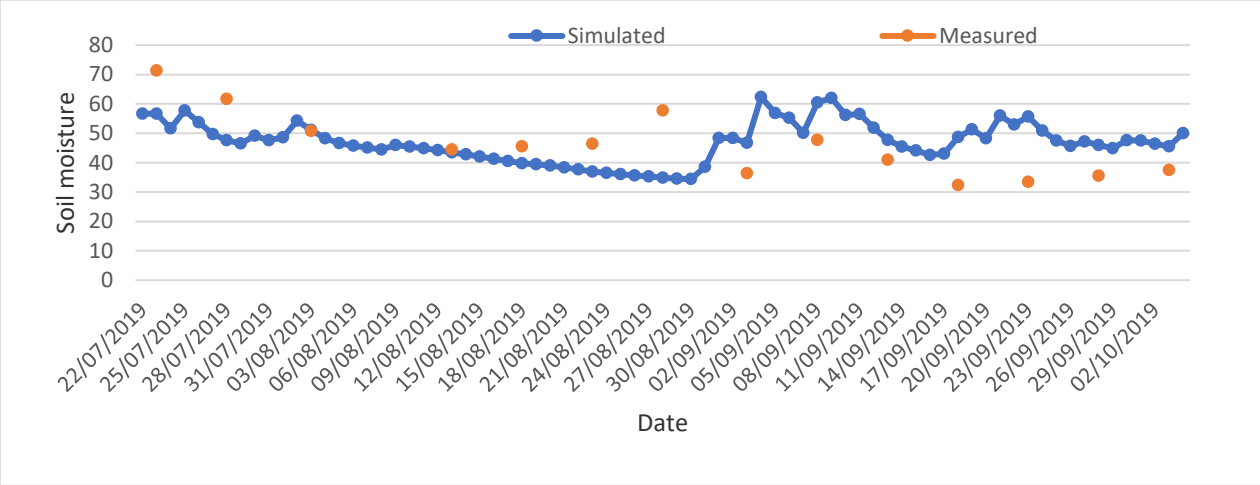
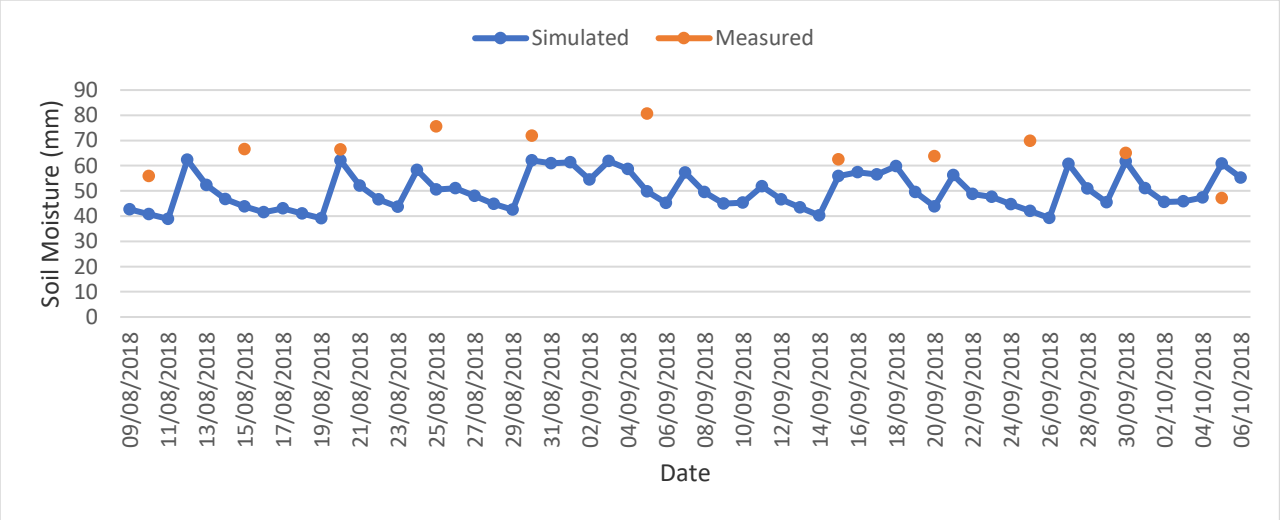
A1. Biochar poultry manure 2018



A2. Biochar poultry manure 2019



B1. Biochar corn cobs for 2018

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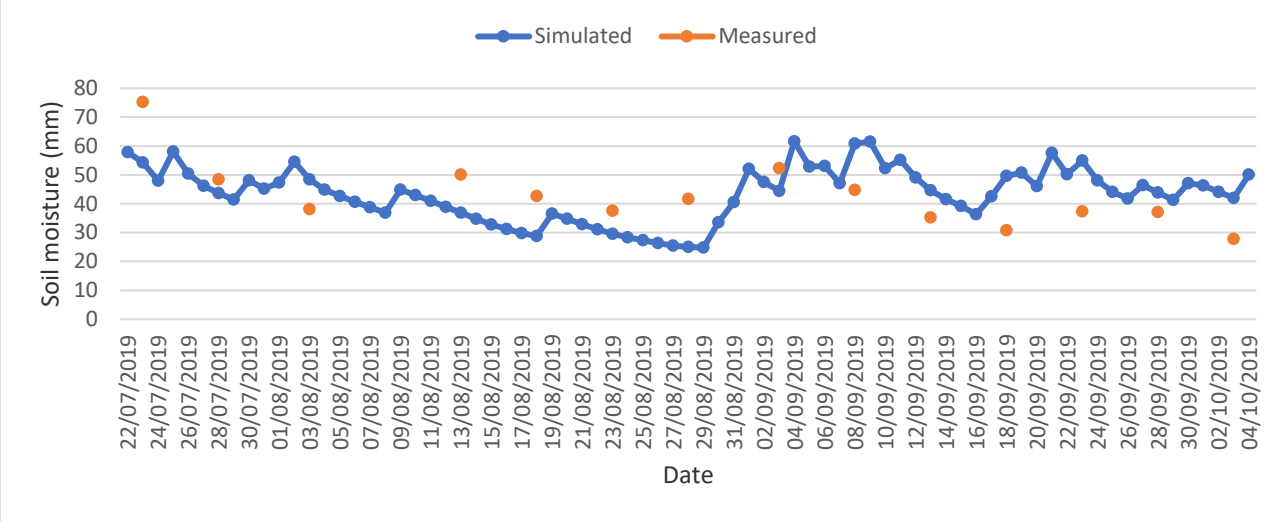
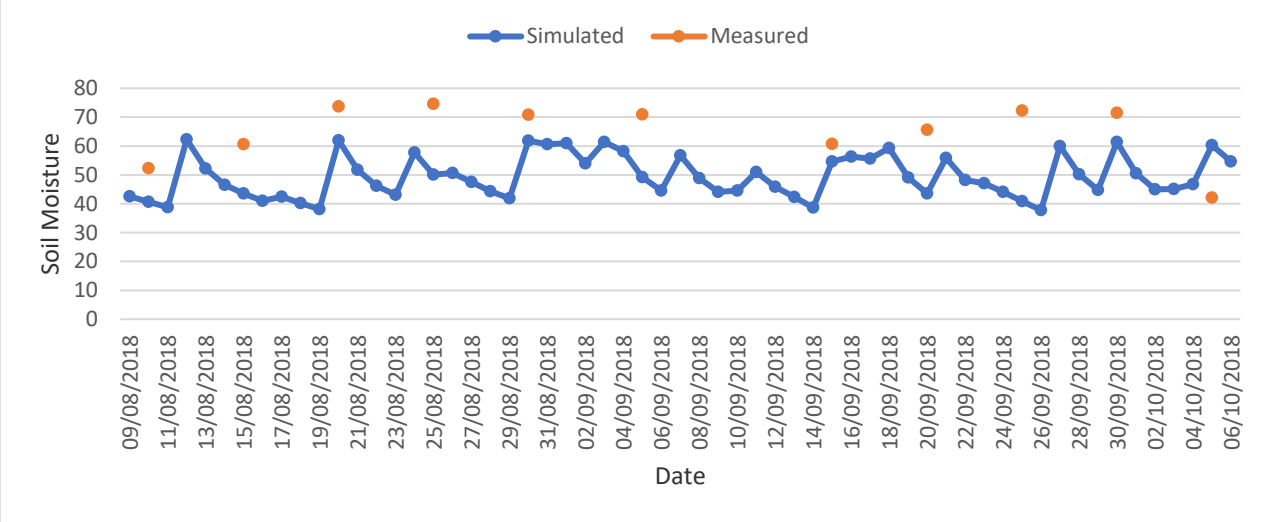


