EVALUATION OF PIGEONPEA – WHITE YAM (*CAJANUS CAJAN [L] MILLSP – DIOSCOREA ROTUNDATA [L] POIR*) CROPPING SYSTEM FOR IMPROVED YAM PRODUCTIVITY AND LIVELIHOOD OF SMALLHOLDER FARMERS

By

Eric Owusu Danquah

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences – Doctor of Philosophy

2020

ABSTRACT

EVALUATION OF PIGEON PEA – WHITE YAM (*CANJANUS CAJAN* [L] MILLSP – *DIOSCOREA ROTUNDATA* [L] POIR) CROPPING SYSTEM FOR IMPROVED YAM PRODUCTIVITY AND LIVELIHOOD OF SMALLHOLDER FARMERS

By

Eric Owusu Danquah

Yam (*Dioscorea spp*.) production along the West Africa yam belt is a major contributor to deforestation and soil degradation resulting from shifting cultivation practice in search of fertile land and stakes for yams to climb. This study reports on, field evaluation, simulation evaluation, and economic analysis of integrating pigeonpea into the yam cropping system described as pigeonpea-yam cropping system for improved and sustained yam production on continuously cropped fields. The study was conducted in the forest and forest-savannah transition agro-ecological zones of Ghana in 2017, 2018, and 2019 cropping seasons. In 2017, pigeonpea arrangement options of pigeonpea in an alley (PA), pigeonpea as a border (PB), sole pigeonpea, and no pigeonpea field were laid-out at Fumesua and Ejura in the forest and forest-savannah transition zones respectively. These arrangements considered the ability to obtain enough pigeonpea biomass and stakes for the yam production in the 2018 and 2019 cropping seasons. The study used an integrated soil fertility management of pigeonpea biomass and fertilizer for yam production in both locations in the 2018 and 2019 cropping seasons. The treatments were arranged in a split-plot design in 3 replications with cropping system (yam in PA, Yam in PB and sole yam) and inorganic fertilizer level (No fertilizer, half rate – 23-23-30 N-P_2O_5-K_2O kg/ha and full-rate – 45-45-60 N-P_2O_5-K_2O kg/ha) as main plot and subplots respectively. Significantly ($P \leq 0.05$) higher sunlight reached the yam leaves above-canopy (AC), mid-canopy (MC), and below-canopy (BC) of the sole yam fields than the leaves of yam in PB and PA. The lower sunlight reaching these various canopy levels resulted in a significant ($P \leq 0.05$) suppression of weeds in the PA than PB compared to sole yam fields for both locations and years. The N and other nutrient contributions, moisture conservation from the pigeonpea biomass and maintained bulking medium (ridges), resulted in a significant ($P \leq 0.05$) higher and similar tuber yield per stand and total tuber yield recorded for the pigeonpea-yam fields with a half and full fertilizer rates in both locations and years. Land Equivalent Ratio (LER) indicated productivity efficiency with the pigeonpea-yam intercropping systems than sole yam production with about 27 – 63% and 34 – 68% more land needed for the sole yam to produce yam as in a pigeonpea-yam intercrop for Fumesua and Ejura respectively across years. The Systems Approach to Land Use Sustainability (SALUS) crop model evaluated the long-term (10 years) implication on Integrated Soil Fertility Management (ISFM) of pigeonpea residue and fertilizer. The results revealed, the use of pigeonpea residue, pigeonpea residue in addition to a half and full recommended inorganic fertilizer rate improved the dry tuber yield range to 4.52-7.26 t/ha, 5.80-8.84 t/ha and 7.0-9.99 t/ha, respectively, indicating the influence of the pigeonpea residue in sustaining long-term yam tuber yield. Even when a farmer has no access to fertilizer, the use of pigeonpea residue alone presents a better sustainable yam production option than the use of inorganic fertilizer alone for sole yam production. The economic analysis results revealed, planting yam with pigeonpea (PA and PB) without fertilizer had better IER than planting sole yam with full fertilizer rate in both locations. Planting yam with pigeonpea (PA and PB) with half fertilizer rate presented a slightly lower Net Profit Value (NPV) and Internal Rate of Return (IRR) than planting yam with pigeonpea (PA and PB) with full fertilizer rate; however, the difference in values would only result in marginal income gain. These evaluations thus indicate Integrated Soil Fertility Management (ISFM) with pigeonpea in a pigeonpea-yam cropping system would provide stakes for staking the yams, biomass for improving soil and yam productivity, and profit to smallholder farmers. Therefore, promoting farmers' adoption would sustain yam production on continuously cropped fields to address the deforestation associated with yam production along the West Africa yam belt.

This thesis is dedicated to my beloved wife (Florence Owusu Danquah), Kids (Kwadwo Owusu-Fordjour, and Abena Agyeiwaah Owusu-Danquah). Thanks for your prayers, tolerance, support during the study
And to all yam farmers in Ghana and along the West Africa yam belt, may the findings of this research contribute to better livelihood

ACKNOWLEDGEMENTS

Praise and adoration be unto the Almighty God for his abundant grace and opportunities throughout my life and through this Ph.D. journey. I would not take these blessings and opportunities for granted.

My sincere gratitude goes to my major advisor Dr. Cholani Weebadde for her encouragement and support through the program. I am privileged to have her as my advisor and have benefited from her professional network. I have had the opportunity to observe and apply her farmer centered approach of “seeing is believing” and “learning by doing” for my work towards technology development and transfer. My heartfelt gratitude also goes to my committee members Dr. Sieglinde Snapp (Dept. of Plant, Soil and Microbial Sciences, MSU), Dr. Bruno Basso (Dept. Earth and Environmental Sciences, MSU) and Dr. Kurt Steinke (Dept. of Plant, Soil and Microbial Sciences, MSU) for their useful advice, time and contributions which have enriched the work. I also wish to thank Prof. Stella Ama Ennin (Former director, CSIR – CRI) for her continuing encouragement and advice towards my research as the In-country advisor. Special thanks go to Dr. S. Snapp again and her laboratory members for opening up her laboratory facility to me and for sharing their experiences in the estimation of biological nitrogen fixation. Of the lab members, special mention goes to Vanessa Thomas and Chiwimbo Gwenambira, for assisting me with processing and packaging of samples sent to the UC Davis laboratory for analysis. I also wish to acknowledge Dr. Lin Liu (Dept. Earth and Environmental Sciences – MSU) for her valuable support with the simulation studies using SALUS. The assistance I received from the graduate secretary and the PSM office staff throughout my stay at MSU is much appreciated.

This study would not have been possible without the assistance of my colleagues at CSIR – Crops Research Institute. Special thanks to Mr. Felix Frimpong, Dr. Stephen Yeboah, Mr. Isaac Tawiah, Mr. Kwame Obeng Dankwa, and the technical staff of the RCM Division for their assistance in the field data collection. I am also thankful to Dr. Enock Bessah for assisting me with the map illustration of the study area. Much appreciation also goes to Farmers and Agriculture Extension officers from Ejura municipal, Techiman municipal, and Atebubu-Amantin district for sharing their experiences and assisting in the planting and harvesting of yams field at Ejura.

I wish to express my profound gratitude to the Borlaug Higher Education for Agricultural Research and Development (BHEARD) for the scholarship opportunity to pursue a Ph.D. degree at Michigan State University. The BHEARD program allowed me to pursue my passion for addressing food security challenges in the face of climate change in Ghana and Africa as a researcher with the CSIR – Crops Research Institute.

I am grateful to the Alliance for African Partnerships (AAP), MSU for the financial support to conduct my field research. Sincere gratitude goes to the Co-PIs, Dr. Hashini Galhena Dissanayake (CANR and James Madison College, MSU), and Dr. Patricia P. Acheampong (CSIR – CRI), who assisted me with the economic analysis of my research. I am grateful to Dr. Princess Hayford for sharing her experiences in pigeonpea-sorghum research in Ghana and Mali, which was very useful for this study. Many thanks to Ms. Patricia Sutherland for the administrative assistance provided. The AAP also sponsored the Africa R&D Connect platform at MSU, which allowed me to connect with other Africans at MSU and connect with faculty members and students working in Africa to widen my professional network. Many thanks to Dr. Isaac Osei-Bonsu, my CSIR – CRI colleague and a fellow spartan, who assisted me in coordinating the Africa R&D Connect Seminar Series. I appreciate the spiritual nurturing environment the university SDA church provided during my stay in East Lansing.

Last but not least, special thanks go to my wife (Florence Owusu Danquah) and my children (Kwadwo and Agyeiwaah) for bearing with my absence during my studies. Many thanks to my parents, siblings, other family members, and friends for your continued prayer support and being part of this journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

BNF – Biological Nitrogen Fixation

CAADP – Comprehensive African Agricultural Development Program

TCRI – Crops Research Institute

CSIR – Council for Scientific and Industrial Research

ECEC – Effective Cation Exchange Capacity

EPIC – Environmental Policy Integrated Climate

FAOSTAT – The Food and Agriculture Organization Corporate Statistical Database

ICRISAT – The International Crops Research Institute for the Semi-Arid Tropics

ISFM – Integrated Soil Fertility Management

IER – Income Equivalent Ratio

LER – Land Equivalent Ratio

MoFA – Ministry of Food and Agriculture, Ghana

OC – Organic Carbon

PA – Pigeonpea in Alley

PB – Pigeonpea as Border plant

PPMED – Policy Planning, Monitoring and Evaluation Division, MoFA, Ghana

SALUS – System Approach to Land Use Sustainable

SOC – Soil Organic Carbon

SOM – Soil Organic Matter

INTRODUCTION AND RATIONALE OF RESEARCH

In countries of West Africa, white yam (*Dioscorea rotundata* (L) Poir) is an important food security and a cash crop to smallholder farmers. Yam, one of the two major root crops produced and consumed in Ghana, is currently a major non-traditional export crop bringing in foreign exchange to the country. Ghana, since 2008 has ranked second in West Africa, Africa, and the world yam production, and contributing to about 16% to the National Agricultural Gross Domestic Product. Ghana is also the leading exporter of yam in Africa, contributing about 94% to exported yam from West Africa (Anaadumba, 2013). However, yam production faces constraints with soil fertility sustenance and stakes for staking. Yam is a heavy soil nutrient feeder that needs fertile soils, with a ton of yam extracting a reported 3.8-4.0kg/ha of N, 0.39-1.1kg/ha of P_2O_5, and 4.2-5.9kg/ha of K_2O (Ferguson and Haynes 1970; Le Buanec *et al*., 1972).

Staking is a significant contributing factor in the cost of yam production (Asante, 1996; Owusu Danquah *et al*., 2014). To address this constraint, farmers clear new areas yearly in search of fertile lands and stakes, leading to deforestation and soil degradation. The struggle for fertile lands and stakes, coupled with the increasing human population, has led to pressure on cropland and forestlands in the yam growing communities (Akwag *et al.,* 2010; Asante, 1996). As a result, the distances to fields farmers would typically want to use for yam production are farther away and more difficult to access, thereby increasing the drudgery associated with yam production. As a result, farmers tend to grow yam on non-fallowed infertile land leading to reduced yields (Akwag *et al.,* 2010; Otoo, 2001; Ennin *et al*., 2014). Currently, across all yam varieties, farmers can only achieve just about 20% or 10t/ha of the potential yield of 50 t/ha (Frossard, 2017). Therefore, soil fertility maintenance with mineral fertilizer seemed to be a viable means of addressing this issue. The CSIR – Crops Research Institute of Ghana has suggested an optimum fertilizer rate of 45-45-60 N-P_2O_5-K_2O kg/ha for yam production on continuously cropped fields in the major yam growing areas of the forest-savannah transition zones of Ghana (Ennin *et al*., 2014). However, as pointed out by Kotschi *et al*., (1998), the use of mineral fertilizer alone has not promoted good soil health

Furthermore, it is becoming increasingly difficult for smallholder farmers who earn less than US $1per day to afford fertilizers. For these reasons, alternative ways of sustaining the soil for yam and other crop production is gaining more considerable attention (Otoo *et al.*, 2008; Garrity, 2004). While traditional organic materials such as crop residues and animal manure seemed to be cheap sources for soil amelioration, they are bulky and availability in most cases is limited in supply to offer a real alternative (Kotschi *et al*., 1998; Young, 1997; Diby, 2011). This study evaluates the adoption of leguminous shrub, pigeonpea, in the yam cropping system for sustaining soil fertility for yam production. The pigeonpea would provide readily available biomass for soil fertility improvement and stakes for the staking of the yam. Despite all the positive attributes of pigeonpea, as observed by Pinstrup-Andersen (1982), the adoption of any agricultural intervention depends on their usability and ability to meet the farmer's needs. Therefore, we depended on an earlier socio-economic survey on farmers' knowledge and willingness to adopt the pigeonpea-yam cropping system (Acheampong *et al*., 2019). This survey guided the designing and development of a cost-effective pigeonpea-yam cropping system that considers the local context, gender differences, and resource constraints. Working on the hypothesis that yam productivity would improve significantly with the inclusion of pigeonpea in the yam cropping system, the specific objectives of the study were to;

i. estimate N contribution from the biomass of the pigeonpea and implications on yam productivity in a pigeonpea-yam cropping system.

ii. stimulate long-term yam productivity in the pigeonpea-yam and implications on sustainable yam production on continuously yam cropped fields.

iii. evaluate the profitability of the pigeonpea-yam cropping system.