B2. Biochar corn cobs for 2019



C1. Biochar groundnut shells for 2018

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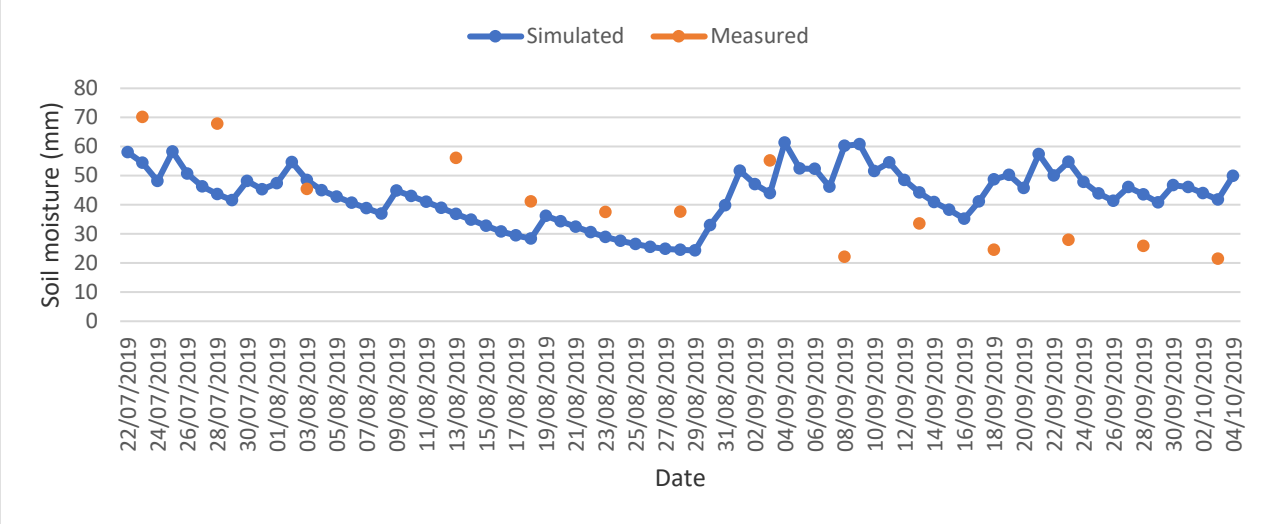
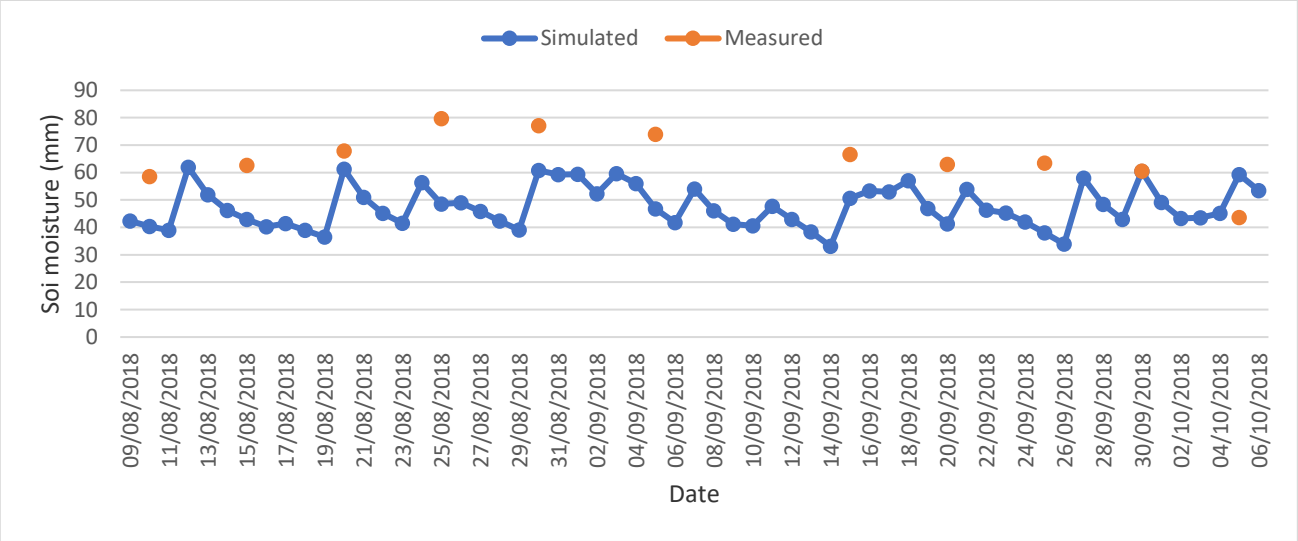


C2. Biochar groundnut shells for 2019



D1. Biochar poultry manure+45N30P30K+Cowpea for 2018

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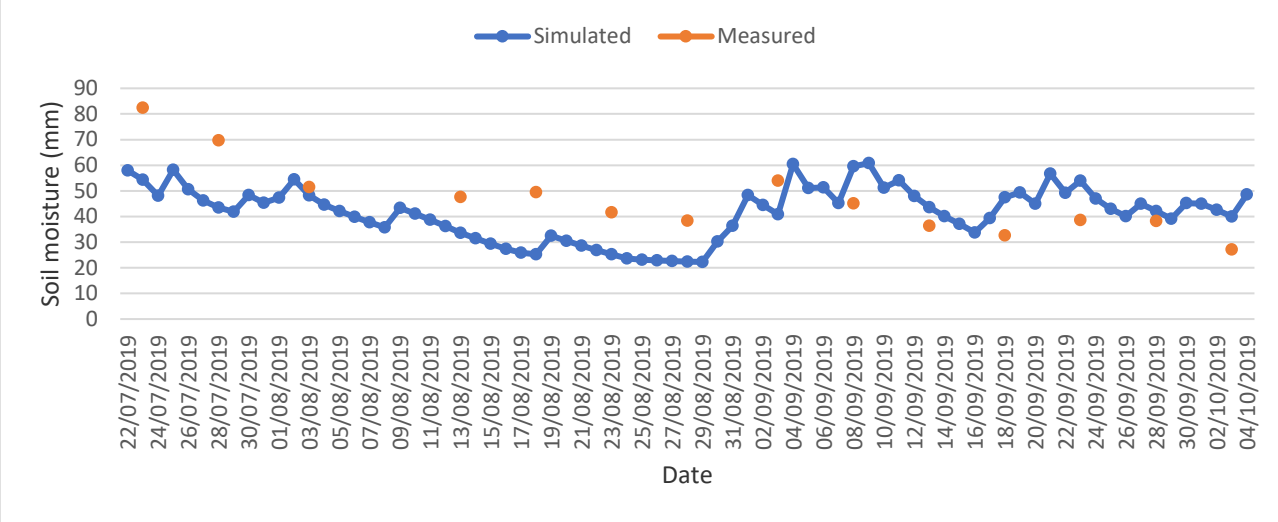
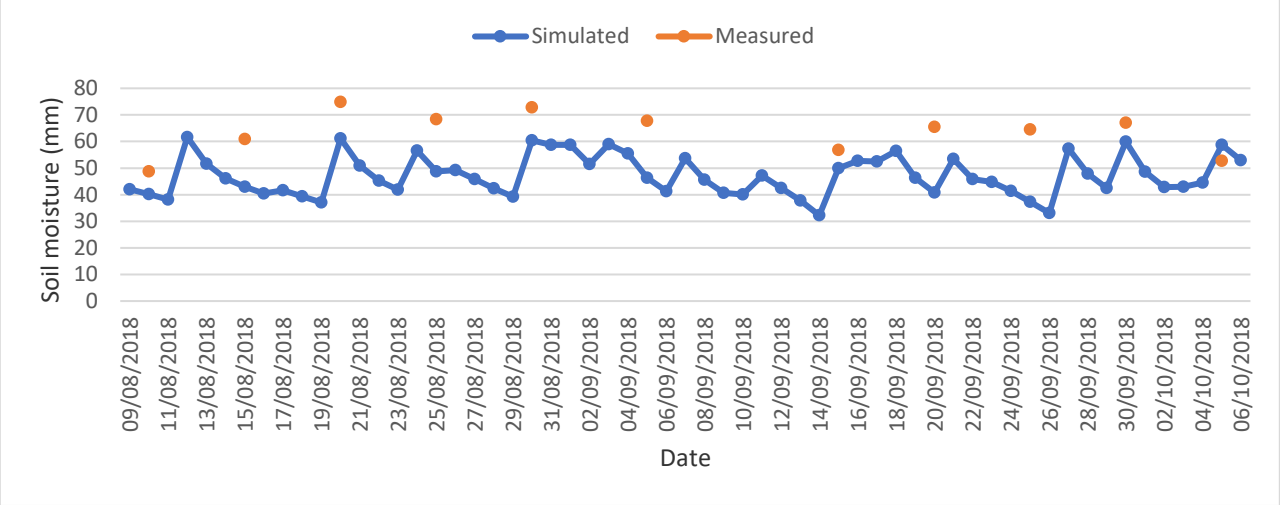


D2. Biochar poultry manure+45N30P30K+Cowpea for 2019



E1. 90N60P60K for 2018

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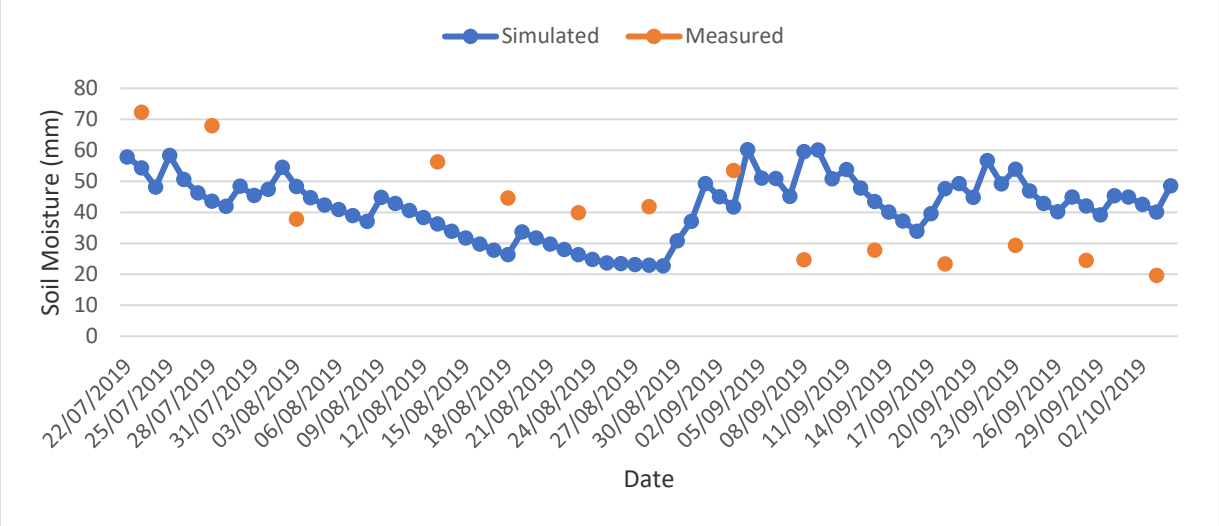
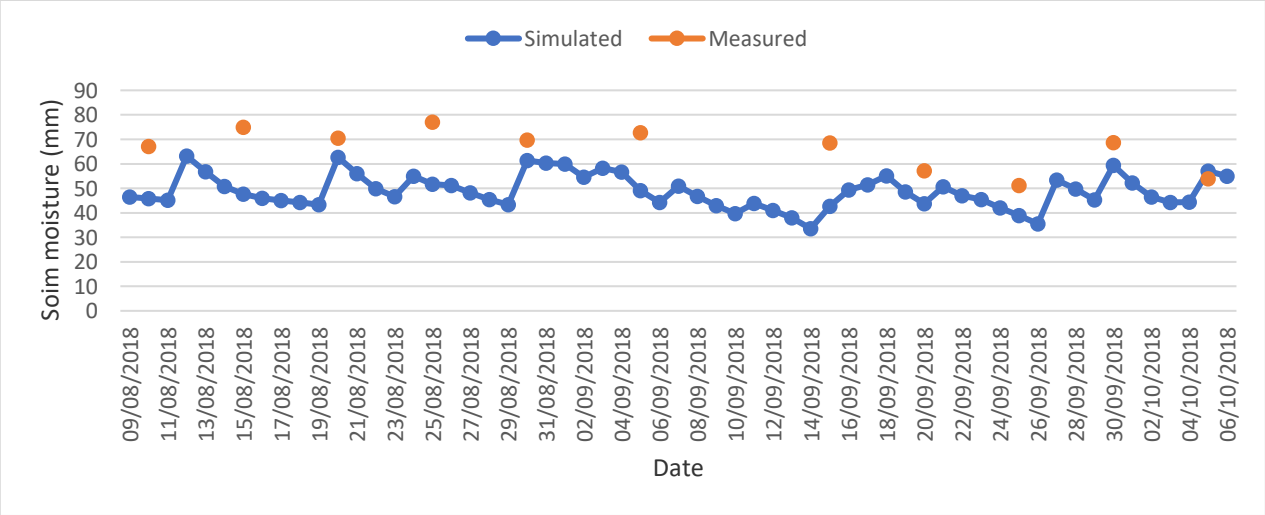