CHAPTER 1

LITERATURE REVIEW

Description of major species of yams in West Africa

Yams are a monocot (Monocotyledons) species, related to lilies and grasses. Native to Africa and Asia, yam tubers vary in size from that of potato from small to over 60 kg per tuber. It belongs to the genus *Dioscorea,* a large genus that contains important species used as food rich in carbohydrates (Mandal, 1993; Mignouna *et al*., 2009; Bai *et al*., 1998). In many parts of the world, and specifically in West Africa and the Pacific islands, *Dioscorea* is a primary staple food, and a food security crop (Coursey, 1967; Scott *et al*., 2000). The most famous and widespread species of yam cultivated and native to Africa include white or guinea yam (*Dioscorea rotundata*), yellow yam (*Dioscorea cayenesis*), and water yam (*Dioscorea alata*) (Aseidu *et al.*, 2008; Mignouna *et al*., 2007).

Dioscorea rotundata (white or guinea yam) is native to Africa and the most cultivated yam in Africa. The name emanates from the color of the fresh tuber, which is firm and white with a roughly cylindrical shape, whiles the skin is smooth and brown (Coursey, 1967; Akoroda, 1983; Demuyakor *et al*., 2013; Otoo *et al*., 2009). The yellow yam (*Dioscorea cayenesis*) is also native to Africa and has yellow flesh resulting from carotenoids (Kay, 1987; Hamon and Toure, 1990). Although most taxonomists now regard *D. rotundata* and *D. cayenesis* as the same species, the *D. cayenesis* has a more extended period of vegetation and a shorter dormancy than white yam (Sartie *et al*., 2012; Djeri *et al*., 2015; Asiedu *et al*., 2008). The growth period of both species is between 7 – 12 months (Ennin *et al*., 2016; Mandal, 1993).

Dioscorea alata (water or greater yam), another economically important yam, originating from Asia, has the most extensive distribution world-wide of any cultivated yam in Asia, the Pacific islands, Africa, and the West Indies (Mignouna and Dansi, 2003). Even in

Africa, the popularity of water yam is second only to white yam. Compared to white yam, water yam stores longer than white yam, making it a vital role in the food security niche. It is easier to propagate, grows vigorously to suppress weed, and can be grown without stakes (Sartie and Asiedu 2014; Obiediegwu *et al.*, 2009; Owusu Danquah *et al.*, 2014). Also, it has high protein content (7.4), starch (75-84%), crude fiber (2%), and vitamin C (13 – 24.7mg/100) than *D. rotundata* (Behera *et al.*, 2009; Oluwole *et al.*, 2017). Despite these attributes, *D. rotundata* has more preference and market value than *D. alata* due to *D. alata's* supposedly unattractive food quality traits, especially its less suitability for 'fufu' or pounded yam resulting from it lacking the favorite cohesive and elastic dough in fufu. Also, it is susceptible to pests and diseases, tubers lacking smooth and aesthetics making them unappealing to consumers in the market (Obidiegwu, 2009). Other yam species produced in fewer quantities globally include *D. esculenta* (Chinese yam) – native to China, *D. bulbifera* (aerial yam) – native to both Africa and Asia, and *D. dumentorum* (Bitter yam) – native to West Africa (Kay 1987; Schultz, 1993; Ike and Inoni, 2006; Coursey, 1967; Lebot, 2009).

Importance and significance of yam in West Africa and Ghana

Yam production in West Africa has food, social, and cultural values (Egesi *et al.*, 2007; Nweke, 2016: Nweke, 2019). The West African "yam belt" extends from Cote d'Ivoire to Nigeria and produces about 92% of the 50 – 60 million tons of global yam produced annually (FAOSTAT, 2019; Nweke, 2016). Yam is a significant food security crop and a major source of income for smallholder farmers (FAOSTAT, 2016; Wanyera *et al.*, 1996; Nweke, 2016). Currently, Ghana is the second-largest producer of yam in West Africa after Nigeria, with an estimated production volume of 7m tons since 2013, taking over from Cote d'Ivoire, which used to occupy this position (Figure 1.1; MoFA, 2017). Ghana is also Africa's leading exporter of yams, exporting over 94% of the total yam exports from West Africa (Anaadumba, 2013).

Ghana's yam export increased from US$ 32.6 million in 2017 to US$ 38 million in 2018 (Ghana Export Promotion Authority (GEPA) report, 2019).

Constraints of yam production

Among the significant challenges of yam production are soil fertility regeneration, scarcity of stakes for staking, Seedbed preparation, and high cost of seed yam (Akwag *et al.*, 2010; Ennin *et al.*, 2014).

Soil fertility regeneration

Yam is a heavy soil nutrient feeder, and as a result, farmers move to new lands each year in search of fertile lands and stakes, leading to deforestation. This struggle for fertile land coupled with increasing human population has led to pressure on cropland and forestland in the yam growing communities (Ennin *et al.*, 2014; Asante, 1996; Ekanayake and Asiedu, 2003). The length and quality of fallowed land and available fertile land keeps reducing. The distance to yam fields is increasing and becoming harder to access. As a result, farmers often do not have a choice except to grow yam on non-fallowed land where pressure on land is intense. For example, in Sekyere-West and Ejura-Sekyedumasi districts of Ghana, major yam growing areas, the forested land before 1983 was 782km^2, it was predicted to decrease to 78.2km^2 in a decade whiles the grasslands would increase from 1337km^2 to 2247km^2 in the same period (Akwag *et al*., 2000). MoFA report 2017 revealed agricultural lands between 1975 and 2000 increased from 13% to 28% of the total land area cover. As of 2013, agricultural land has reached 32% and keeps increasing due to agriculture expansion.

Staking

Staking is an essential practice in yam production; it exposes the leaves and vines to sunlight and helps increase photosynthetic efficiency resulting in high tuber yields. Diby *et al.*, 2011, observed in a study that the higher leaf area index of water yam (*D. alata*), as compared to white yam (Dente) (*D. rotundata*), served as an advantage to capture sunlight to produce more yields. The stakes also lift the leaves and vines from the ground to reduce soil-borne diseases (Ndegwe, 1990). Otoo *et al*. (2008) observed a significant increase in tuber yields between 45 – 56% in staked white yam (*D. rotundata*) varieties compared to their non-staked counterparts. Diseases such as leaf spot were very severe on the non-staked white yam contributing to the reduction in tuber yields. A similar study evaluated the various staking options, including no staking, staking practiced by farmers/optimum staking, and trellis staking and a 50% number of stakes on white yam and water yam varieties. The findings indicate that the no-staking option resulted in a significant reduction of tuber yields of white yam. Also, the mosaic virus significantly affected the no-staked white yam; thus, accounting partly for the reduction in tuber yields (Owusu Danquah *et al*., 2014; Ennin *et al*., 2014). As such, staking is crucial to yam productivity and a significant component of the cost of yam production. Farmers would, therefore, cut trees and shrubs in search of stakes for their yam production, contributing to deforestation and land degradation. In Ghana, the forest-savanna transition and the guinea savanna zones produce the most quantity of yam. In the forest-savannah transition zone, farmers leave selected trees and shrubs as stakes. Most trees die and get weak upon burning, but farmers continue to use them as stakes (Asante, 1996; Wholey and Haynes, 1971). In the guinea savannah, where stakes are scarcer and more difficult to obtain, farmers cannot provide support for their yams, thereby affecting yields (Asante, 1996).

Seedbed preparation

Seedbed preparation is also a significant constraint in yam production. The approach to cultivating yam involves preparing mounds, and this approach of land preparation is labor-intensive and time-consuming, adding to the drudgery associated with cultivating yam (Ennin *et al*., 2014; Ekanayake and Asiedu, 2003). Yam is often referred to as a “man’s crop” due to the effort required to cultivate the crop. Land clearing and mounding are done solely by men in almost all yam-growing areas. Women only cut setts and put them on the mounds for the men to plant (Nweke *et al*., 1991; Baudoin and Lutaladio, 1998). Tetteh and Saakwa (1991) observed mounding to be the highest cost of operation in the production of yam for the savannah and transition zones of Ghana. It is to address this constraint that resulted in the promotion of mechanized ridging as an alternative. On mounds, only about 5,000 to 6,000 plants per hectare are achieved compared to about 9,000 to 10,000 plants per hectare achieved with ridging (Ennin *et al*., 2014; Anchirinah *et al*., 1996).

Fertilizer application also significantly increases tuber yields by about 30% on ridges than on mounds. Ridges are more favorable to mounds when it comes to other farm operations such as weeding, fertilizer application, and harvesting (Eninn *et al*., 2009; Ennin *et al*., 2014). As yam is a heavy nutrient feeder, a recommended fertilizer rate of 45-45-60 $N\text{-}P_2O_5\text{-}K_2O$ kg/ha is optimum to sustain yam production on continuously cropped fields (Ennin *et al*., 2014; Ennin *et al*., 2016). However, for smallholder farmers who earn less than US $1per day, purchasing fertilizer to improve yam yields is not a viable option. Therefore, it is becoming increasingly apparent that farmers need alternative ways of sustaining soil fertility for yam and other crop production (Garrity 2004). Besides, the use of mineral fertilizer alone does not promote good soil health (Kotschi *et al*., 1998). Although traditional organic material such as crop residue and animal manure are cheap sources for soil amelioration, its availability in most cases is limited in supply to offer a real alternative (Kotschi *et al*., 1998; Young, 1997; Diby, 2011). It appears increased yam production is directly linked to the area under cultivation. Figures from PPMED (2007), of the Ministry of Food and Agriculture, Ghana indicate that yam production in Ghana increased by 51.6% with a corresponding increase in area under cultivation of about 53.6% during the same period, suggesting that, a 1% increase in area under yam cultivation lead to a corresponding 1% increase in yam productivity. While the potential yield for yam across variety is estimated to be about 52Mt/ha, farmer's fields only reach about 33.5% of this potential (MoFA, 2017). These figures call for technologies that would address the problem of deforestation associated with yam production by sustaining soil fertility and the provision of stakes, especially on continuously cropped fields.