E2. 90N60P60K for 2019



F1. Biochar groundnut shells+45N30P30K+Cowpea for 2018

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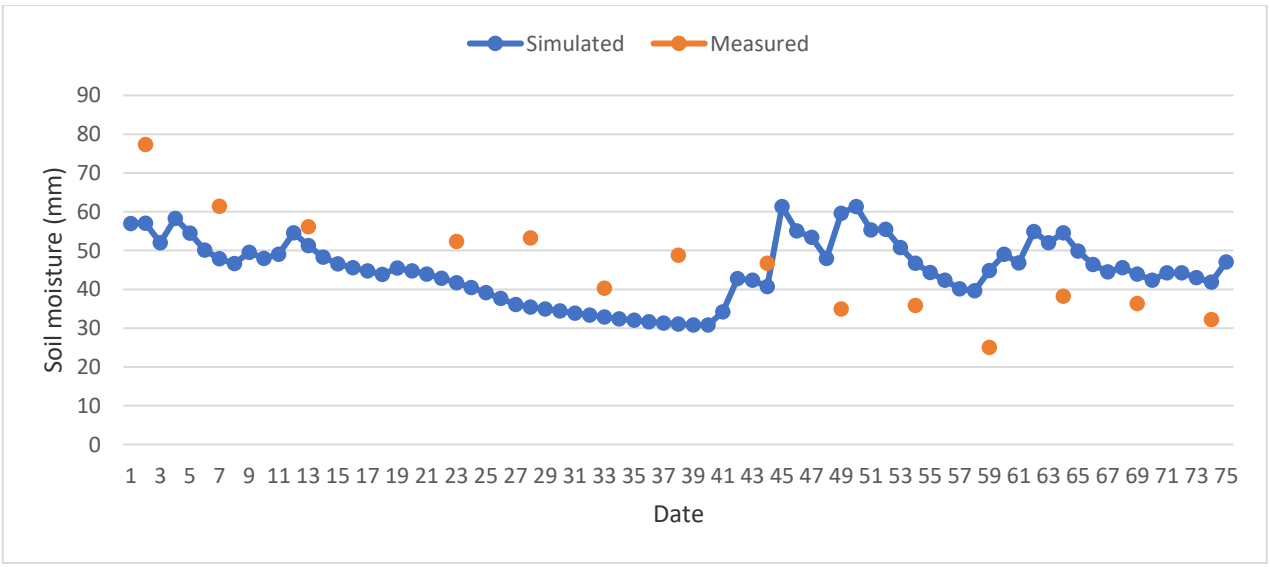
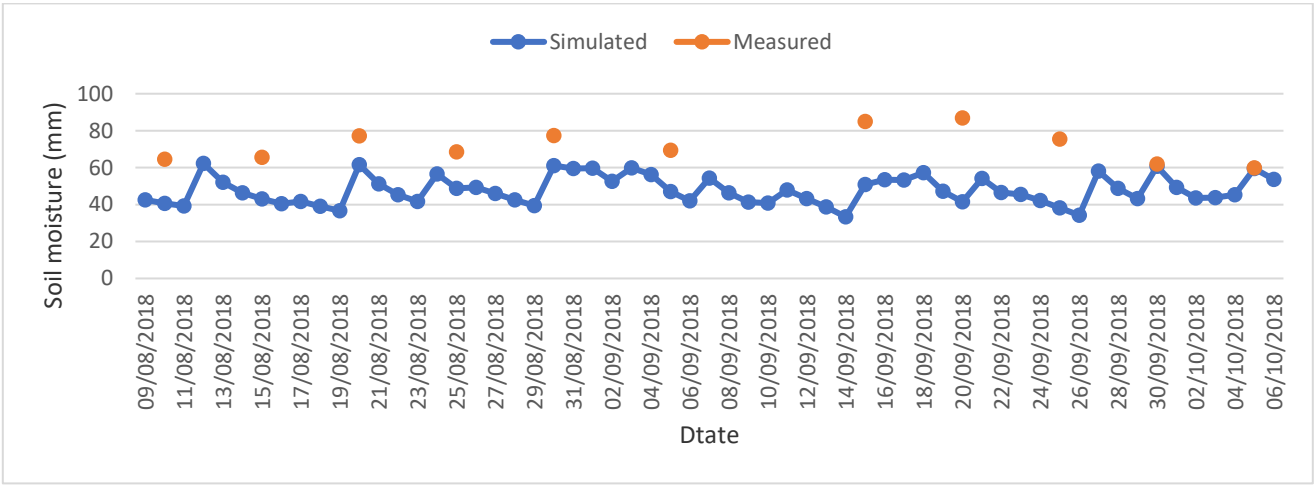


F2. Biochar groundnut shells+45N30P30K+Cowpea for 2019



G1. Biochar corn cobs+45N30P30K+Cowpe for 2018

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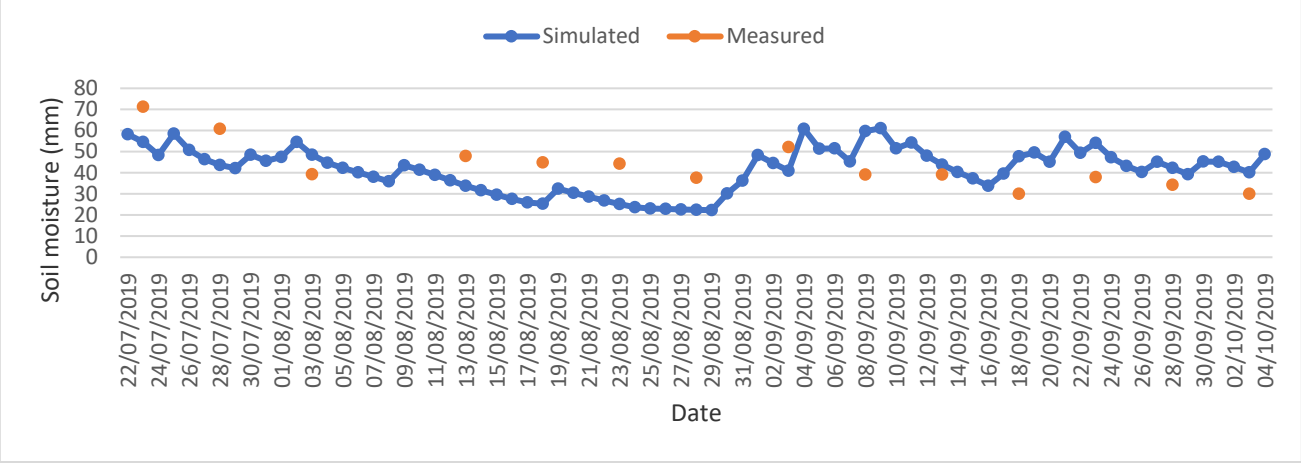

G2. Biochar corncobs+45N30P30K +Cowpea for 2019

Figure 7.1. A-G. Impact of the three different sources of biochar and inorganic fertilizer applied under measured and simulated soil water content curved for all treatment and sampling time.

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Table 7.1. Comparison of physical properties used to model upland rice-cowpea intercrop yield in three different sources of biochar and inorganic fertilizer.

	2018					2019				
Treatments	**DUL mm^{-1}**	**LL mm^{-1}**	**KL day^{-1}**	**SAT $cm^3\ cm^{-3}$**	**KS $cmday^{-1}$**	**DUL mm^{-1}**	**LL mm^{-1}**	**KL day^{-1}**	**SAT $cm^3\ cm^{-3}$**	**KS $cmday^{-1}$**
Initial soil test	15.8	5.8	100	41.7	48.25	16.2	5.9	100	41.76	48.32
Control	12.3	6.4	74	42.2	43.1	13.3	5.4	78.1	51.2	53.3
N90P60K60	12.3	5.5	68	41.9	64.7	14.8	6.5	84.2	52.9	74.6
ChGs+N45P30K30+C	13.4	6.1	73	41.5	55.67	14.5	7.3	82.1	51.7	55.65
ChPM+N45P30K30+C	13	5.0	80	42.1	64.68	14.1	7.4	90.2	52.3	74.67
ChCc+N45P30K30+C	15.3	7.3	80	41.2	57.17	16.2	8.2	90.1	51.3	67.18
ChPM+N45P30K30	13.8	5.5	78	41.6	58.53	14.2	6.7	88.1	51.7	68.52
ChGs+N45P30K30	13.8	4.9	79	41.8	64.04	13.6	5.7	89.2	51.7	74.05
ChCc+N45P30K30	12.9	5.8	70	42.4	64.67	13.7	6.6	80.3	52.5	74.68

Ch-biochar, Gs-groundnut shells, Cc-corn cobs, PM-poultry manure, C-cowpea, Nitrogen (N), Phosphorus (P), Potassium (K), Cowpea (C), LS-loamy soil, SL-sandy loam, Saturation Hydraulic Conductivity (KS) SAT: volumetric water content at saturation, LL: wilting point, DUL: field capacity, Maximum rate a plant can extract water from, KL: A Layer thickness (mm).

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7.9 Conclusion

Three different sources of biochar+45N30P30K treatments improved soil physical properties in upland rice during two cropping seasons in a field experiment. It also increased DUL and KL, as well as a minor increase in SAT. Higher water intake with lower LL for the three different sources of biochar treatment was achieved by increasing the soil's water-holding capacity. The integration of field-level observations with a modeling component to estimate more accurate soil parameters as a result of the three sources of biochar+45N30P30K application was a crucial unique component in this study. It was discovered that biochar+45N30P30K improved soil hydraulic characteristics.

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CHAPTER EIGHT

8.0 GENERAL DISCUSSIONS, CONCLUSION, AND RECOMMENDATION

8.1 General discussions

8.1.1 Modeling Approach

APSIM model established P modules for soils with primarily N-limiting conditions, where P dynamics have little impact on crop development (Delve et al., 2009; Gaydon et al., 2017). APSIM is appropriate for this study area since it was built using data primarily from the semi-arid tropics, where resource-poor smallholder farmers encounter P-limiting conditions in soils. This model thus works well in modeling crop development and grain yield in Northern Ghana, where soil P is poor and soil organic matter (organic P) is essential for plant P feeding (Adjei-Nsiah et al., 2021). The C:P ratio utilized to initiate the soil P module changes over time, depending on the P concentrations of successive surface residue additions. This ratio is essential because it determines whether organic P is mineralized or immobilized in these heavily worn tropical soils, especially in multi-year simulations (Probert, 2004). In addition, using the APSIM model to simulate yield under P limiting conditions, accurate calculation of labile P and P sorption capacities is critical.

8.1.2 Intercropping challenges

Intercropping is seen as a long-term cropping strategy that provides high productivity while also conserving resources. However, the literature to date has primarily reported on case studies that have been restricted to a few seasons or locations. However, it has been demonstrated that the success of intercropping is dependent on the site-specific exploitation of crop variety by environment by management interaction. Intercropping is limited by

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several variables. Farmers may be hesitant to forgo cereal production for 'companion crops,' such as legumes because they are primarily interested in the cereal components of intercrop systems, which are often planted as monocultures. It is necessary to address the difficulties in planting and harvesting mixed crops, as well as knowledge gaps in terms of management demands such as fertilizer or insecticides and pesticide input. Furthermore, intercropping will only be implemented when niches can be identified in which its benefits can be demonstrated without being too time-consuming. There is a need for a rigorous quantitative investigation that pinpoints and defines niches using three distinct sources of biochar and inorganic fertilizer with intercrop. This study investigates two seasonal field experiments in the same agroecological zone. The data gathered during these experiments were utilized to test the APSIM process-based model.

Intercropping systems are difficult to study because of their complexities. The rice-cowpea intercrop systems tested in this study had two canopy layers, the higher of which absorbed more direct solar radiation. While light interception was an important element of the intercrop systems evaluated, measuring it at different layers/heights was not a primary emphasis of the data collection, indicating a knowledge gap that needs to be addressed. The concept of complementary resource usage, in which different crops require resources, such as nutrients and water, at different times, is an important aspect of intercropping. This is known as the mixing effect' (Dowling et al., 2021; Dwivedi et al., 2015). In complementary and competitive facilitative interaction with species are analyzed to focus on nutrients and water, (Dowling et al., 2021) discovered that nitrogen application was only beneficial after the soya beans had bloomed and that nitrogen application before that hampered the pea's N_2 fixation. Indeed, a detailed understanding of such management issues is required for

successful intercropping systems. The benefits of N_2 fixation through monoculture legume integration, even for low-input smallholder farmers, are not straightforward and require institutional support (van Vugt et al., 2018). While using cereal-grains intercropping to solve nutrient management issues (Sethuraman et al., 2021), it is clear that legumes must be well integrated into agricultural systems around the world (Muoni et al., 2020; Sennhenn et al., 2017a; Sennhenn et al., 2017b; Varshney et al., 2018; Watson et al., 2017) and should thus play a key role in the development of future intercropping systems. Intercropping as a system has some unique issues, particularly in the tropics. While many of these problems, such as cultivar choice and density, may be translated straight from a low-input subsistence system in the Northern part of Ghana to a large farm in the Ashanti region, some aspects of intercropping alter depending on the context. The increased adoption of mechanized practices in modern agriculture has resulted in system component simplification (Maitra and Gitari, 2020; Maitra et al., 2019). Low-input systems may not have tapped into such methods and may be subsistence-based, yet they are nonetheless adaptable. Those who cultivate using modern methods, on the other hand, maybe less open to new approaches that necessitate further investment. Legumes are traditionally viewed as less financially viable than cereals, therefore incorporating them into a farming system is fraught with risk (Johansen and Siddique, 2018; Nemecek et al., 2008). Highly mechanized farms may choose to import legumes because of the additional necessity and hence expense of technology that can simultaneously handle multi-species stands (Adjei-Nsiah et al., 2018) unless regulation supports otherwise (Adjei-Nsiah et al., 2018; Kermah et al., 2018). As a result, integrated evaluation frameworks that systematically analyze sustainable development in agricultural landscapes have been developed. They include environmental, economic, and social

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variables and emphasize that intercropping is more than just an issue of biotic trade-offs (Poggi et al., 2021; Sattler and Nagel, 2010; Spangenberg et al., 2018). It is commonly known that predicted worldwide population growth would necessitate increased food production through sustainable techniques (Sarkar et al., 2020; Tilman et al., 2002). According to Clay and Zimmerer (2020), yield progress began to stall in the 1990s, compared to the 30 years following the green revolution. Agriculture presents significant difficulties that must be tackled with new ideas and technology. This exemplifies why intercropping has the potential to become a contemporary, mechanized, and intensified system, not merely by converting marginal to productive land, but also by addressing the issues raised above. Farmers and machinery makers will develop solutions to overcome the problems, with the knowledge and lessons learned being expanded to low-input systems at the same time (Hobbs et al., 2019). This emphasizes the relevance of research like that of (Hajjarpoor et al., 2018; Shilomboleni and De Plaen, 2019; Zhang et al., 2016), who use upscaling modeling exercises to discover yield gaps that can attract the attention of linked businesses and help fund-related research and development. The culmination of marginal advances, such as GPS devices that allow for accurate inter-row seeding and management of various species – previously only doable as part of labor-intensive subsistence farming systems – could be the key to our agricultural future (Raturi, 2017; Robertson et al., 2016). The importance of precision agronomy and the usage of user-friendly computer-based technologies (Varshney et al., 2018). They emphasize the need of breeding crops with specific systems and stakeholder demands in mind, as argued in chapter two, which discovered that some cowpea crop varieties were better suited to the intercropping system depending on site selection. This is also evident in Chapter 7 when there is a definite need

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to seed the cowpea intercrop after the rice to avoid it outcompeting the cereal. The utilization of specific genetic material and timing certain production stages, as well as those of possible companion crops, with resource availability, are two major aspects of genetic advantages mentioned by Varshney et al. (2018). This is where simulation models come in handy. Furthermore, research should focus on developing a comprehensive understanding of intercrop systems and their many forms, which should be accomplished through collaborative efforts (Reynolds et al., 2018; Rötter et al., 2018; Varshney et al., 2018).

8.1.3 Nutrient use efficiency

Management strategies and biotic/abiotic stress have an impact on physiological efficiency (PE) as a measure of nutrient use efficiency. In this study, the efficiency of N and K usage increased with increasing application of inorganic P fertilizer, with the impact being greater on the three different biochar sources than on the control plots due to the lower accessible soil P concentration. However, comparing grain yields under control settings from both systems using this index for nutrient use efficiency in contrast in the two cropping seasons provides good comparisons, as grain yields under control conditions differed greatly. The changes in PE between cropping seasons argue against the usually offered "blanket" fertilizer recommendations and the three different sources of biochar, as N and P responses varied between systems. Due to the high cost of fertilizer and the fact that most farmers are cash-strapped at the start of the planting season, it would be more cost-effective to use various sources of biochar and practice intercropping, as the advantages are greater. To maintain or boost food security, however, agriculture must be expanded, as well as the usage of three different sources of biochar and inorganic fertilizer with cowpea intercrop. The

results demonstrate that this can be done in a physiologically efficient manner as well, though not as effective as on the control soils. According to this study, the use of three different sources of biochar and inorganic fertilizer with cowpea intercrop is recommended, because its (rational) application is highly lucrative.

8.1.4 Nitrate (NO_3^-N) and potassium (K^+) loss

The APSIM biochar and inorganic fertilizer rice model predicted nitrate (NO_3^-N) and potassium (K^+) leaching values that varied with annual rainfall. Soil chemical analysis includes physical properties of soil types (primarily plant available soil water holding capacity) as well as initial soil NO_3^-N and K^+ levels. Although measured values of nitrate NO_3^-N and K^+ leaching are also variable, they generally differ less. As a representation of a highly variable system, this demonstrates the limitations of site and season-specific measurement. The variability associated with rainfall, soil type, and initial soil NO_3^-N and K^+ chemical analysis can be considered using a simulation model to overcome this limitation. Furthermore, the large amount of output data generated by the simulation model allows for a thorough analysis of the system and the search for simple approximations that can account for the majority of treatment differences. The simple framework of threshold rainfall and NO_3^-N and K^+ leaching rates developed here as a first approximation of NO_3^-N and K^+ leaching below the potential root depth of rice crops grown in northern Ghana's agricultural areas. Knowing a soil's plant available water holding capacity is enough to estimate the start of potential NO_3^-N and K^+ leaching because the threshold for starting NO_3^-N and K^+ leaching was not significantly affected by the initial soil mineral N in the profile, nor by the three different sources of biochar and fertilizer N and K_2O application. Furthermore, above the

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annual rainfall threshold, the rate of NO_3^-N and K^+ leaching in the chemical analysis varied primarily with soil type and initial mineral N, but less with the different sources of biochar application rate. For example, using (chapter 2, Table 3 and chapter 3, Table 3.3) with no fertilizer N, zero kg N ha^{-1} NO_3^-N and K^+ leaching is estimated for the sandy loam soil, while 90 and 45 kg N ha^{-1} are predicted for the deep sandy duplex and acid sandy loam, respectively, based on the initial soil NO_3^-N and K^+ chemical analysis and soil profile for an average rainfall year at UDS-Nyankpala (133.29 mm). These estimates of NO_3^-N leaching can be useful in determining the loss of valuable nitrogen and potassium resources from cropping systems, which could harm groundwater, wetlands, and river systems. The data can be used to estimate acidification rates based on projected or historical rainfall, as well as to budget for different rates of biochar as lime. Additional model runs could be performed to broaden the estimate to account for a broader range of initial soil NO_3^-N chemical analysis and N and K_2O fertilizer application rates, as well as other factors such as initial soil water profile.