General description of pigeonpea

Pigeonpea [*Cajanus cajan* (*L.) Millsp*.] belongs to the family Fabaceae, tribe Phaseoleae subtribe *Cajaninae* and genus *Cajanus* (Sharma and Green, 1980; Singh and Oswalt, 1992). The plant is an erect woody shrub with branching. It has a robust taproot system, and harvest duration depends on the variety. Pigeonpea can grow up to a height of about 1 – 2m, and 3 – 4m when used as perennials in the cropping system (Singh and Oswalt, 1992; Mula and Saxana. 2010). The origin of pigeonpea has led to a significant dispute among historians. Vavilov (1951) argued that the plant originated in India based on the crop's genetic diversity. Plukenet (1692) reported that the plant originated from Barbados, based on its use as animal feed, while others considered the plant to have originated from Eastern Africa since it occurred there in the wild form (Zeven and Zhukovsky, 1975). An extensive review by De (1974) and Vernon Royes (1976) suggest India as the primary center of origin and Africa, the secondary center of origin of pigeonpea. At present, several countries in the tropics and subtropics cultivate pigeonpea. Pigeonpea can be cultivated in a broad range of conditions and soil types because it is drought tolerant with an ability to use residual moisture during the dry season

(Phatak *et al*., 1993; Mullen *et al*., 2003; Cook *et al*., 2005; Mula and Saxena, 2010). The only known cultivated food crop of the 32 species that fall under the *Cajaninae* sub-tribe is pigeonpea. Pigeonpea takes up about 5% of the world's total legume production (Hillocks *et al*., 2000; FAOSTAT 2019: Young *et al*., 2003), with India producing around 70% and East Africa about 18% (FAOSTAT, 2019). Production in Africa is mainly in East Africa, with an average yield of about 718 Kg/ha. An increase in production has been observed recently in East Africa, but this is mainly due to expansion in area under cultivation than an increase in productivity (Jones *et al*., 2002; Damaris, 2007). Indigenous or wild varieties are highly photoperiod sensitive (McPherson *et al*., 1985), and they take about 175 to 280 days to reach maturity. Improvement work mainly by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) on pigeonpea resulted in the development of early, medium, and long maturing lines. These new lines mature in about 110-150 days, 150 - 200 days, and 220 – 270 days for short, medium, and long duration lines, respectively (Saxena *et al*., 2007; Kananji *et al*., 2009; Mula and Saxena, 2010). These lines are also relatively insensitive to the photoperiod compared to the indigenous or wild accessions (Saxena *et al*. 2007).

Pigeonpea and its role in addressing constraints in yam production

With their ability to fix biological nitrogen, sustainable cropping systems often use leguminous crops and shrubs as a significant constituent, an approach that could also benefit yam cultivation (Ennin and Dapaah, 2008; Asafu-Agyei *et al*., 1997; Kombiok *et al*., 1997; Eze, 2010). The proposed study adopts integrated soil nutrient management with leguminous shrub - pigeonpea (*Cajanus cajan*) for sustainable yam production. The drought-tolerant nature of pigeonpea and its ability to adapt to a wide range of soils suggests its suitability for sustainable farming and soil fertility management in Africa (Adjei-Nsiah, 2012; Troedson *et al*.,1990; Damaris, 2007). Compared to other legumes, the ability to adapt to drought results from its unique character traits of the deep taproot system of the plant, which allows it to withstand severe drought conditions. As such, pigeonpea could give some grain yields under conditions when other legumes such as cowpea and field beans dry up and will not yield (Valenzuela and Smith, 2002; Flower and Ludlow, 1987; Subbarao *et al*., 2000).

Pigeonpea can maintain photosynthetic functions under stress conditions. Its distinct polycarpic and flowering ability enables pigeonpea to protect the reproductive structures and produce yields better than other legumes (Lopez *et al*., 1987; Mligo and Craufurd, 2005). Thus, pigeonpea could be a valuable crop that could protect smallholders against total loss and food insecurity (Snapp, 2003; Snapp 1998). Also, the grains of pigeonpea can serve as an additional source of income and nutrition to smallholder farmers as its grains are nutritionally well balanced and are an excellent source of protein (20–30%), carbohydrates, and high levels of vitamins A and C (Snapp, 2003). The plant's ability to fix atmospheric nitrogen makes it very useful in crop production, especially for smallholder farmers. Although abundant in the atmosphere, nitrogen is considered the most limiting nutrient in crop production (Vance, 2001). Pigeonpea can fix about 235 kg N/ha and produces more N per unit area from its biomass than other legumes (Peoples *et al*., 1995; Giller and Cadisch, 1995). However, differences in the N contribution from pigeonpea grown in different locations have been observed. Through biological nitrogen fixation, pigeonpea contributed 38 – 117 kg N/ha and 6 – 72 kg N/ha in pigeonpea – maize intercropping systems in Malawi and Tanzania, respectively (Adu-Gyamfi *et al*., 2007). Phiri *et al*., (2013) using the long term (about eight months maturity duration) and medium-term (about six months maturity duration), pigeonpea as intercrop also observed biomass of about 2 – 2.6 t/ha which contributed about 49.6 – 50.6 kg/ha N to the soil. Gwenembia (2015), using a medium maturing pigeonpea variety observed an above-ground biomass yield of 11.83 Mg/ha, 6.99 Mg/ha, 5.08 Mg/ha and 3.57 Mg/ha for sole pigeonpea, pigeonpea – groundnut intercrop, pigeonpea – soybean intercrop and pigeonpea – maize intercrop, respectively. The slow initial growth nature of the plant makes it a good companion crop for integration into cropping systems (Snapp, 1998). Due to the extensive root system of especially the late-maturing pigeonpea, it improves the nutrient cycling efficiency for the benefit of the associated crops in the cropping system (Snapp, 1998). It also can form root symbiotic associations and secretion of organic acids from its roots, improving the uptake of P even from soils with fixed P (Otani *et al.*, 1996; Vance, 2001). In a study where pigeonpea was used as a preceding crop and plowed into the soil before planting the yam, there was a significant increase in yam tuber yields. When yam followed pigeonpea as a preceding crop, tuber yields were higher, and yields from 3t/ha poultry manure and 15-15-20 kg/ha $N\text{-}P_20_5\text{-}K_20$ was similar to the yields when manure and fertilizer were doubled to 6t/ha and 30-30-40 kg/ha $N\text{-}P_20_5\text{-}K_20$ (Ennin *et al.*, 2013). Although this unique leguminous shrub can be used in soil fertility management, it has received little research attention, especially in West Africa. Therefore, pigeonpea falls into the category of "orphan crops" (Naylor *et al*., 2004; Damaris, 2007). Kumar Rao and Dart (1987) and others observed the ability of the long- to medium-maturing varieties of pigeonpea to fix more N and produce more biomass than early maturing varieties. This biomass attribute presents a unique opportunity for its use in cropping systems such as white yam, which takes about 8 – 12 months, depending on the variety to maturity (Ennin *et al.*, 2016). As such, we believe that the adoption and use of the long and medium maturity varieties of pigeonpea as perennials in a yam cropping system would provide biomass and readily available stakes to smallholder farmers for sustainable yam production in Ghana and West Africa.

Knowledge of the use of pigeonpea in cropping systems in Ghana

Farmers’ knowledge, perceptions, and importance attached to a crop, tree/shrub, and technologies are fundamental towards the adoption of agricultural technologies (Pinstrup Andersen, 1982; Feder and Umali, 1993). Farmers in West Africa are used to intercropping or rotating legumes such as cowpea, groundnut, and Bambara groundnut with cereals (maize, sorghum, millet and guinea corn). However, the cultivation of a legume such as pigeonpea known to fix more N per unit area is observed to be novel and negligible in Ghana despite its potential for soil fertility improvement and sustainable crop yields (People *et al*., 1995; Hayford, 2018; Adjei-Nsiah, 2012). Field research on pigeonpea in Ghana revealed a significant return of biomass to the soil, which resulted in increased soil carbon and yields of associated crops (Hayford, 2018; Agyare *et al*., 2002). In a farmer-field demonstration trial using cover crops for improved soil fertility management, farmers selected pigeonpea over mucuna (Adjei-Nsiah *et al*., 2007). Acheampong *et al*. (2019) observed in a socio-economic survey on pigeonpea-yam cropping system that a majority (75%) of yam farmers had no knowledge of pigeonpea and its use in cropping systems. However, they were willing to adopt upon alert on its importance for soil fertility and as a source of stakes for staking yams. The major bottleneck indicated by farmers to hinder the adoption of pigeonpea in their cropping system was the marketing of produce, land tenure, and access to high and early yielding varieties. Therefore, breeding and releasing improved varieties that meet farmers’ aspirations alongside offering participatory farmer demonstrations to showcase the potential of pigeonpea in cropping systems, was identified as the way forward towards adoption (Adjei-Nsiah *et al*., 2012; Acheampong *et al*., 2019). Thus, farmers, when educated on the potential benefits of integrating pigeonpea in their cropping systems and are encouraged to adopt it, pigeonpea would play a vital role in soil fertility sustenance and food security.

Intercropping and crop productivity

In Africa and Asia, intercropping, the practice of growing two or more crops together in the same field at a given time, is common and is more productive than monoculture (Morris and Garrity, 1993; Sakala, 1998). Intercropping results in increased productivity compared to the sole crops as a result of complementary use of resources, where the different crop components explore resources at different niches for the benefit of another component crop(s) (Ofori and Stern, 1987; Rao and Singh, 1990; Willey, 1990). Thus, interactions between crop species in a field for both below ground and above ground resources result in competition or facilitation between or among the crops (Vandermeer, 1990; Rao *et al*., 1997). When species in a cropping system share the same or similar resources, and a crop interacts negatively or interferes with the growth and development of the other, it is described as competition and reduced productivity. For example, Budelman (1990) evaluated the effect of growing three leguminous perennials – *Leucaena leucocephala*, *Flemingia macrophylla,* and *Gliricidia sepium,* on the yield of yams. The study found that given the high root density of the *L. leucocephala* at the upper soil stratum, it competed with the yam. Simultaneously, the weak insufficiently lignified branches of the *F. macrophylla* could not support the yam leaves and vines, resulting in reduced tuber yields. However, because *G. sepium's* roots do not compete with the yam and its lignified branches could hold the yam leaves and vines, the study found intercropping *G. sepium* with yam to improve tuber yield than *L. leucocephala and F. macrophylla*. Another study by Simpson (1999) found that soybean yield was severely affected when intercropped with maize, due to shading, small shallow root systems, and inherently low water use efficiency. However, another soybean-maize intercrop study observed that it facilitated a higher photosynthetic active radiation capture by soybean-maize intercrop than their respective sole crop. This higher capture resulted in a significantly ($P \leq 0.05$) higher dry matter productivity on the soybean-maize intercrop than their corresponding sole crops (Ennin *et al.*, 2002). The example of *G. sepium*-yam and soybean-maize intercrop above are examples of facilitative interaction. A facilitative interaction is when one crop in an intercropping system exerts a positive influence on the other crop’s growth. The positive influence could be providing soil nutrients or a conducive microclimate. Zhang and Li (2003) compared yield advantages of a set of cereal-legume cropping systems and observed interspecific facilitation in maize-peanut intercropping, where maize improved the iron nutrition of peanut. The nitrogen and phosphorus uptake by intercropped maize was enhanced by faba bean whiles P uptake by associated wheat from phytate-P was facilitated by chickpea. Furthermore, Li *et al.* (2001) evaluated the yield advantage, N, P, and K uptake by wheat, maize, and soybean in an intercropping system. They found that the yields and nutrient uptake of intercropped wheat, maize, and soybean were significantly higher than in their sole cropping systems.

Crop arrangement

Agro-ecological and adaptive management practices are essential for sustainable intensification and crop production. The cultivation of woody trees/shrubs in specific intercropping combinations with food crop species enhances resource use efficiency in agro-ecological systems (Young, 1997; Ong 1991). Strategies for growing crop/s and woody trees together can be in mixed, strip, and relay to increase resource use efficiency and facilitation in cropping systems to increase crop productivity.

In mixed intercropping, crops and woody tree species are grown together at the same time in a field without any spatial arrangement. In contrast, in strip intercropping, the crop/s and woody tree species are grown simultaneously in separate but adjacent rows or strips. On the other hand, relay intercropping involves planting the crop/s and woody species together in a staggered arrangement such that only parts of the life cycle of the crop species overlap (Bybee-Finley and Ryan, 2018: Young, 1997). The improvement in resource use efficiency in intercropping systems results from the increase in total above and below-ground resource capture (sunlight, water, and nutrients) of the crop/s and the woody trees (Ong, 1991; Young, 1997). The addition of organic inputs from the woody trees or crops intercepts and reduces run-off to prevent erosion. Also, the liter fall and root turn-over improve nutrient cycling and retention in the cropping system for the benefit of associated plants (Rao *et al*., 1998; Ong, 1996). The use of mineral fertilizer only does not promote soil and environmental health and has been observed not to be efficient in yam production. Hgaza *et al.* (2012) observed a maximum recovery of just 30% of N fertilizer in yam tuber, leaving the rest to go waste and to the environment. Therefore, intercropping or rotating yams with legume crops or woody perennials have been observed to be the way forward in supplying N, improving nutrient cycling, and increasing yam productivity (Frossard *et al*., 2017; Ennin *et al*., 2013; Maliki *et al*., 2012a).