8.1.5 Biochar on soil hydrological properties

Chapter eight showed that biochar-added soils had a different pore size distribution than control soils without biochar, with lowermost frequent pore diameters and overall porosity, as well as increased saturated water content, field capacity, and soil water content. Differences in soil pore geometry parameters determined by fitting observed soil water content gave quantitative evidence of a shift in pore size distribution to lower average pore sizes, reducing macro-porosity in favor of meso- and microporosity, and so improving soil water retention. When compared to non-treated sandy loam soils, this enhancement can help

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biochar-amended sandy loam soils retain more plant-accessible water for crop use and reduce leaching losses of water and nutrients. Chapter 6 showed that three different sources of biochar application improved soil physical qualities in rice-cowpea plots under field conditions during two years. The three different sources of biochar treatment increased DUL and KL, as well as a modest increase in SAT, whereas there was no significant change in LL15, KS for the biochar treatment, an increase in the soil's capacity to hold water led in increased water intake with reduced LL. The integration of field-level observations with a modeling component for the calculation of more realistic soil parameters as a result of biochar application was a crucial unique component in this study. We discovered a negative association between clay, SOC, soil pH, and CEC in our suitability analysis study, which means that the lower the value of any of these soil parameters, the greater the likelihood of increased yield following biochar and inorganic fertilizer with cowpea intercrop application. When the model's behavior was examined, it was discovered that soil properties dominated the crop yield response to biochar and inorganic fertilizer with cowpea intercrop, and that increasing the biochar application rate resulted in a higher probability of crop yield increases for soils of lower quality. Although the model built in this study is computationally quick and precise enough to be used for large-scale modeling, there are a few drawbacks to our findings. For example, our knowledge suggests that crop residue, soil characteristics (such as inorganic N available in the soil), and biochar properties (such as the amount of labile C and N pools) are all potential drivers of crop yield responses that aren't explicitly stated in the model. Because there is currently insufficient data in the literature to cover all probable soil-biochar interactions, the model concentrates on what is available. Our model provides the way for the adoption of more computationally complex process-based crop models by

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selecting the best out of the three different sources of biochar, soil types, and biochar types with a high and low probability of crop yield response. The simulated three different sources of biochar (given their basic soil properties) all showed a very high probability of yield increase, whereas the APSIM model suggested that not all of these three different sources of biochar suitable area can consistently show positive yield response to biochar. Some stress mechanisms on the crop that biochar is not designed to ameliorate, such as heat stress, could be one probable reason for this variation in response to biochar. The APSIM model was used to explain the complexities of interactions between a changing weather environment (year-to-year fluctuation) and soil with three different biochar sources. In addition, our statistical model may capture chemical processes (such as pH), whereas APSIM focuses on water and nitrogen.

8.2 Conclusions

To maintain soil fertility, biochar, and inorganic fertilizer were used to restore soil fertility, along with a combination of cowpea intercrop systems. Significant differences in all analyzed soil quality measures were observed in the 2018 and 2019 cropping seasons following biochar application, but for all treatments. Biochar at a rate of 5 t ha^{-1} in combination with 45N30P30K kg ha^{-1} reduced bulk density and increased plant available water considerably. Various trends (a decline, an increase, no effect) were detected in the soil water content dynamics over the 2018 and 2019 cropping seasons. When compared to the control treatment without biochar and inorganic fertilizer addition, all three different sources of biochar treatments showed a relative increase in soil water content during the dry period. Biochar and inorganic fertilizer in combination with a cowpea intercrop appear to be

a potential method for increasing intensive agriculture's sustainability by improving soil physical and hydro-physical features by positively altering soil structure.

The application of the three different sources of biochar was an effective amendment to sandy loam soil, improving the capacity of the soil to hold water and inorganic fertilizer. The impact of three different sources of biochar and inorganic fertilizer, along with a cowpea intercrop, on soil organic carbon storage, nutrient recovery, and nutrient usage efficiency, as well as improved economic returns in upland rice cropping systems is studied. The probable synergistic relationships between biochar and inorganic fertilizer in combination with cowpea intercrop improve rice grain yield, grain NPK absorption, and NUE under field conditions. Results averaged across experimental sites, showed a positive effect of the application of biochar and inorganic fertilizer in combination with cowpea intercrop as compared to inorganic fertilizer as a sole input. This combination increased rice grain yield, grain NPKS uptake, and NUE.

In the short term, the combination of cowpea intercrop with three different sources of biochar and inorganic fertilizer enhanced soil organic carbon storage, productivity, and average apparent nutrient efficiency and apparent efficiency recovery above the world averages of 20 kg grain kg^{-1} N and 55 percent, respectively. Furthermore, when biochar was used in combination with inorganic fertilizer and a cowpea intercrop, economic returns (gross margin, gross returns, and value cost ratio) improved. High temperatures, on the other hand, affected the productivity and profitability of the sole fertilizer application. To ensure higher productivity, it is necessary to grow cowpea and add biochar to avoid the reproductive stage of the upland rice plant coinciding with temperatures exceeding 34 °C. Soil characteristics and rice-cowpea intercrop responses differ when biochar is made from three different

sources of feedstocks, as do soil conditions. Biochar could be a beneficial resource for the study area's resource-poor farmers. Biochar's application in upland rice has the potential to be employed as a climate change adaptation and mitigation tool. The fact that the positive effects of biochar treatment lasted for two cropping seasons after a one-time application shows that biochar can help improve fertilizer efficiency in most tropical agricultural systems. The amendment of biochar to sandy loam soil significantly reduced the leaching of NH_4^+N and NO_3^-N when receiving repeated applications with N concentrations. Soil analysis indicated that biochar impacted NH_4^+N and NO_3^-N leaching through enhanced soil retention of both NH_4^+N and NO_3^-N. The APSIM provided a flexible working environment in which users could construct a user-specific model by choosing a set of modules from a variety of crops, soils, and utility modules. For both cropping seasons in the research area, it successfully captured the effects of biochar and inorganic fertilizer (NPK) with a combination of cowpea intercrop applications on rice grain and biomass production.

8.3 Recommendations and perspectives on the future

This investigation specifies that it is economically and agronomically practicable to use biochar and inorganic fertilizers for upland rice-cowpea intercrop production in Nyankpala. Farmers, however, often find it difficult to purchase inorganic fertilizers. There is a need for policies in the agricultural sector that favor some procedures for accessing credit services to support farmers in purchasing fertilizers. An additional investigation into water availability and efficiency interactions of its economic use of biochar and inorganic fertilizer on upland rice-cowpea intercrop yield could complement this experiment. The higher use efficiency of inorganic fertilizers as compared to biochar incorporation emphasizes the importance of

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organic carbon in enhancing the efficiency of inorganic fertilizers. There is a need to endorse strategies that enhance soil organic carbon. Even though the benefits of leguminous crops like cowpea have been documented for Nyankpala, farmers are unwilling to accept these systems because of their exhaustive nature, among other motives. It is obvious from model simulations that continuous cultivation of a crop cannot be sustained for a very long period. Continuous removal of crop residues from our farmlands at the end of each cropping season, even with the application of biochar and inorganic fertilizers. This necessitates research into alternative sources, such as potential feedstock, that are acceptable to farmers to reduce soil acidity, improve soil organic carbon, and reduce global warming. As a result, future generations are likely to face the consequences of current farming practices, necessitating government interventions in the form of appropriate stimulus packages for farmers to encourage them to use soil fertility approaches that will conserve our farmlands, such as biochar, leguminous crops, and farm yard manure. Future generations should not suffer for what current farmers are practicing. Evaluation of the APSIM model revealed its credible performance in predicting both grain and biomass yield of upland rice in response to three different sources of biochar and inorganic fertilizer with cowpea intercropping inputs and in creating a logical trend in soil organic carbon dynamics. A follow-up experiment incorporating biochar to maintain soil moisture dynamics, time series, biomass accumulation, N and P uptake, and leaf development could improve the sturdiness of its ability to predict plant physiological processes. Given the present sturdiness, the model can be used to study the impact of various climate change scenarios on future crop production and soil degradation processes. It is recommended to scale up this study on the use of biochar in the upland rice growing area of Nyankpala so that it can serve as a tool for policy

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recommendations. It can also serve as an input to the decision support systems being developed for planting food and jobs to evaluate the impact of climate change. The incorporation of additional soil degradation developments such as a soil erosion subroutine in future models would further enhance its usefulness as a tool to assess long-term biochar use in upland rice production tendencies in the Nyankpala district. To determine how long biochar will survive in the soil and have an impact on the environment, a long-term study is required (polycyclic aromatic hydrocarbons in soils and greenhouse gas emissions). Before disseminating biochar technology to farmers, extension officers would need to be properly trained to ensure efficient production and application of the technology to increase productivity and profitability in upland rice.

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APPENDIX A

BIOCHAR AND MINERAL FERTILIZER CALCULATION

standard fertilizer 90 nitrogen: 60 phosphates: 60 muriate of potash

$$\frac{R \times A \times 100}{10{,}000\ m^2 \times C}$$

R- Rate of fertilizer to be applied (kg/ha)
A- Area of the plot (m^2)
C - Concentration of element in fertilizer (%)
10,000 m^2 = area per ha (m^2)

90kg Nitrogen

Urea contains 46 % N
If 10,000 m^2 = 90 kg N
Then 12 m^2 = kg N

$$W \text{ kg N} = \frac{12\ m^2 \times 90 \text{ kg N}}{10{,}000\ m^2}$$

$$W \text{ kg N} = \frac{0.108 \text{ kg N}}{10{,}000\ m^2}$$

Therefore, if 100 kg urea = 46kg N
Then W kg urea = 0.108 kg N

$$100 \text{ kg urea} \times \frac{0.108 \text{ kg N}}{46 \text{ kg N}}$$

= 0.234 kg urea or 0.234*1000=234 g
The total amount of urea to be applied for the whole plot = 0.234 kg urea x 4 = 0.939 kg urea
The total amount of 90 kg N urea for the four (4) replications = 4 x 0.234 kg urea = 3.756 kg urea

60 kg Phosphate

Urea contain 21 % TSP
If 10,000 m^2 = 60 kg TSP
Then 12 m^2 = kg TSP

$$W \text{ kg N} = \frac{12\ m^2 \times 60 \text{ kg N}}{10{,}000\ m^2}$$

$$W \text{ kg N} = \frac{0.072 \text{ kg TSP}}{10{,}000\ m^2}$$

Therefore, if 100 kg TSP = 21% TSP
Then W kg TSP = 0.072 kg TSP

$$\frac{100 \text{ kg TSP} \times 0.072 \text{ kg TSP}}{21\% \text{ TSP}}$$

= 0.342 kg TSP or 0.342*1000=342 g
The total amount of TSP to be applied for the whole plot = 0.342 kg TSP x 4 = 1.368 kg TSP

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The total amount of 60kg of P TSP for the three (4) replications = 4 x 0.342 kg TSP =5.472 kg TSP

60kg Muriate of Potash

Muriate of Potash contain 60 % K_2O

If 10,000 m^2 = 60 kg K_2O

Then 12 m^2 = kg K_2O

$$W \text{ kg } N = \frac{12\ m^2 \times 60 \text{ kg } K_2O}{10{,}000\ m^2}$$

$$W \text{ kg } N = \frac{0.72 \text{ kg } K_2O}{10{,}000\ m^2}$$

Therefore, if 100 kg K_2O = 60 kg K_2O

Then W kg K_2O = 0.72 kg K_2O

$$\frac{100 \text{ kg } K_2O \times 0.72 \text{ kg } K_2O}{60 \text{ kg } K_2O}$$

= 0.12 kg K_2O or 0.12*1000 = 120 g

The total amount of K_2O to be applied for the whole plot = 0.12 kg K_2O x 4 = 0.48 kg K_2O