Intercropping yam with *Gliricidia sepium*, a woody legume improved biological nitrogen fixation and provided live stakes for the yam vines to climb (Budelman, 1990; O'Sullivan *et al.,* 2008). Substitutive and Additive series crop arrangements are the most used approaches in Agriculture studies for arranging mixed crop components in intercropping systems (Hamilton, 1994; Geno and Geno, 2001). In the substitutive/replacement approach, proportional populations of each crop component in the polyculture are related to the population of the sole crop. However, the population of the component crops should always add up to 100%. Whiles in the additive/superimposed approach, the component crops are planted in the same fields using the optimum planting density of the sole crops such that the final population of the polyculture is generally more than the planting densities of the sole crops. Thus, the constituent monoculture crop population compared to the intercrop population is used in distinguishing between the arrangement approach used. For example, if two crop components are involved in a substitutive/replacement approach, the bi-culture population of each crop component would be a percentage of the population of the monoculture. Whiles in the additive/superimposed series, the bi-culture has the same population of each crop as in their monoculture (Bybee-Finley and Ryan, 2018; Gebru, 2015; Cousens, 1996). The substitutive method is useful for evaluating of weed-crop interactions, competition, and yield advantage in intercropping (Rodriguez,1997; Firbank and Watkinson, 1990). With the substitutive intercropping, the population of each component crop is adjusted down with the intention that if one plant all the component crops with optimum population, competition for above ground (sunlight) and below ground (water and nutrients) resources would result in the low overall productivity of the cropping system. However, Sullivan (2003) observed that the challenge would be determining the optimum planting density for each component crop in the mixture. In the additive approach, the challenge will be in dealing with competition for resources and the practicality of combining the component crops at their optimum populations on the same unit area as the sole crops.

Evaluation of intercropping systems

Several intercropping efficiency indicators exist, such as the Relative yield total (RYT), Area Time Equivalency Ratio (ATER), Protein production, and Financial Returns. The most widely used indicator of efficiency in intercropping systems is the Land Equivalent Ratio (LER). It is the total area required under sole cropping to give the yields obtained in the intercrop. That is a summary of ratios of yields of intercrop to the yield of the sole crop. When LER is greater than one (1), it means there is a yield advantage for using intercrop. LER equal to 1 means no gain or loss in using intercrop whiles less than one means yield loss for using intercrop (Willey 1985; Ofori and Stern, 1987). The LER may overestimate the advantages of intercropping, where one component crop can be harvested early, leaving the other to occupy the whole land as a sole crop. Besides, LER does not compare and account for differences between the yield obtained with the potential yield. As such, it does not indicate whether the yield is higher or lower than the potential yield of the crop/s (Willey, 1979). Fukai and Trenbath (1993) observed that the best productivity from an intercrop could be obtained if the component crops differ significantly in growth duration so that their optimum requirement for growth resources occur at different times.

Factors influencing N fixation and dynamics

Intercropping of cereals and other crops with legumes is an ancient practice with the potential benefit of maximizing the use of resources such as sunlight and nutrients. It is a prevalent practice, especially in the tropics, to address soil fertility loss in the face of limited access to inorganic fertilizers (Willey, 1990; Morris and Garrity, 1993). The leguminous crops and shrubs in cropping systems fix N and improve soil nutrition by incorporating their biomass to benefit the associated crops (Ennin and Dapaah, 2008; Asafu-Agyei *et al.*, 1997; Kombiok *et al*., 1997; Budelman, 1990). However, the crop species used (Dakora and Keya, 1997; Eaglesham *et al.,* 1982), agronomic management (People *et al*., 1995), plant species morphology (Wahua and Miller, 1987), and the planting density of legumes in the mixture and competitive ability of the associated crops (Fujita *et al*., 1992; Danso *et al.,* 1987) among others, influence the quantity of nitrogen fixation in the cropping system. Through the biological nitrogen fixation (BNF), seasonal grain legumes and tree legumes fix about 43 – 58 kg N/ha and 15 – 210 kg N/ha respectively for sustainable crop production in Africa (Dakora and Keya, 1997). Eaglesham *et al*. (1982) observed that although cowpea fixed less N compared to soybean, its residue, left on the soil, contributes more N than soybean. Soybean has a high harvest index for N, resulting in loss of more N in the harvested seeds than the N left in the soil and the residue. Peoples, *et al*. (1995) observed that sufficient Nitrogen-fixing symbioses between legumes and their N_2 – fixing bacteria (rhizobia) is affected by the environmental factors, which is also greatly influenced by management practices. There is a strong influence of soil management practices on the absence and presence of enough effective rhizobia in the soil for N-fixation. Biological Nitrogen Fixation (BNF) is an adaptation strategy used by leguminous crop species to obtain N for growth and development. Increasing soil mineral N through management practices limits the presence of effective rhizobia. As such, there is reduced BNF due to the presence of less nodulation and nitrogenase activity (Peoples *et al*., 2009; Wahab *et al*., 1996; Herridge *et al*., 1984; Purcell and Sinclair, 1990).

Wahua and Miller (1978) observed that in sorghum – soybean cropping system with a taller sorghum variety, N fixation at the early stage of podding, was reduced by 99% while yields were reduced by 75%. The shading effect from the tall sorghum affected the podding, and yield. Also, the difference in nitrogen-fixing and non-nitrogen-fixing associated crop root morphology and depth can influence their different abilities to use soil N (Chalk, 1985). Increasing planting density of faba beans either as a sole crop or intercropped with barley increased competition for N, which results in an increasing proportion of the fixed N in the faba beans. The density effect was more pronounced in the intercrop barley field than sole faba bean fields (Danso *et al*., 1987). Fujita *et al*., 1992 observed that the intermingling of root systems transfers N through, and therefore, the distance between the cereal and legume root systems is vital for the interaction. However, the most effective planting distance varies with the type of legume and cereal. Corre-hellou *et al*. (2006), using a pea–barley intercrop, found that, in the intercrop, barley competed strongly for soil N with competition increasing steadily during the vegetative phase. This stiff competition from the barley for soil N influenced the N fixation response of the pea and the quantity of N used by the pea. Using an optimum arrangement of plants and pruning of the above-ground structures could address the shading of associated crops in an intercropping system. The pruned biomass, when added to the soil, could further increase soil nutrition.

Nitrogen-fixation in cropping systems

The main aim of intercropping with legumes is to fix N by the legumes for the transfer and benefit of the non-legume associated crops. There are interactions both above and below ground, that aid in the transfer of nutrients in the system. Ong *et al*. (1991) observed in alley cropping systems of the semi-arid tropics, that below ground interactions are more important than atmospheric or above-ground interactions. Fujita *et al*. (1990) observed that the inoculation of cowpea seeds used in cowpea–maize intercropping system increased nitrogen-fixation of the cowpea, and the N transferred to the associated maize crop. In a soybean–sorghum-intercropping system, 32–58% of total N of the sorghum planted at 0.125 X 0.125m was due to the nitrogen-fixation from the soybean. As such, the relative proximity of the legume and non-legume crops' root system is vital for ensuring N transfer between crops in cropping systems. The same study also observed N transfer to be high when other N sources such as the soil are limited. Thus, integration of pigeonpea into the yam cropping systems in Ghana and West Africa where soils are limited in N and other nutrients (Ennin *et al*., 2002) would aid the high transfer of N to yam. Using an isotopic method of ^{15}N abundance, Snoeck *et al*. (2000) show that about 30% of the N-fixed in a legume–coffee intercropping systems end up in the coffee. Nutrients included in a system are in the continuous dynamic transfer. Plants return their nutrients to the soil either through natural litterfall or deliberate pruning in agroforestry systems (Nair *et al*., 1995; Nair *et al*., 1998). The pigeonpea used in a pigeonpea–yam cropping system needs pruning to avoid a closed canopy. The biomass from pruning can be incorporated into the soil to contribute N to the system. The above and below ground interactions between the species and the associated crop are a significant determinant of crop yields, especially for root and tuber crops.

Methodologies for estimating N fixation in cropping systems

There are four main approaches used in the estimation of Biological Nitrogen Fixation (BNF) in the intercropping system. These are a) Total Nitrogen Difference (TND) b) Acetylene Reduction Assay (ARA) c) Ureide Xylem Sap technique, and d) ^{15}N labeling technique (Unkovich *et al*., 2008; Danso 1995). The Total Nitrogen Difference (TND) technique is the oldest approach used in BNF estimation. It estimates BNF as the difference between the total N fixed by a nitrogen-fixing plant and a non-nitrogen-fixing reference plant. This approach assumes that both the nitrogen-fixing plant and the non-nitrogen-fixing reference plant absorbs equal quantities of soil N for growth and development. This assumption requires that the physiological attributes, maturity period, root morphology, and root depth operations of the nitrogen-fixing plant and the non-nitrogen-fixing plants should be similar, but this is not always the case, hence a significant weakness of this approach (Danso *et al*., 1992; Rennie and Rennie, 1983). Despite this weakness, estimations using this approach compared with the more sophisticated and expensive methods revealed similar results (Hardarson *et al*., 1988; Hardy, 1973). Thus, the approach is simple and inexpensive when compared to others. However, because BNF is higher in soils and systems with low N, this approach is observed to give a more reliable result when plants are grown on soils with low initial N (Rennie, 1984; Patterson and LaRue, 1983). Also, the choice of reference crop affects the estimation of BNF, therefore a mutant non–nodulating version of a legume and more than one reference non-legume crops would help improve on the reliability of the results (Unkovich *et al*., 2008; Kermah *et al*., 2018).

The Acetylene Reduction Assay (ARA) is an indirect approach in estimating BNF pioneered by Hardy *et al*., (1968). The ARA focuses on the nitrogenase enzyme that catalyzes the reduction of acetylene to ethylene (Dilworth, 1966). Nitrogenase is the enzyme involved in N_2 fixation. Depending on the study's objective, the whole plant with nodules, root with nodules, or detached nodules is incubated in a gas-tight chamber containing 0.03 to 0.1% (v/v) acetylene for a period. After the period, the gas from the gas-tight chamber is injected into a gas chromatograph fitted with a P column and assayed for ethylene production. The quantity of ethylene produced is converted to a total amount of N-fixed by multiplying by a conversion factor of 3 (Unkovich *et al*., 2008). The technique's sensitivity and rapidity enable a large number of analyses per day to make it advantageous. However, the ARA technique measures BNF over a short duration whiles BNF in plants occurs over a very long duration. The method uses extrapolations to cover a more extended period, including periods where measurements are not taken but does not account for seasonal and other variations in BNF (Zapata *et al*., 1987a; Zapata *et al*., 1987b; Rainbird, 1983). Also, it is challenging to assess the active nodules of the plants, limiting field application of the technique resulting in variations in sampling and results (Vessey, 1994; Witty and Minchin, 1988). Due to these limitations, many researchers shy away from using this technique.

Herridge and Peoples pioneered the Ureide Xylem Sap approach on the assumption that an abundance of ureides relative to other N solutes provides an indirect measure of nitrogen-fixation (Herridge 1978; Peoples *et al*., 1989). The soil N absorbed by the plant is transported through the xylem to the shoot either as amides (asparagine and glutamine) or as ureides (allantoin and allantoic acid) (Peoples *et al*., 1989). The Ureide Xylem Sap approach determines the amount of N flowing through the xylem sap of the shoot or the N composition of the plant's tissue. Unkovich *et al*. (2008) suggested the analysis of the extracted xylem sap for Ureides or Amides and calibrated based on the plant type. This approach is less complicated and straight forward in comparison to the ^{15}N labeled approach. However, only a small proportion of nitrogen-fixing plants uses export ureides in their xylem, hindering the use of this approach in BNF estimations in most nitrogen-fixing plants (Danso, 1995; Unkovich *et al*., 2008).