The total amount of 60 kg K_2O for the three (4) replications = 4 x 0.48 kg K_2O = 1.92 kg K_2O

Half of the standard fertilizer is 45 kg nitrogen: 30 kg phosphate: and 30 kg migrate of potash

$$\frac{R \times A \times 100}{10{,}000\ m^2 \times C}$$

R - Rate of fertilizer to be applied (kg/ha)

A - Area of the plot (m^2)

C - Concentration of element in fertilizer (%)

10,000 m^2 - area per ha

45kg Nitrogen

Urea contains 46 % N

If 10,000 m^2 = 45kg N

Then 12 m^2 = kg N

$$W \text{ kg } N = \frac{12\ m^2 \times 45 \text{ kg } N}{10{,}000\ m^2}$$

$$W \text{ kg } N = \frac{0.054 \text{ kg } N}{10{,}000\ m^2}$$

Therefore, if 100 kg urea = 46 kg N

Then W kg urea = 0.054 kg N

$$\frac{100 \text{ kg urea} \times 0.054 \text{ kg } N}{46 \text{ kg } N}$$

= 0.117 kg urea or 0.117*1000 = 117 g

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The total amount of urea to be applied for the whole plot = 0.117 kg urea x 4 = 0.468 kg urea
The total amount of 46 kg N urea for the three (4) replications = 4 x 0.468 kg urea = 1.872 kg urea

30 kg Phosphate (TSP)
Urea contain 21 % TSP
If 10,000 m^2 = 60 kg TSP
Then 12 m^2 = kg TSP

$$W \text{ kg N} = \frac{12\ m^2 \times 30 \text{ kg N}}{10{,}000\ m^2}$$

$$W \text{ kg N} = \frac{0.036 \text{ kg TSP}}{10{,}000\ m^2}$$

Therefore, if 100 kg TSP = 21% TSP
Then W kg TSP = 0.036 kg TSP

$$\frac{100 \text{ kg TSP} \times 0.036 \text{ kg TSP}}{21\% \text{ TSP}}$$

= 0.171 kg TSP or 0.171*1000 =171 g
The total amount of TSP to be applied for the whole plot = 0.171 kg TSP x 4 = 0.685 kg TSP
The total amount of 30 kg of P TSP for the four (4) replications = 4 x 0.685 kg TSP =2.742 kg TSP

30kg Muriate of Potash
Muriate of Potash contains 60 % K_2O
If 10,000 m^2 = 30 kg K_2O
Then 12 m^2 = kg K_2O

$$W \text{ kg N} = 12\ \frac{m^2 \times 30 \text{ kg } K_2O}{10{,}000\ m^2}$$

$$W \text{ kg N} = \frac{0.036 \text{ kg } K_2O}{10{,}000\ m^2}$$

Therefore, if 100 kg K_2O = 60 kg K_2O
Then W kg K_2O = 0.06 kg K_2O

$$\frac{100 \text{ kg } K_2O \times 0.06 \text{ kg } K_2O}{60 \text{ kg } K_2O}$$

= 0.24 kg K_2O or 0.24 *1000 = 24 g
The total amount of K_2O to be applied for the whole plot = 0.24 kg K_2O x 4 = 0.24 kg K_2O
The total amount of 30 kg K_2O for the three (4) replications = 4 x 0.24 kg K_2O = 0.96 kg K_2O

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Lysimeters Fertilizer calculation

90 Nitrogen:
Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 0.234 kg
Therefore 0.0707175 m^2 = W

$$12\ m^2 / 12\ m^2\ W = \frac{0.234\ kg \times 0.0707175\ m^2}{12\ m^2}$$

0.016/12
= 1.3g

60 Phosphate (TSP)
Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 342 g
Therefore 0.0707175 m^2 = W
$12m^2 / 12m^2$ W =342 g x 0.0707175 m^2 / 12 m^2
24.185385 / 12 m^2
= 2.015 g

60 Muriate of Potash (K_2O)
Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 120g
Therefore 0.0707175 m^2 = W
$12m^2 / 12m^2$ W =120 g x 0.0707175 m^2 / 12 m^2
8.4861 /12 m^2
= 0.707g

45 kg Nitrogen
Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 1.378g
Therefore 0.0707175 m^2 = W
$12m^2/12m^2$ W =1.378 g x 0.0707175 m^2/ 12 m^2
= 0.008g

30 kg of Phosphate (TSP)
Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 2.015g
Therefore 0.0707175 m^2 = W
$12m^2/12m^2$ W =2.015 g x 0.0707175 m^2/ 12 m^2
= 0.142g

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30 Muriate of Potash

Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 0.707
Therefore 0.0707175 m^2 = W
$12m^2/12m^2$ W = 0.707g x 0.0707175 m^2/ 12 m^2
0.049/12
= 0.004g

Biochar Calculation

Plot size 4 m x 3 m =120 m^2
5 tonnes of biochar
12 m^2 x 5000kg
10,000 m^2
=6 kg x 4 replicate
24 kg of biochar
Area of lysimeter = 0.0707175 m^2
Area of the Plot = 12 m^2
But 12 m^2 = 600g
Therefore 0.0707175 m^2 = W
$12m^2/12m^2$ W = 600g x 0.0707175 m^2/ 12 m^2
42.4305/12
= 3.535g

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APPENDIX B

Soil nutrient content and nutrient interpretation

Nutrient	Rank/Grade
Soil pH (Distilled Water Method)	
<5.0	Very Acidic
5.0 - 5.5	Acidic
5.6 - 60	Moderate Acidic
6.1 - 6.5	Slightly
6.6 – 7.0	Neutral
7.1 – 7.5	Slightly Alkaline
7.6 – 8.5	Alkaline
> 8.6	Very Alkaline
Organic Matter Content (%)	
<1.5	Low
1.6-3.0	Moderate
> 3.0	High
Nitrogen (%)	
< 0.1	Low
0.1- 0.2	Moderate
> 0.2	High

From Soil Research Institute (CSIR) Analytical Laboratory

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APPENDIX C

2018 STRAW						
Trtm	Control	**n**	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-Ys_mean)
16/10/2018	925	804.3	803.8224	924.5308	743158.5	646130.4
16/10/2018	2625	2551.3	2550.822	2624.531	6694712	6506695
16/10/2018	1325	1012.8	1012.322	1324.531	1340852	1024797
16/10/2018	781	702.7	702.2224	780.5308	548106.2	493116.3
16/10/2018	815	724.5	724.0224	814.5308	589738.5	524208.4
16/10/2018	2082	2104.4	2103.922	2081.531	4379379	4426489
16/10/2018	1567	1692	1691.522	1566.531	2649822	2861248
16/10/2018	2025	1728.1	1727.622	2024.531	3497625	2984679
Total	12145	11320.1	11316.28	12141.25	20443393	19467363
Mean	1518.125	1415.013				
Total	12145	11320.1	11316.28	12141.25	20443393	19467363

2019 STRAW						
Trtm	Control	n	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-(Ys_mean)
16/10/2018	418	374.4	374.0908	417.6548	156240.8	139943.9
16/10/2018	1272	1270.9	1270.591	1271.655	1615753	1614401
16/10/2018	505	559.5	559.1908	504.6548	282198.3	312694.3
16/10/2018	525	424.9	424.5908	524.6548	222763.6	180277.3
16/10/2018	575	467.2	466.8908	574.6548	268301	217987
16/10/2018	625	788	787.6908	624.6548	492034.8	620456.7
16/10/2018	745	742.7	742.3908	744.6548	552824.8	551144
16/10/2018	875	744.5	744.1908	874.6548	650910	553819.9
Total	5540	5372.1	5369.626	5537.238	4241026	4190724
Mean	692.5	671.5125				

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2018 BIOMASS						
Trtm	Control	**N**	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]-Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-Ys_mean)
16/10/2018	0	2279.8	2279.322	-0.46922	-1069.5	5195310
16/10/2018	0	7967.4	7966.922	-0.46922	-3738.23	63471852
16/10/2018	3250	3404.5	3404.022	3249.531	11061475	11587368
16/10/2018	0	2369.7	2369.222	-0.46922	-1111.68	5613215
16/10/2018	0	2499.1	2498.622	-0.46922	-1172.4	6243114
16/10/2018	5752	6644.2	6643.722	5751.531	38211574	44139047
16/10/2018	2875	5217.6	5217.122	2874.531	14996779	27218366
16/10/2018	3952	5370.2	5369.722	3951.531	21218623	28833918
Total	15829	35752.5	35748.68	15825.25	85481360	1.92E+08
Mean	1978.625	4469.063				

2019 BIOMASS						
Trtm	Control	**n**	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]-Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-Ys_mean)
16/10/2018	0	1422.6	1422.291	-0.34525	-491.046	2022911
16/10/2018	0	4103.5	4103.191	-0.34525	-1416.63	16836174
16/10/2018	2536	2326.9	2326.591	2535.655	5899431	5413025
16/10/2018	0	1828.2	1827.891	-0.34525	-631.079	3341185
16/10/2018	0	1982.7	1982.391	-0.34525	-684.42	3929873
16/10/2018	2825	3441	3440.691	2824.655	9718763	11838353
16/10/2018	3075	3244.2	3243.891	3074.655	9973844	10522827
16/10/2018	4235	3285.6	3285.291	4234.655	13912072	10793135
Total	12671	21634.7	21632.23	12668.24	39500887	64697483
Mean	1583.88	2704.338				

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2018 LAI						
Trtm	Control	**N**	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]-Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-Ys_mean)
16/10/2018	0.19375	0.286	-0.19163	-0.27547	0.052787	0.03672
16/10/2018	0.86	0.903	0.425375	0.390781	0.166229	0.180944
16/10/2018	0.25	0.335	-0.14263	-0.21922	0.031266	0.020342
16/10/2018	0.29	0.236	-0.24163	-0.17922	0.043304	0.058383
16/10/2018	0.32	0.243	-0.23463	-0.14922	0.03501	0.055049
16/10/2018	0.86	0.703	0.225375	0.390781	0.088072	0.050794
16/10/2018	0.42	0.552	0.074375	-0.04922	-0.00366	0.005532
16/10/2018	0.56	0.563	0.085375	0.090781	0.00775	0.007289
Total	3.75375	3.821	2.22E-16	-1.7E-16	0.420758	0.415052
Mean	0.469219	0.477625				