The use of ^{15}N labeling approach explores the fact that the soils or medium in which nitrogen-fixing plants are grown have measurably different ^{15}N:^{14}N ratio from that of the almost constant ^{15}N:^{14}N ratio of 0.3663% in the atmosphere. Also, nitrogen-fixation and use by a plant will result in a different ^{15}N:^{14}N ratio in the plant tissue than the soil or medium in which it is grown (Danso 1993; Unkovich *et al.*, 2008). This approach has evolved with three main methods, namely, the use of ^{15}N – labeling gas, A – value, and ^{15}N Isotope techniques. Over, the years the of use ^{15}N – labeling gas, A – value techniques were proved to be impractical and associated with too many errors as compared to the ^{15}N isotope technique, resulting in the extensive use of the ^{15}N isotope technique in the estimation of BNF (Fried *et al.*, 1983; Danso *et al.*, 1993).

The ^{15}N isotope approach consists of the ^{15}N natural abundance and ^{15}N isotope dilution techniques. Both techniques use similar principles, where nitrogen-fixing and non-nitrogen-fixing reference plants are grown in either enriched or regular soil or medium and total soil ^{15}N analyzed, and the percentage of the atmospheric ^{15}N resulting from the atmosphere is estimated. The ^{15}N isotope dilution technique uses N enrichment of the soil or planting medium, whiles there is no enrichment of the soil or planting medium in the ^{15}N natural abundance approach. The ^{15}N isotope dilution technique was popular in the 1970 – 1990s before improving the use of mass spectrometry. Since the discovery and use of high – precision mass – spectrometry analysis, the ^{15}N natural abundance technique has been widely used in BNF estimations. However, where a high-precision mass spectrometer facility is not available, the recommended method is the isotope dilution technique (Peoples *et al.*, 1991; Unkovich *et al.*, 2008). The ^{15}N natural abundance technique considers that a non-nitrogen-fixing plant depends on the soil N when planted in soil medium. Therefore, the isotopic composition (^{15}N value) for a non-nitrogen-fixing plant would be similar to that of the soil N. In contrast, a nitrogen-fixing-plant could depend on the nitrogen available in the soil, and the atmospheric nitrogen fixed by the plant. Therefore, for a nitrogen-fixing plant, the isotopic composition (^{15}N value) of the plant tissue would reflect contributions from the atmospheric N_2 and the soil N. The exploitation of the differences in isotopic composition (^{15}N value) between a nitrogen-fixing plant and a referenced non-nitrogen-fixing plant with the equation below (Eqn. 1.1), provides an estimation of BNF (Unkovich *et al*., 2008).

$$\%Ndfa = \frac{(\delta 15N\ reference\ crop - \ \delta 15N\ legume)X\ 100}{(\delta 15N\ reference - B)} \qquad 1.1$$

Where %Ndfa – the percentage of N due to Biological Nitrogen Fixation (BNF); $\delta 15N$ – the natural abundance of reference crop or legume (pigeonpea); B - The smallest weighted value of reference crop (Unkovich *et al*., 2002).

The ^{15}N natural abundance technique is more applicable in the field and observed to be less prone to severe errors from the reference plants than other approaches. Also, aside from the BNF estimation, other useful agronomic details such as the N use efficiency of the reference plant, and the N transfer between plant components in a cropping system can be obtained at no extra cost.

Use of modeling and SALUS in cropping systems

The conventional approach of crop production functions in statistical analyses without reference to underlying biological and physical principles has contributed to the progress of studies of cropping systems and agricultural science. However, information obtained from this type of analysis is rather site-specific. Therefore, there is a limit to applying these functions to sites other than those with similar climate, soil, and crop management parameters to where the data and information are obtained (Oteng-Darko *et al*., 2013; Jones *et al*., 2017). It is common knowledge that even soils within a small area of land are heterogeneous (Farley and Fitter, 1999). Also, with climate variability and weather extremes, long-term (more than ten years) field data is required to develop statistical relationships that are useful in making agricultural decisions (James and Cutforth, 1996: Jones 1993; Jones *et al*., 2017). Field experimentation requires large amounts of resources and may not be able to provide enough information in space and time to make an appropriate and effective decision on management practices (Penning *et al*., 1992). Therefore, there is a need for adopting approaches that quantitatively combine the plant, soil, and climatic systems to make a more accurate prediction of growth and yields in crop production systems. Thus the use of modeling in crop production enables the development of sustainable land management options across diverse agro-ecological and socio-economic conditions (Penning *et al*., 1992; Jones 2017).

Crop models serve two primary purposes; for scientific understanding and decision/policy support (Van Ittersum *et al*., 2003; Ritchie, 1991). The crop models for scientific understanding tends to be more mechanistic and based on known physical, chemical, and biological hypotheses in an agricultural system. The model helps increase the scientific bases of agricultural systems, their interactions, and their responses. Examples of these models include the use of AgMIP for simulating maize and wheat yields (Van Ittersum *et al*., 1998; Jones *et al*., 2017; Asseng *et al*., 2013). The models for decision/policy support, on the other hand, describes how an agricultural system responds to the external environmental drivers' in response to the policy or decision under consideration. Thus, results from model help guide public policy processes, and the possible outcomes, should a particular decision be made (Van Ittersum et 1998; Thornton and Herrero, 2001; Basso *et al*., 2016). The most widely used crop models at present include; Decision Support System for Agrotechnology Transfer (DSSAT), The Agricultural Production Systems sIMulator (APSIM), The Environmental Policy Integration Climate (EPIC), The Agricultural Production System (CropSyst), Simulateur Multidisciplinaire pour les Cultures Standard (STICS), Root Water Quality (RZWQM), and System Approach to Land Use Sustainability (SALUS), (Asseng *et al*., 2014; Jones *et al*., 2003; Jones *et al*., 2016; FAO, 2015; Keating *et al*., 2003). These crop models used in agricultural systems guide field management decisions such as nitrogen application rate, response to N by crops, loss of the N to the environment (Asseng *et al*., 2001; Basso *et al*., 2016; Van Delden *et al*., 2003). Sowing decisions on best timing, cultivar to use, planting density to maximize yields and profit can be made with models (Asseng *et al*., 2008; Batchelor *et al*., 2002; Ritchie, 1991). Crop models can also guide decision making on nutrient use and dynamics, component interactions in rotation, and intercropping systems (Corre-Hellou *et al*., 2009; Adiku *et al*., 1998).

The Systems Approach to Land Use Sustainability (SALUS) model, used in this study, was developed by the Michigan State University (MSU). The model contains crop growth modules, SOM and nutrient cycling modules, and soil water balance and temperature modules. It simulates not only the effects of climate and management on the water balance, SOM, and N and P dynamics, but also heat balance, plant growth, and plant development. (Basso *et al*. 2006, Basso *et al*., 2010; Basso and Ritchie 2015). It operates on the principle that; potential crop growth is influenced by intercepted sunlight by using solar radiation data and Leaf Area Index (LAI) and account for limitations resulting from nitrogen and water. In crop growth simulations, the genetic coefficients and climate data (daily solar radiation, precipitation, and air temperature) are the primary external inputs required. Though the SALUS is similar to the DSSAT family of models, it simulates not only crop yields in cropping systems, but also water, nutrient dynamics, and soil as influenced by management strategies over the years. In a simulation, the SALUS model considers the effect of rotation, tillage practice, planting date, planting density, irrigation, and fertilizer applications. Therefore, the use of SALUS modeling would enable the simulation of management scenarios of using pigeonpea biomass and other soil amendments in yam production. Also, in making the right decisions for sustainable yam production, the long-term effect of integrated amendments on soil and implications on yam production can be simulated to serve as a guide.

Use of model in yam production

While research on yam using crop models is limited, modeling approaches in studying the physiology and yield in yams (*Dioscorea spp.*), would enable a greater understanding of the influence of various ecological and biotic factors on the production of yam. The model would also permit the prediction of yield under various conditions to serve as a tool in the evaluation of soil amendment options in sustaining yam production (Onwueme and Haverkort, 1991). Srivastava (2010) modeled the effect of fertilizer and fallow land availability for water yam (*Dioscorea alata*) and white yam (*Dioscorea rotundata*) production in the bush savannah of the republic of Benin using Environmental Policy Integrated Climate (EPIC) model. At the time, the best scenario under the prevalent cropping patterns for tuber yields was the assumption that 50% bush savannah was available as a fallow. Since population increase has put pressure on the land and therefore the 50% of bush savannah as a fallow is not feasible, the study recommended using mineral fertilizer as an essential option for sustaining yam production. However, because of the high cost of mineral fertilizers, farmers are not able to afford them. Therefore, fertilizer subsidy from the government and integration of legumes into yam cropping systems was suggested as the way forward. In another study evaluating the effect of climate variability and CO_2 on the productivity water yam (*Dioscorea alata*) on three soil types in the savannah zones of West Africa, Srivastava (2012) observed a decline of about 33% in tuber yields of yam upon increasing the ambient CO_2 concentration to 350 ppmv. “Ferruginous” soil type was the most vulnerable to climate change followed by “Ferralitic” and “Raw mineral soil” with a projected decrease in yam productivity of about 48%, 36%, and 33%, respectively, in a decade. The study concluded with a strong recommendation of including management options in the evaluation of the climatic variables. Using a model proposed for modeling the growth of potatoes on yam, Marcos *et al.*, (2009 & 2011) showed the relationship between sink and source in yam and its influence on tuber bulking. The leaf area and level of radiative use efficiency control sink and source in yam and its influence on tuber bulking. Thus, both photoperiod and temperature affect the development and yields of water yam (*Dioscorea alata*), especially between the emergence and tuber initiation stage. The study, therefore, recommended using modeling in yam growth and predicting yam yields to serve as a guide for management options. To assist researchers and other stakeholders in the physiology study of yam, Cornet *et al*. (2015), using the allometric model, has suggested a more acceptable and accurate approach for predicting leaf area and leaf biomass of *Dioscorea alata* and *D. rotundata* in different environments. A stochastic frontier production function studies on yam in Nigeria revealed that labor for land preparation and maintenance, distance to farm, and farming experience are significant factors influencing and reducing yam output. It was, therefore, recommended improvement in these factors would improve on yam productivity and income of smallholder farmers (Ojo, 2004).

APPENDIX

APPENDIX

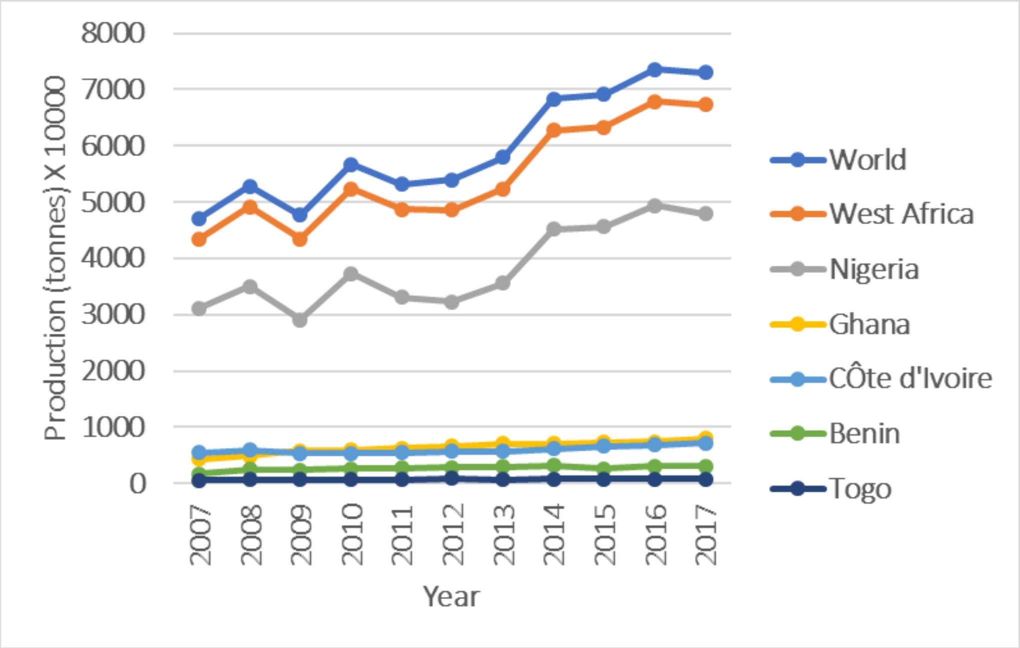

Figure 1.1: Yam production trends in major producing countries of West Africa and the world.
Source: Drawn by Author with data from FAOSTAT, 2019.
http://www.fao.org/faostat/en/#data/QC

REFERENCES

REFERENCES

Acheampong, P. P., Owusu Danquah, E., Dissanayake, H. G., Hayford, P and Weebadde, C. (2019). A socioeconomic study of transition zone yam farmers; Addressing constraints and exploring opportunities for integrating pigeonpea into yam cropping systems. *Sustainability* 11 (3): 717.