2019 LAI						
Trtm	Control	N	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]-Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-Ys_mean)
16/10/2018	0.121	0.162	-0.14725	-0.22425	0.033021	0.021683
16/10/2018	0.69	0.493	0.18375	0.34475	0.063348	0.033764
16/10/2018	0.35	0.241	-0.06825	0.00475	-0.00032	0.004658
16/10/2018	0.251	0.191	-0.11825	-0.09425	0.011145	0.013983
16/10/2018	0.26	0.205	-0.10425	-0.08525	0.008887	0.010868
16/10/2018	0.52	0.408	0.09875	0.17475	0.017257	0.009752
16/10/2018	0.21	0.384	0.07475	-0.13525	-0.01011	0.005588
16/10/2018	0.36	0.39	0.08075	0.01475	0.001191	0.006521
Total	2.762	2.474	-2.2E-16	-8.3E-17	0.124415	0.106816
Mean	0.34525	0.30925				

2018 YIELD						
Trtm	Control	n	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]-Ys_mean)*(Ym[i]-Ym_mean)	Sqr(Ys[i]-Ys_mean)
16/10/2018	850	808.2	807.7224	849.5308	686185	652415.4
16/10/2018	2696.525	3481.9	3481.422	2696.056	9386109	12120302
16/10/2018	1720.675	1589.9	1589.422	1720.206	2734134	2526263
16/10/2018	1885.45	1118.8	1118.322	1884.981	2108016	1250645
16/10/2018	1500.075	1212.4	1211.922	1499.606	1817406	1468756
16/10/2018	3000.4	2970.2	2969.722	2999.931	8908962	8819251
16/10/2018	2574.95	2208.8	2208.322	2574.481	5685284	4876688
16/10/2018	2103	2303.7	2303.222	2102.531	4842596	5304833
Total	16331.08	15693.9	15690.08	16327.32	36168691	37019153
Mean	2041.384	1961.738				

2019 YIELD						
Trtm	Control	N	8			
Date	Measured	Simulated	(Ys[i]-Ys_mean)	(Ym[i]-Ym_mean)	(Ys[i]-Ys_mean)*(Ym[i]-Ym_mean)	Sqr (Ys[i]-Ys_mean)
16/10/2018	682	691.8	691.4908	681.6548	471358	478159.5
16/10/2018	1483	2068.1	2067.791	1482.655	3065820	4275759
16/10/2018	1431	1297.2	1296.891	1430.655	1855403	1681926
16/10/2018	1127	1027.9	1027.591	1126.655	1157740	1055943
16/10/2018	1381	1112.7	1112.391	1380.655	1535828	1237413
16/10/2018	1811	1982.1	1981.791	1810.655	3588339	3927495
16/10/2018	1406	1869.7	1869.391	1405.655	2627718	3494622
16/10/2018	1815	1909.4	1909.091	1814.655	3464341	3644627
Total	11136	11958.9	11956.43	11133.24	17766546	19795943
Mean	1392	1494.863				

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SUMMARY OUTPUT
Regression 2018 Yield vs Tillers

Regression Statistics	
Multiple R	0.786741
R Square	**0.618961**
Adjusted R Square	0.580857
Standard Error	3.447954
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	193.1157	193.1157	16.24406	**0.002398**
Residual	10	118.8839	11.88839		
Total	11	311.9995			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-5.42155	5.108056	-1.06137	0.313481	-16.803	5.95991	-16.803	5.95991
X Variable 1	0.430873	0.106906	4.030392	0.002398	0.192672	0.669075	0.192672	0.669075

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*
1	8.662837	0.739663
2	16.17597	2.550026
3	14.69506	6.140937
4	23.31253	1.248722
5	16.63399	1.248757
6	16.87614	-1.49614
7	19.35366	-1.47191
8	13.07929	-1.13004
9	15.23365	-4.8164
10	8.824415	1.782335
11	12.62127	-6.10252
12	11.78667	1.306582

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SUMMARY OUTPUT
Regression 2018 Yield vrs Spikelets/panicles

Regression Statistics	
Multiple R	0.853667
R Square	**0.728747**
Adjusted R Square	0.701622
Standard Error	2.909135
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	227.3689	227.3689	26.86601	**0.000411**
Residual	10	84.63067	8.463067		
Total	11	311.9995			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.83873	3.312773	-0.55504	0.591065	-9.22004	5.542592	-9.22004	5.542592
X Variable 1	0.667739	0.128827	5.183243	0.000411	0.380696	0.954783	0.380696	0.954783

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*
1	4.838668	4.563832
2	17.02491	1.701088
3	19.19507	1.640935
4	20.36361	4.197641
5	19.02813	-1.14538
6	17.52572	-2.14572
7	17.19185	0.689903
8	12.1838	-0.23455
9	13.35235	-2.9351
10	10.34752	0.259232
11	11.18219	-4.66344
12	15.02169	-1.92844

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SUMMARY OUTPUT
Regression 2018 Yield vrs grains/panicle

Regression Statistics	
Multiple R	0.784572
R Square	**0.615554**
Adjusted R Square	0.577109
Standard Error	3.463337
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	192.0525	192.0525	16.01144	**0.002513**
Residual	10	119.947	11.9947		
Total	11	311.9995			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3.27236	4.618804	-0.70849	0.494827	-13.5637	7.018977	-13.5637	7.018977
X Variable 1	0.040593	0.010145	4.00143	0.002513	0.017989	0.063197	0.017989	0.063197

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*
1	5.627686	3.774814
2	14.23343	4.492567
3	19.52069	1.315311
4	20.51522	4.046029
5	18.35364	-0.47089
6	16.24279	-0.86279
7	17.3794	0.502349
8	13.69557	-1.74632
9	14.20299	-3.78574
10	9.575369	1.031381
11	13.24905	-6.7303
12	14.65966	-1.56641

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SUMMARY OUTPUT
Regression 2019 Yield vrs Tillers

Regression Statistics	
Multiple R	0.860767
R Square	**0.74092**
Adjusted R Square	0.715013
Standard Error	1.854553
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	98.35962	98.35962	28.59819	**0.000325**
Residual	10	34.39365	3.439365		
Total	11	132.7533			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	12.15632	2.181028	5.573663	0.000236	7.296682	17.01595	7.296682	17.01595
X Variable 1	0.169592	0.031713	5.347727	0.000325	0.098931	0.240253	0.098931	0.240253

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*
1	17.98689	-4.15714
2	24.85537	0.722628
3	26.04252	0.296233
4	29.41231	-1.39131
5	25.59649	-1.48174
6	24.94017	-0.43492
7	24.36695	-0.09445
8	22.16225	0.829251
9	22.1419	1.182852
10	21.29394	2.813562
11	21.33634	1.448664
12	21.42113	0.266368

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SUMMARY OUTPUT
Regression 2019 Yield vrs spikelets/panicle

Regression Statistics	
Multiple R	0.941029
R Square	**0.885536**
Adjusted R Square	0.87409
Standard Error	1.232697
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	117.5578	117.5578	77.36397	**5.08E-06**
Residual	10	15.19543	1.519543		
Total	11	132.7533			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.57014	2.755457	-0.20691	0.840231	-6.70968	5.569404	-6.70968	5.569404
X Variable 1	0.672256	0.07643	8.795679	5.08E-06	0.501959	0.842553	0.501959	0.842553

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*
1	15.22788	-1.39813
2	25.47979	0.098211
3	25.98398	0.354769
4	28.67301	-0.65201
5	24.13528	-0.02053
6	24.13528	0.369973
7	24.80753	-0.53503
8	21.61432	1.377184
9	22.79076	0.533985
10	23.12689	0.980607
11	21.27819	1.506812
12	24.30334	-2.61584

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SUMMARY OUTPUT
Regression 2019 Yield vrs grains/panicles

Regression Statistics	
Multiple R	0.853116
R Square	**0.727806**
Adjusted R Square	0.700587
Standard Error	1.90091
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	96.61868	96.61868	26.73855	**0.000419**
Residual	10	36.1346	3.61346		
Total	11	132.7533			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.625429	3.302114	2.00642	0.072607	-0.73214	13.983	-0.73214	13.983
X Variable 1	0.034204	0.006615	5.170933	0.000419	0.019466	0.048942	0.019466	0.048942

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*
1	17.75025	-3.9205
2	24.06943	1.508572
3	25.54875	0.790003
4	30.11497	-2.09397
5	24.78771	-0.67296
6	23.78725	0.718005
7	24.91597	-0.64347
8	22.91505	0.076454
9	21.98299	1.341761
10	21.34167	2.765835
11	21.57254	1.212458
12	22.76968	-1.08218

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2018 data
Statistix 10.0 12/02/2020, 16:45:14

1. **LAI**

Statistix 10.0 12/02/2020, 16:53:48

Analysis of Variance Table for Rice LAI

Source	DF	SS	MS	F	P
TRT	11	34.0957	3.09961	6.93	0.0000
Error	36	16.1101	0.44750		
Total	47	50.2058			

Grand Mean 3.3584
CV 19.92

Analysis of Variance Table for Rice_Cowpea Intercrop LAI

Source	DF	SS	MS	F	P
Treatment	5	7.2684	1.45368	4.20	0.0105
Error	18	6.2283	0.34602		
Total	23	13.4967			

Grand Mean 1.8180
CV 32.36

1. **CANOPY**

Statistix 10.0 12/02/2020, 17:20:00

Analysis of Variance Table for Rice Canopy

Source	DF	SS	MS	F	P
TRT	11	1.197E+08	1.088E+07	8.55	0.0000
Error	36	4.580E+07	1272108		
Total	47	1.655E+08			

Grand Mean 6576.2
CV 17.15

Analysis of Variance Table for Rice_Cowpea Canopy

Source	DF	SS	MS	F	P
Treatment	5	1.526E+07	3052204	0.65	0.6685
Error	18	8.513E+07	4729336		
Total	23	1.004E+08			

Grand Mean 9126.3
CV 23.83

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1. **CHLOROPHYLL**

Statistix 10.0 12/02/2020, 17:51:32

Analysis of Variance Table for Rice Chlorophyll

Source	DF	SS	MS	F	P
TRT	11	43583.2	3962.11	5.57	0.0000
Error	36	25629.7	711.94		
Total	47	69212.8			

Grand Mean 252.67
CV 10.56

Analysis of Variance Table for Cowpea Chlorophyll

Source	DF	SS	MS	F	P
Treatment	5	28714.1	5742.83	2.34	0.0841
Error	18	44218.5	2456.58		
Total	23	72932.6			

Grand Mean 512.90
CV 9.66

1. **NUMBER OF TILLERS**

Statistix 10.0 13/02/2020, 15:23:20

Analysis of Variance Table for Rice No. of Tillers

Source	DF	SS	MS	F	P
TRT	11	4160.87	378.261	4.61	0.0002
Error	36	2954.00	82.056		
Total	47	7114.87			