Adiku, S. G. K., Rose, C. W., Gabric, A., Braddock, R. D., Carberry, P. S., & McCown, R. L. (1998). An evaluation of the performance of maize and cowpea in sole and intercropping systems at two savanna zones of Ghana: a simulation study. In: Tijskens, L.M.M., Hertog, M.L.A.T.M. (Eds.), *International Symposium on Applications of Modelling as an Innovative Technology in the Agri-food-chain. Model-It. Acta Horticulturae* No. 476, International Society for Horticultural Science, Wageningen, Netherlands, pp. 251–262.

Adjei-Nsiah, S. (2012). Role of pigeonpea cultivation on soil fertility and farming system sustainability in Ghana. Hindawi Publishing Corporation. *International Journal of Agronomy*, vol. 2012,

Adjei-Nsiah, S., Kuyper, T. W., Leeuwis, C., Abekoe, M. K., & Giller, K. E. (2007). Evaluating sustainable and profitable cropping sequences with cassava and four legume crops: Effects on soil fertility and maize yields in the forest/savannah transitional agro-ecological zone of Ghana. *Field Crops Research*, 103(2), 87–97.

Adu-Gyamfi, J. J., Myaka, F. M., Sakala, W. D., Odgaard, R., & Høgh-Jensen, H. (2007). Nitrogen and phosphorus budgets and nitrogen fixation in farmer-managed intercrops of maize-pigeonpea in semi-arid Southern and Eastern Africa. *Plant Soil*, 259 (1–2): 127 - 136. *Agronomy* 4:677–688.

Akoroda, M. O. (1983). Flora biology and control in white yam. *Euphylytica*, 32: 831-838.

Akwag, A. A., Berchie, J. N., Echavez, M. L., Dapaah, H. K., Kebede, T., Njue, S. W., Paraoam, I., & Labrada, H. R. (2000). Sustainable farming practices – towards Reducing the Expansion of the Forest-Savanna Transition Zone of the Sekyere-West and Ejura Sekyeredumase Districts of the Ashanti Region of Ghana. International Center for Development Oriented Research in Agriculture and crops Research Institute, *Working Document Series* 86, Ghana.

Agyare, W. A., Kombiok, J. M., Karbo, N., & Larbi, A. (2002). Management of pigeonpea in short fallows for crop-livestock production systems in the Guinea savanna zone of northern Ghana. *Agroforestry Systems*, 54, 197–202.

Anaadumba, P. (2013). Analysis of incentives and disincentives for yams in Ghana. *Technical note series*, MAFAP, FAO, Rome.

Anchirinah, V., Ojha, R., Owusu-Sekyere, R., Ramnanan, N., Zhou-Sheng, K., & Zhan, S. K. (1996). Production and marketing of yams in the forest/savanna transition zone of Ghana. *Working document No.* 53, Ottawa, Canada: IDRC. 99 p.

Asafu-Agyei, J. N., Ahenkora, K., Banful, B., & Ennin-Kwabiah, S. (1997). Sustaining food production in Ghana: The Role of Cereal/Legume Based Cropping Systems. In Bezuneh, T. *et al* (eds.). 1997. Technology options for sustainable agriculture in Sub-Saharan Africa. *Publication of the Semi-Arid Food Grain Research and Development Agency (SAFGRAD) of the scientific, technical and research commission of OAU,* Ouagadougou, Burkina Faso. Pp 409-416.

Asante, A. K. (1996). Use of bast fibre plants as staking materials for yam production in the Guinea Savanna zones of Ghana. *Ghana Journal of Agricultural Science. National Science of and Technology Press* 28-29, 99-103.

Asiedu, R., Ng, S. Y. C., Bai, K. V., Ekanayake, I. J., & Wanyera, N. M. W. (1998). Genetic improvement. In: Orkwor, G. C., Asiedu, R., Ekanayake, I. J. (Eds.), *Food Yams: Advances in Research.* NRCRI and IITA, Ibadan, Nigeria, pp.63–104.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P. J., Rötter, R. P., Cammarano, D., & Brisson, N. (2013). Uncertainty in simulating wheat yields under climate change. *Nature climate change*, 3(9), p.827.

Asseng, S., Fillery, I. R. P., Dunin, F. X., Keating, B. A., & Meinke, H. (2001). Potential deep drainage under wheat crops in a Mediterranean climate. Temporal and spatial variability. *Australian Journal of Agricultural Research* 52 (1). 45 – 56.

Asseng, S., Milroy, S. P., & Poole, M. L. (2008). Systems analysis of wheat production on low water-holding soils in a Mediterranean-type environment: I. Yield potential and quality. *Field Crops Research,* 105(1-2), pp.97-106.

Asseng, S., Zhu, Y., Basso, B., Wilson, T., & Cammarano, D. (2014). Simulation modeling: Applications in cropping systems. In Neal Van Alfen, editor-in-chief. *Encyclopedia of Agriculture and Food Systems*. Vol. 5. San Diego: Elsevier 2014, pp. 102 – 112.

Bai, K. V., & Ekanayake, I. J. (1998). Taxonomy, morphology and floral biology. In: Orkwor, G.C., Asiedu, R., Ekanayake, I.J. (Eds.), *Food Yams: Advances in Research*. NRCRI and IITA, Ibadan, Nigeria, pp. 13–37.

Basso, B., & Ritchie, J. T. (2015). Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model. Pages 252-274 in S. K. Hamilton, J. E. Doll., & G. P. Robertson, (ed). *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability. Oxford University Press,* New York, New York, USA.

Basso, B., Cammarano, D., Troccoli, A., Chen, D., & Ritchie, J. T. (2010). Long-term wheat response to nitrogen in a rainfed Mediterranean environment: field data and simulation analysis. *European Journal of Agronomy* 33:132–138.

Basso, B., Dumont, B., Cammarano, D., Pezzuolo, A., Marinello, F., & Sartori, L. (2016). Environment and economic benefits of variable rate nitrogen fertilization in nitrate vulnerable zone. *Science of the total environment*, 545 – 546 (2016) 227 – 235.

Basso, B., Ritchie, J.T., Grace, P.R., & Sartori, L. (2006). Simulation of tillage systems in Ed. Baudoin, W. O., & Lutaladio, N. B. (1998). *Yam cultivation and Utilization for improved food security. FAO's Position paper,* Rome, Italy: FAO. 40p.

Batchelor, W. D., Basso, B., & Paz. J. O. (2002). Examples of strategies to analyze spatial and temporal yield variability using crop models. *European Journal of Agronomy* 18:141–158

Baudoin, W. O., & Lutaladio, N. B. (1998). Yam cultivation and utilization for improved food security. *FAOs position paper, Rome, Italy: FAO*. 40p.

Behera, K. K., Maharana, T., Sahoo, S., & Prusti, A. (2009). Biochemical quantification of protein, fat, starch, crude fibre, ash and dry matter content in different collection of greater yams (*Dioscorea alata L.*) found in Orissa. *Nature and Science*, 7(7), pp.24-32.

Budelman, A. (1990). Woody legumes as live support systems in yam cultivation II. The yam-*Gliricidia sepium* association. *Agroforestry Systems*, 10(1), pp.61-69.

Bybee-Finley, K., & Ryan, M. (2018). Advancing intercropping research and practices in industrialized agricultural landscapes. *Agriculture*, 8(6), p.80.

Chalk, P. M. (1985). Estimation of N_2 fixation by Isotope dilution: an appraisal of techniques involving ^{15}N enrichment and their application. *Soil Biology and Biochemistry* 17, 389 – 410

Cook, B. G., Pengelly, B. C., Brown, S. D., Donnelly, J. L., Eagles, D. A., Franco, M. A., Hanson, J. Mullen, B. F., Partridge, I. J., Peters, M & Schultze-Kraft, R. (2005). *Tropical forages: an interactive selection tool.* CSIRO, Australia.

Cornet, D., Sierra, J., & Tournebize, R. (2015). Assessing Allometric Models to Predict Vegetative Growth of Yams in Different Environments. *Agronomy Journal*. vol. 107, Iss. 1. 2015 pp. 241 – 248.

Corre-Hellou, G., Faure, M., Launay, M., Brisson, N., & Crozat, Y. (2009). Adaptation of the STICS intercrops model to simulate crop growth and N accumulation in barley intercrops. *Field Crops Research*. 113 (1), 72 – 81.

Corre-Hellou, G., Fustec, J., Crozat, Y. (2006). Interspecific Competition for Soil N and its Interaction with N_2 Fixation, Leaf Expansion and Crop Growth in Pea–Barley Intercrops. *Plant and Soil*. 2006, Vol. 282, Iss. 1–2, pp 195–208

Coursey, D. G. **(**1967). Yams. An account of the Nature, Origins, Cultivation and Utilization of the Useful Members of the *Dioscoreaceae*. *Tropical Agricultural Series. Longmans, Green and Co. Ltd. Londres,* UK. p. 230.

Cousens, R. O. G. E. R. (1996). Design and interpretation of interference studies: are some methods totally unacceptable. *New Zealand Journal of Forestry Science*, 26(1/2), pp.5- 18.

Dakora, F. D., & Keya, S. O. (1997). Contribution of legume nitrogen fixation to sustainable agriculture in Sub-Saharan Africa. *Soil Biology and Biochemistry*, Vol. 29, 5–6, 1997, Pg. 809-817.

Damaris, A. O. (2007). The potential of pigeon pea (*Cajanus cajan* (L.) Millsp.) in Africa. *Natural Resources Forum* 31 (2007) 297–305. Blackwell Publishing Ltd., 9600 Garsington Road, Oxford, OX4 2DQ, UK and 350 Main Street, Malden MA 02148, USA.

Danso, S. K. A. (1995). Assessment of biological nitrogen fixation. *Fertilizer research*, 42(1-3), pp.33-41.

Danso, S. K. A., Bowen, G. D., & Sanginga, N. (1992). Biological nitrogen fixation in trees in agro-ecosystem. *Plant and Soil* 141: 177–196.

Danso, S. K. A., Hardarson, G., & Zapata, F. (1993). Misconceptions and practical problems in the use of ^{15}N soil enrichment techniques for estimating N_2 fixation. *Plant and Soil* 152: 25–52.

Danso, S. K. A., Zapata, F., Hardarson, G., & Fried, M. (1987). Nitrogen fixation in fababeans as affected by plant population density in sole or intercropped systems with barley. *Soil Biology and Biochemistry*, 19(4), pp.411-415.

De, D. N. (1974). Pigeonpea. In Evolutionary studies in world crops: diversity and change in the *Indian subcontinent* (Hutchinson, J., ed.). Pg. 79-87. London, UK: Cambridge University Press.

Demuyakor, B., Dukrog, T. M & Chikpah, S. K. (2013). Yam germplasm in Ghana–A survey on varietal identification and characterization of *Dioscorea rotundata–alata* in northern region of Ghana. *Int. J. Agron. Plant Prod*, 4(4), pp.719-726.

Diby, L. N., Sangakkara, R, Tie, B. T., Girardin, O., & Frossard, E. (2011). Growth and nutrient use efficiencies of yams (*Dioscorea spp.*) grown in two contrasting soils of West Africa. *Hindawi Publishing Corporation International Journal of Agronomy*.

Dilworth, M. J. (1966). Acetylene reduction by nitrogen-fixing preparations from *Clostridium pasteurianum*. *Biochimica et Biophysica Acta (BBA)-General Subjects*, 127(2), pp.285-294.

Djeri, B., Tchobo, P. F., Adjrah, Y., Karou, D. S., Ameyapoh, Y., Soumanou, M. M., & Souza,C. (2015). Nutritional potential of yam chips (*Dioscorea cayenensis and Dioscorea rotundata Poir*) obtained using two methods of production in Togo. *African Journal of Food Science*, 9(5), pp.278-284.

Eaglesham, A. R. J., Ayanaba, A., Rao, V.R., Eskew, D. L. (1982). Mineral N effects on cowpea and soybean crops in a Nigerian soil. *Plant and Soil*. June 1982, vol. 68, Iss. 2, pp 183–192.

Egesi, C. N., Odu, B. O., Ogunyemi, S., Asiedu, R., & Hughes, J. (2007). “Evaluation of water yam (*Dioscorea alata L.*) Germplasm for reaction to yam anthracnose and virus diseases and their effect on yield,” *Journal of Phytopathology*, vol. 155, no. 9, pp. 536– 543, 2007.

Ekanayake, I. J., & Robert Asiedu, R. 2003. Problems and Perspectives of Yam-Based Cropping Systems in Africa, *Journal of Crop Production*, 9:1-2, 531-558.

Ennin, S. A., & Dapaah, H. K. (2008). Legumes in sustainable maize and cassava cropping systems in Ghana. *Agricultural and Food Science Journal of Ghana*. vol. 7:519-540.

Ennin, S. A., Clegg, M. D., Francis, C.A. (2002). Resource utilization in soybean/maize intercrops. African Crop Science Journal, 10(3), pp.251-261.

Ennin, S. A., Isaaka, R. N., Acheampong, P. P., Numafo, M., & Owusu Danquah, E. (2014). Mechanization, Fertilization and Staking Options for Environmentally Sound Yam Production. *African Journal of Agricultural Research*. vol. 9 (29) 2222-2230.

Ennin, S. A., Otoo, E., & Tetteh, F. M. (2009). Ridging, a Mechanized Alternative to Mounding for Yam and Cassava Production. *West African Journal of Applied Ecology*, vol. 15, 2009.

Ennin, S. A., Owusu Danquah, E., Acheampong, P. P. (2013). Chemical and Integrated Nutrient Management options for sustainable Yam production. Yams 2013. *First global conference on yams*. 3-6 Oct 2013, Accra-Ghana.

Ennin, S. A., Owusu Danquah, E., Frimpong, F., Akom, M., Osei-Adu, J., Lamptey, J. N. L., Oteng-Darko, P., Osei, K., Osman, A. S., Aidoo, A. K., Adama, I., Appiah-Danquah, P and Haleegoah, J. (2016). Yam Production and Marketing Guide. Eds. H. Adu-Dapaah, J. N. L. Lamptey, I. S. Banning, B. N. Frimpong, J. Osei-Adu and S. A. Ennin. *CSIR – Crops Research Institute.* Kumasi, Ghana.

Eze, S. C., & Orkwor, G. C. (2010). Studies on effects of mineral fertilizer, organic manure and cultivar on the yield and storability of Yam (*Dioscorea rotundata.* Poir). *African Journal of Food Agriculture, Nutrition and Development,* Vol. 10, No. 6, 2010, pp. 2755- 2771.

FAOSTAT. (2015). *FAO Statistics Division* 2015

FAOSTAT. (2016). *FAO Statistics Division* 2016

FAOSTAT. (2019). *FAO Statistics Division* 2019

Feder, G., & Umali, D. L. (1993). The adoption of agricultural innovations: a review. *Technological Forecasting and Social Change*, 43 (3-4), 215-239.

Ferguson, T. U., & Haynes, P. H. (1970). The response of yams (*Dioscorea spp.*) to nitrogen, phosphorus, potassium and organic fertilizers. *Tropical Root and Tuber Crops Tomorrow: Proceedings of the 2nd International Symposium on Tropical Root and Tuber Crops*. Plucknett, D. L, (ed.), Vol. I, pp. 93-96. Honolulu, Hawaii: College of Tropical Agriculture, University of Hawaii.

Firbank, L. G., & Watkinson, A. R. (1990). On the effects of competition: from monocultures to mixtures. On the effects of competition: *from monocultures to mixtures*., pp.165-192.

Flower, D. J., & Ludlow, M. M. (1987). Variation among accessions of pigeonpea (*Cajanus cajan*) in osmotic adjustment and dehydration tolerance of leaves. *Field Crops Res.*, 17 (3–4) (1987), pp. 229–243.

Fried, M., Danso, S. K. A., Zapata, F. (1983). The methodology of measurement of N_2 fixation by non-legumes as inferred from field experiments with legumes. *Canadian Journal of Microbiology*, 29(8), pp.1053-1062.

Frossard, E., Aighewi, B. A., Aké, S., Barjolle, D., Baumann, P., Bernet, T., Dao, D., Diby, L. N., Floquet, A., Hgaza, V. K., Ilboudo, L. J. (2017). The challenge of improving soil fertility in yam cropping systems of West Africa. *Frontiers in plant science*, 8, p.1953.

Fujita, K., Ofosu-Buadu, K. G., & Ogata, S. (1992). Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant and Soil*. 1992, vol. 141, Iss. 1–2, pp 155–175.

Fujita, K., Ogata, S., Matsumoto, K., Masuda, T., Ofosu-Budu, G. K., & Kuwata, K. (1990). Nitrogen transfer and dry matter production in soybean and sorghum mixed cropping system at different population densities. *Soil Science and Plant Nutrition*, 36(2), pp. 233-241.

Fukai, S., & Trenbath, B. R. (1993). Processes determining intercrop productivity and yields of component crops. *Field Crops Research*, 34, 247–271.

Garrity, D. P. (2004). Agroforestry and the Achievement of the Millennium Development Goals. In: Nair, *et al*. (eds) 2004. *New Vistas in Agroforestry*, Kluwer Academic Publishers, Netherland.

Gebru, H. (2015). A Review on the Comparative Advantages of Intercropping to Mono Cropping System. *Journal of Biology, Agriculture and Healthcare*. vol.5, No.9, 2015.

Geno, L., & Geno, B. (2001). Polyculture Production: Principle, benefits and risk of multiple cropping. *A report for the Rural Industry Research and Development Corporation (RIRDC), Publication*, No. 01134.

Ghana Export Promotion Authority (GEPA). (2019). Yams – Potential Market Report, 2019, *GEPA, Market Reports*, ACCRA, Ghana.

Giller, K. E., & Cadisch, G. (1995). Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant Soil* (1995) 174: 255–277.

Gwenembira, C. P. (2015). Below and above ground pigeonpea productivity in on-farm sole and intercrop systems in central Malawi. *Master's thesis*, Department of Plant, Soil and Microbial Sciences, Michigan State University.

Hayford, P. (2018). Evaluating water-use efficiency in Sorghum-Pigeonpea (*Sorghum bicolor l. moench-Cajanus cajan [l] millsp*.) diversified cropping systems in marginal areas of Ghana and Mali. *PhD. Thesis*, Department of Plant, Soil and Microbial Sciences, Michigan State University.

Hamilton, N. S. (1994). Replacement and additive designs for plant competition studies. *Journal of Applied Ecology*, pp.599-603.

Hamon, P., Toure, B. (1990). Characterization of traditional yam varieties belonging to the *Dioscorea cayenensis-rotundata* complex by their isozymic patterns. *Euphytica*, 46(2), pp.101-107.

Hardarson, G., Zapata, F., & Danso, S. K. A. (1988). Dinitrogen fixation measurements in alfalfa-ryegrass swards using nitrogen-15 and influence of the reference crop. *Crop Science*, 28(1), pp.101-105.

Hardy, R. W., Holsten, R. D., Jackson, E. K., & Burns, R. C. (1968). The acetylene-ethylene assay for N_2-fixation: laboratory and field evaluation. *Plant physiology*, 43(8), pp.1185-1207.

Hardy, R., Burns, R. C., & Holsten, R. D. (1973). Applications of the acetylene-ethylene assay for measurement of nitrogen fixation. *Soil Biology and Biochemistry*, 5(1), pp.47-81.

Herridge, D. F., Atkins, C. A., Pate, J. S., & Rainbird, R. M. (1978). Allantoin and allantoic acid in the nitrogen economy of the cowpea (*Vigna unguiculata [L.] Walp*.). *Plant Physiology*, 62(4), pp.495-498.

Herridge, D. F., Roughley, R. J., & Brockwell, J. (1984). Effect of rhizobia and soil nitrate on the establishment and functioning of the soybean symbiosis in the field. *Australian Journal of Agricultural Research*, 35(2), pp.149-161.

Hgaza, V. K., Diby, L. N., Oberson, A., Tschannen, A., Tie, B. T., Sangakkara, U. R., Aké, S., & Frossard, E. (2012). Nitrogen use by yam as affected by mineral fertilizer application. *Agronomy Journal*, 104(6), pp.1558-1568.

Hillocks, R. J., Minja, E., Nahdy, M. S., & Subrahmanyam, P. (2000). Diseases and pests of pigeonpea in eastern Africa. *International Journal of Pest Management*, 46: 7–18

Ike, P. C., & Inoni, O. E. (2006). Determinants of yam production and economic efficiency among small-holder farmers in south-eastern Nigeria. *J. Cent. Eur. Agric*.7(2):337 342.

James, Y. W., & Cutforth, H. W. (1996). Crop Growth Models for Decision Support systems. Canadian J. *Plant Science*. 76(1): 9-19.

Jones, J. W. (1993). Decision support systems for agricultural development. Pages 459–47 1 in F.W.T. Penning de Vries, P. Teng., & K. Metsellaar, (eds). *Systems approaches for agricultural development*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., & Keating, B. A. (2017). Brief history of agricultural systems modeling. *Agricultural systems*, 155, pp.240-254.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T., (2003). The DSSAT cropping system model. *European journal of agronomy*, 18(3-4), pp.235-265.

Jones, R., Freeman, H. A. & Monaco, G. L. (2002). Improving the access of small farmers in eastern and southern Africa to global pigeonpea markets. *Agricultural Research and Extension Network Paper No. 120 (No. 120)*. Agricultural Research & Extension Network.

Kananji, G. A. D., Mviha, P. J. Z., Siambi, M., & Silim, S. N. (2009). A Manual for pigeonpea production in Malawi. *Patancheru* 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Kay, D. E. (1987). Root Crops. London: Tropical Development and Research Institute.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargrea, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., & Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18(3-4), pp.267-288.

Kermah, M., Franke, A. C., Adjei-Nsiah, S., Ahiabor, B. D. K., Abaidoo, R. C., & Giller, K. E., (2018). N_2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. *Agriculture, ecosystems & environment*, 261, pp.201-210.

Kombiok, J. M., Dogbe, W & Kanton, R. (1997). Cropping Systems and Long-Term Soil Fertility Management for Sustainable Agriculture in Northern Ghana. In Bezuneh, et al (eds.). 1997. Technology options for sustainable agriculture in Sub-Saharan Africa. *Publication of the Semi-Arid Food Grain Research and Development Agency (SAFGRAD) of the scientific, technical and research commission of OAU*, Ouagadougou, Burkina Faso. Pp 417-424.

Kotschi, J., Waters-Bayer, A., Adelhelm, R. & Hoesle, U. (1989). Ecofarming in agricultural development (No. 630.2745 E18e). *Tropical Agroecology*. Weikersheim, DE: Margraf.

Kumar Rao, J. V., & Dart, P. J. (1987). Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea (*Cajanus cajan (L.)* Millsp) of different maturity groups. *Plant and Soil,* 99(2), pp.255-266.

Le Buanec, B. (1972). Absorption and uptake of major nutrients by yams. GERDAT. Groupement d'Etudes et de Rechèrche pour le Dévelopment de l'Agronomie Tropicale. IRAT. Institut de Rechèrches Agronomiques Tropicales et des Cultures Vivrières. Nogent-sur-Marne (Côte d'Ivoire) Reunion d'Agronomie de l'IRAT: 1974.

Lebot, V. (2009). Tropical Root and Tuber Crops Cassava, sweet potato, yams and aroids. *Crop production Science in horticulture Series*; 17; MPG books group.

Li, L., Sun, J., Zhang, F., Li, X., Yang, S., & Rengel, Z. (2001). Wheat/ maize or wheat/ soybean strip intercropping: Yield advantage and interspecific interactions on nutrients. *Field crops research*, *71*(2), pp.123-137.

Lopez, F. B., Setter, T. L., & McDavid, C. R. (1987). Carbon dioxide and light responses of photosynthesis in cowpea and pigeonpea during water deficit and recovery. *Plant physiology*, 85(4), pp.990-995.