Grand Mean 46.865
CV 19.33

1. **FILLED AND UNFILLED RICE GRAIN WT.**

Statistix 10.0 13/02/2020, 18:25:47

Analysis of Variance Table for Fill Rice Grain Wt

Source	DF	SS	MS	F	P
TRT	11	398.407	36.2188	3.78	0.0012
Error	36	344.978	9.5827		
Total	47	743.385			

Grand Mean 10.732
CV 28.84

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Analysis of Variance Table for Unfill Rice Grain wt

Source	DF	SS	MS	F	P
TRT	11	24.4128	2.21935	1.59	0.1444
Error	36	50.3138	1.39760		
Total	47	74.7266			

Grand Mean 2.2729
CV 52.01

1. **HEIGHT**

Statistix 10.0 13/02/2020, 18:30:39

Analysis of Variance Table for Rice Height

Source	DF	SS	MS	F	P
TRT	11	688.63	62.6025	0.90	0.5524
Error	36	2513.20	69.8110		
Total	47	3201.82			

Grand Mean 166.84
CV 5.01

Analysis of Variance Table for Cowpea Height

Source	DF	SS	MS	F	P
Treatment	5	1655.0	331.000	0.44	0.8129
Error	18	13457.0	747.611		
Total	23	15112.0			

Grand Mean 171.50
CV 15.94

1. **HEIGHT AT MATURITY**

Statistix 10.0 14/02/2020, 06:48:15

Analysis of Variance Table for Rice

Source	DF	SS	MS	F	P
TRT	11	3869.52	351.774	6.76	0.0000
Error	36	1873.56	52.043		
Total	47	5743.08			

Grand Mean 119.34
CV 6.04

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1. BULK DENSITY AND POROSITY

Statistix 10.0 14/02/2020, 06:56:20

Analysis of Variance Table for Bulk

Source	DF	SS	MS	F	P
TRT~01	12	0.15161	0.01263	1.26	0.2828
Error	39	0.39241	0.01006		
Total	51	0.54402			

Grand Mean 0.9953
CV 10.08

Analysis of Variance Table for Porosity

Source	DF	SS	MS	F	P
TRT~01	12	187.423	15.6186	1.14	0.3606
Error	39	536.000	13.7436		
Total	51	723.423			

Grand Mean 63.538
CV 5.83

Statistix 10.0 14/02/2020, 08:01:49

Analysis of Variance Table for number of Panicle

Source	DF	SS	MS	F	P
TRT~01	11	50350.2	4577.29	21.85	0.0000
Error	36	7542.2	209.51		
Total	47	57892.5			

Grand Mean 66.896
CV 21.64

Analysis of Variance Table for NSP(number of seeds per panicle

Source	DF	SS	MS	F	P
TRT~01	11	1536.42	139.674	8.33	0.0000
Error	36	603.50	16.764		
Total	47	2139.92			

Grand Mean 25.292
CV 16.19

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Analysis of Variance Table for NSED(number of seeds per spikelets)

Source	DF	SS	MS	F	P
TRT~01	11	466202	42382.0	6.79	0.0000
Error	36	224574	6238.2		
Total	47	690776			

Grand Mean 444.50
CV 17.77

Analysis of Variance Table for Panicle length

Source	DF	SS	MS	F	P
TRT~01	11	1513.71	137.610	12.99	0.0000
Error	36	381.33	10.593		
Total	47	1895.05			

Grand Mean 71.251
CV 4.57

Analysis of Variance Table for Straw

Source	DF	SS	MS	F	P
TRT~01	11	1963.53	178.503	11.01	0.0000
Error	36	583.54	16.210		
Total	47	2547.07			

Grand Mean 13.365
CV 30.12

Analysis of Variance Table for H

Source	DF	SS	MS	F	P
TRT~01	11	348260	31660.0	7.31	0.0000
Error	36	155982	4332.8		
Total	47	504242			

Grand Mean 227.56
CV 28.93

Analysis of Variance Table for ToGrain

Source	DF	SS	MS	F	P
TRT~01	11	258783	23525.7	5.07	0.0001
Error	36	167047	4640.2		
Total	47	425830			

Grand Mean 212.71
CV 32.02

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1. **GIRTH**

Analysis of Variance Table for Cowpea

Source	DF	SS	MS	F	P
Treatment	5	59.821	11.9642	0.72	0.6179
Error	18	299.737	16.6521		
Total	23	359.558			

Grand Mean 25.067
CV 16.28

1. **COWPEA YIELD**
2. Statistix 10.0 14/02/2020, 17:24:43

Analysis of Variance Table for Biomass

Source	DF	SS	MS	F	P
TRT	5	4.3537	0.87075	0.53	0.7520
Error	18	29.6725	1.64847		
Total	23	34.0263			

Grand Mean 3.1875
CV 40.28

Analysis of Variance Table for pod wt Mean

Source	DF	SS	MS	F	P
TRT	6	450.243	75.0406	24.71	0.0000
Error	17	51.624	3.0367		
Total	23				

Note: SS are marginal (type III) sums of squares

Grand Mean 8.6354
CV 20.18

Cowpea

Analysis of Variance Table for grain wt Mean~01

Source	DF	SS	MS	F	P
TRT	6	48264.3	8044.05	13.55	0.0000
Error	17	10093.2	593.72		
Total	23				

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Note: SS are marginal (type III) sums of squares

Grand Mean 39.530
CV 61.64

2019 Data

1. **LAI**

Statistix 10.0 14/02/2020, 18:53:45

Analysis of Variance Table for Avg

Source	DF	SS	MS	F	P
TRT	11	235.210	21.3827	3.31	0.0032
Error	36	232.745	6.4651		
Total	47	467.954			

Grand Mean 7.3421
CV 34.63

1. **FILLED AND UNFILLED**

Statistix 10.0 14/02/2020, 19:10:04

Analysis of Variance Table for Fill

Source	DF	SS	MS	F	P
TRT	11	398.407	36.2188	3.78	0.0012
Error	36	344.978	9.5827		
Total	47	743.385			

Grand Mean 11.572
CV 26.75

Analysis of Variance Table for Unfill

Source	DF	SS	MS	F	P
TRT	11	27.8130	2.52845	1.70	0.1134
Error	36	53.5808	1.48836		
Total	47	81.3938			

Grand Mean 3.1044
CV 39.30

1. **BULK DENSITY AND POROSITY**

Statistix 10.0 14/02/2020, 19:20:58

Analysis of Variance Table for Bulk

Source	DF	SS	MS	F	P
TRT	12	182.492	15.2077	836.03	0.0000
Error	39	0.709	0.0182		
Total	51	183.201			

Grand Mean 3.9908
CV 3.38

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Analysis of Variance Table for Porosity

Source	DF	SS	MS	F	P
TRT	12	159.25	13.2708	0.37	0.9665
Error	39	1398.00	35.8462		
Total	51	1557.25			

Grand Mean 61.750
CV 9.70

1. **CANOPY**

Statistix 10.0 14/02/2020, 19:29:48

Analysis of Variance Table for Mean

Source	DF	SS	MS	F	P
TRT	11	7.043E+08	6.403E+07	36.00	0.0000
Error	36	6.403E+07	1778480		
Total	47	7.683E+08			

Grand Mean 17847
CV 7.47

1. **HEIGHT**

Statistix 10.0 14/02/2020, 19:45:47

Analysis of Variance Table for Mean

Source	DF	SS	MS	F	P
TRT	11	254042	23094.7	5.00	0.0001
Error	36	166231	4617.5		
Total	47	420273			

Grand Mean 662.04
CV 10.26

1. **CHLOROPHYLL**

Statistix 10.0 14/02/2020, 20:30:25

Analysis of Variance Table for Mean

Source	DF	SS	MS	F	P
TRT	11	493924	44902.2	24.78	0.0000
Error	36	65222	1811.7		
Total	47	559146			

Grand Mean 556.95
CV 7.64

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1. **HEIGHT AT MATURITY**

Statistix 10.0 14/02/2020, 20:40:27

Analysis of Variance Table for Mean

Source	DF	SS	MS	F	P
TRT	11	149721	13611.0	116.74	0.0000
Error	36	4197	116.6		
Total	47	153919			

Grand Mean 233.68
CV 4.62

1. **PANICLE COUNT**

Statistix 10.0 14/02/2020, 20:45:45

Analysis of Variance Table for Panicle

Source	DF	SS	MS	F	P
TRT	11	1494.48	135.862	11.10	0.0000
Error	36	440.45	12.235		
Total	47	1934.93			

Grand Mean 73.441
CV 4.76

Analysis of Variance Table for P

Source	DF	SS	MS	F	P
TRT	11	41672.7	3788.42	10.43	0.0000
Error	36	13073.0	363.14		
Total	47	54745.7			

Grand Mean 113.08
CV 16.85

Analysis of Variance Table for Straw

Source	DF	SS	MS	F	P
TRT	11	1036.00	94.1819	2.07	0.0494
Error	36	1636.50	45.4584		
Total	47	2672.50			

Grand Mean 15.364
CV 43.88

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Analysis of Variance Table for NSP (number of seeds per panicle)

Source	DF	SS	MS	F	P
TRT	11	1040.50	94.5909	8.46	0.0000
Error	36	402.50	11.1806		
Total	47	1443.00			

Grand Mean 35.750
CV 9.35

Analysis of Variance Table for NSPS (number of seeds per spikelets)

Source	DF	SS	MS	F	P
TRT	11	330346	30031.5	8.01	0.0000
Error	36	134907	3747.4		
Total	47	465253			

Grand Mean 492.27
CV 12.44

1. **TILLERS**

Statistix 10.0 14/02/2020, 21:12:38

Analysis of Variance Table for Mean

Source	DF	SS	MS	F	P
TRT	11	13681.2	1243.74	9.33	0.0000
Error	36	4799.5	133.32		
Total	47	18480.7			

Grand Mean 66.667
CV 17.32

1. **COWPEA YIELD**

Statistix 10.0 14/02/2020, 21:17:15

Analysis of Variance Table for Pod wt

Source	DF	SS	MS	F	P
TRT	5	45.9514	9.19027	4.88	0.0037
Error	22	41.4349	1.88340		
Total	27				

Note: SS are marginal (type III) sums of squares

Grand Mean 8.0258
CV 17.10

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Analysis of Variance Table for total grain wt Mean~01

Source	DF	SS	MS	F	P
TRT	5	39.2954	7.85908	10.61	0.0000
Error	22	16.2969	0.74077		
Total	27				

Note: SS are marginal (type III) sums of squares

Grand Mean	7.3437
CV	11.72

Analysis of Variance Table for Biomass

Source	DF	SS	MS	F	P
TRT	7	9.9705	1.42435	1.19	0.3519
Error	20	23.9192	1.19596		
Total	27				

Note: SS are marginal (type III) sums of squares

Grand Mean	3.6260
CV	30.16

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