Maliki, R., Toukourou, M., Sinsin, B., & Vernier, P. (2012a). Productivity of yam-based systems with herbaceous legumes and short fallows in the Guinea-Sudan transition zone of Benin. *Nutrient cycling in Agroecosystems,* 92(1), pp.9-19.

Mandal, R. C. (1993). Tropical Root and Tuber Crops. India, *Agrobotanical Publishers*. p. 396

Marcos, J., Cornet, D., Bussière, F., Sierra, J. (2011). Water yam (*Dioscorea alata L.*) growth and yield as affected by the planting date: Experiment and modelling. *European Journal of Agronomy*, vol. 34, Iss.4, 2011, Pg 247-256

Marcos, J., Lacointe, A., Tournebize, R., Bonhomme, R., & Sierra, J. (2009). Water yam (*Dioscorea alata L.*) development as affected by photoperiod and temperature: Experiment and modeling. *Field Crops Research*, vol. 111, Iss.3, 2009, Pg 262-268.

McPherson, G. A., (1985). Analysis of radioligand binding experiments: a collection of computer programs for the IBM PC. *Journal of pharmacological methods*, 14(3), pp.213-228.

Mignouna, H. D., Abang, M. M., & Asiedu R. (2007) Yams. In: Kole C. (eds) Pulses, Sugar and Tuber Crops. Genome Mapping and Molecular Breeding in Plants, vol 3. Springer, Berlin, Heidelberg

Mignouna, H. D., Abang, M. M., Asiedu, R., & Geeta, R. (2009). Yam (*Dioscorea*) husbandry: Cultivating yams in the field or greenhouse. *Cold Spring Harbor Protocols*, 2009(11), pp.pdb-prot5324.

Mignouna, H. D., & Dansi, A. (2003). Yam (*Dioscorea ssp.*) domestication by the Nago and Fon ethnic groups in Benin. *Genetic Resources and Crop Evolution*, 50(5), pp.519-528.

Ministry of Food and Agriculture (MoFA). (2016). Agriculture in Ghana; facts and figures. *Statistics, Research and Information Directorate (SRID),* Ministry of Food and Agriculture, Republic of Ghana.

Ministry of Food and Agriculture (MoFA). (2017). Agriculture in Ghana; facts and figures. *Statistics, Research and Information Directorate (SRID),* Ministry of Food and Agriculture, Republic of Ghana.

Mligo, J. K., & Craufurd, P. Q. (2005). Adaptation and yield of pigeonpea in different environments in Tanzania. *Field Crops Research*, 94: 43–53.

Morris, R. A., & Garrity, D. P. (1993). Resource capture and utilization in intercropping non nitrogen nutrients. *Field Crops Res*. 34: 319-334.

Mula, M. G., & Saxana, K. B. (2010). Lifting the Level of Awareness on Pigeonpea – A Global Perspective. *Patancheru* 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 540 pp.

Mullen, C. L., Holland, J. F., & Heuke, L. (2003). Cowpea, lablab, and pigeon pea. *Agfact P4. 2.21. NSW Agriculture,* Orange. New South Wales.

Nair, P. K. (1984). Agroforestry with coconuts and other tropical plantation crops. ICRAF reprint No. 8, Reprinted from *Plant Research and Agroforestry,* Nairobi, ICRAF 1983, pp. 79-102.

Nair, P. K. R., Kang, B. T., & Kass, D. B. L. (1995). "Nutrient cycling and soil-erosion control in agroforestry system," in Agriculture and Environment: Bridging Food Production in Developing Countries, ASA special publication no. 60, *American Society of Agronomy*, Madison, WI, Ch. 7.

Nair, P. R., Buresh, R. J., Mugendi, D. N., & Latt, C. R. (1998). Nutrient cycling in tropical agroforestry systems: myths and science. In Agroforestry in sustainable agricultural systems (pp. 13-43). CRC Press.

Naylor, R. L., Falcon, W. P., Goodman, R. M., Jahn, M. M., Sengooba, T., Tefera, H., & Nelson, R. J. (2004). Biotechnology in the developing world: a case for increased investments in orphan crops. *Food Policy*, 29(1), pp.15-44.

Ndegwe, N. A., Ikpe, F. N., Gbosi, S. D., & Jaja, E. T. (1990). Effect of staking method on yield and its components in sole-cropped white Guinea yam (*Dioscorea rotundata Poir*.) in a high-rainfall area of Nigeria. *Tropical Agriculture, Trinidad and Tobago*, 67(1), pp.29-32.

Nweke, F. I. (2016). Yam in West Africa: Food, Money and More. Michigan State University Press.

Nweke, F. I. (2019). African Mysticism: A Worldview that is a Blessing and an Impediment to Technological Change in West African Yam Food Crop Sector. *International Journal of Arts and Humanities*. vol. 7(6): pp, 513-525, 2019.

Nweke, F. I., Ugwu, B. O., Asadu, C. L. A., & Ay, P. (1991). Production costs in the yam-based cropping systems of southeastern Nigeria. *Resource and Crop Management Division Research monograph, (6)*. IITA, Ibadan, Nigeria. p. 29.

Obidiegwu, J. E., Asiedu, R., Ene-Obong, E. E., Muoneke, C. O., & Kolesnikova-Allen, M. (2009). Genetic characterization of some water yam (*Dioscorea alata L.*) accessions in West Africa with some simple sequence repeats. *Journal of Food, Agriculture and Environment*, 7, 634-638.

Ofori, F., & Stern, W. R. (1987). Cereal–legume intercropping systems. *In Advances in agronomy*, vol. 41, pp. 41-90. Academic Press.

Ojo, S. O. (2004). Improving labour productivity and technical efficiency in food crop production: A panacea for poverty reduction in Nigeria. *Food, Agriculture & Environment*, vol.2 (2):227-231.

Oluwole, O., Alagbe, G., Alagbe, O., Ibidapo, O., Ibekwe, D., and Owolabi, S. (2017). A comparative quality evaluation of white yam (*Dioscorea rotundata*) and water yam (*Dioscorea alata*) chips as African fries. *Advances in Nutrition & Food Science*. vol. 2; Iss. 1. Pp. 1-5.

Ong, C. K. (1991). The interactions of light, water and nutrients in agroforestry systems. Pp.107-124. In: Avely. ME., Canneil, M-GR and Ong, C.K. (eds.) *Application of biological research in Asian agroforestry*. Wirock International, USA.

Ong, C. K. (1996). Quantifying the effects of tree crop interaction. pp. 1-23. In: Tree-crop interactions. C. X. Ong and P. Huxley, (eds.) *CAB International*. Wallingford, UK.

Ong, C. K., Corlett, J. E., Singh, R. P., & Black, C. R. (1991). Above and below ground interactions in agroforestry systems. *Forest Ecology and Management*, 45 (1991) 45-57.

Onwueme, I. C., & Havertkort, A. J. (1991). Modelling growth and productivity of yams (*Dioscorea spp*): prospects and problems. *Agricultural systems*. 36(1991) 351-367.

O'Sullivan, J. N., & Ernest, J. (2008). Yam nutrition and soil fertility management in the Pacific. *Australian Centre for International Agricultural Research, Brisbane*. 143p.

Otani, T., Ae, N., & Tanaka, H. (1996). Phosphorus (P) uptake mechanisms of crops grown in soils with low P status: II. Significance of organic acids in root exudates of pigeonpea. *Soil Science and Plant Nutrition*, 42(3), pp.553-560.

Oteng-Darko, P., Yeboah, S., Addy, S. N. T., Amponsah, S. K., & Owusu Danquah. E. (2012). Crop modeling: A tool for agricultural research – A review. *E3 Journal of Agricultural Research and Development* Vol. 2(1). pp. 001-006.

Otoo, E., Akromah, R., Kololesnikova-Allen, M & Asiedu, R. (2009). Ethno-botany and morphological characterization of the yam pona complex in Ghana. In Afr Crop Sci Conf Proc (Vol. 9, pp. 407-414).

Otoo, E. (2001). Yam production in Ghana: A food security enhancer or an environmental degrader? In Akoroda, M. (eds.). *Proceedings of the 8th Symposium of the International Society for Tropical Root Crops, Africa Branch Triennial Workshop*, Ibadan, Nigeria, Nov. 12-16 2001.pp. 387-391.

Otoo, E., Anchirina, V. M., Ennin, S. A., & Asiedu, R. (2008). Sustainable yam production in Ghana the non-staking option. *Journal of Food, Agriculture & Environment (JFAE*) 6: (3&4) 391-396.

Owusu Danquah, E., Ennin, S. A., Lamptey, J. N. L., & Acheampong, P. P. (2014). Staking Options for Sustainable Yam Production in Ghana. *Sustainable Agricultural Research*. Vol. 4 (1):106-113

Patterson, T. G., & LaRue, T. A. (1983). Nitrogen Fixation by Soybeans: Seasonal and Cultivar Effects, and Comparison of Estimates. *Crop Science*, 23(3), pp.488-492.

Penning de Vries, F., Teng, P., Metselaar, K., & Hunt, L.A. (1992). Designing Improved Plant Types: A Breeder's Viewpoint. *Systems Approaches for Agricultural Development, vol. 2*.

Peoples, M. B., Bergersen, F. J., & Turner, G.L. (1991). Use of the natural enrichment of ^{15}N in plant available soil N for the measurement of symbiotic N_2 fixation. In *Stable isotopes in plant nutrition, soil fertility and environmental studies.*

Peoples, M. B., Brockwell, J., Herridge, D. F., Rochester, I. J., Alves, B. J. R., Urquiaga, S., Boddey, R. M., Dakora, F. D., Bhattarai, S., Maskey, S. L., & Sampet, C. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, 48(1-3), pp.1-17.

Peoples, M. B., Faizah, A. W., Rerkasem, B., & Herridge, D. F. (1989). Methods for Evaluating Nitrogen Fixation by nodulated Legumes in the Field, *Monograph No*. 11. ACIAR, Canberra.

Peoples, M. B., Herridge, D. F., & Ladha, J. K., (1995). Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? *In Management of Biological Nitrogen Fixation for the Development of More Productive and Sustainable Agricultural Systems* (pp. 3-28). Springer, Dordrecht.

Phatak, S.C., Nadimpalli, R. G., Tiwari, S. C., & Bhardwaj, H. L. (1993). Pigeonpeas: potential new crop for the southeastern United States. In: J. Janick & J.E. Simon, (eds), *New Crops*. Wiley, New York. p.597–599.

Phiri, A. T., Msaky, J. J, Mrema, J., Kanyama-Phiri, G. Y., Harawa, R. (2013). Assessment of Nutrient and Biomass yield of medium- and long-term duration pigeonpea in pigeonpea –groundnut intercrop system in Malawi. *Journal of sustainable society*. Vol. 2, No. 1. 2013, 36 -48.

Pinstrup-Anderson, P. (1982). Agricultural research and technology in economic development: the impact of agricultural research and modern technology on food production, economic growth and income distribution in developing countries. (*London: Longman*, 1982).

PPMED (Policy Planning, Monitoring and Evaluation Division) (2007). Agriculture in Ghana Facts and Figures. Policy Planning, monitoring and Evaluation. Ministry of Food and Agriculture, Ghana.

Purcell, L. C., & Sinclair, T. R. (1990). Nitrogenase activity and nodule gas permeability response to rhizospheric NH_3 in soybean. *Plant physiology*, 92(1), pp.268-272.

Rainbird, R. M., Atkins, C. A., & Pate, J. S. (1983). Effect of temperature on nitrogenase functioning in cowpea nodules. *Plant physiology*, 73(2), pp.392-394.

Rao, M. R., & Singh, M. (1990). Productivity and risk evaluation in contrasting intercropping systems. *Field Crop Research*. 23, 279–293.

Rao, M. R., Nair, P. K. R., & Ong, C. K. (1998). Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems* 38 :3 -50.

Rao, M. R., Nair, P. K., & Ong, C. (1997). Biophysical interactions in tropical agroforestry systems. Agroforestry Systems 38(1):3-50.

Rennie, R. J. (1984). Comparison of N Balance and ^{15}N Isotope Dilution to Quantify N_2-Fixation in Field-Grown Legumes. *Agronomy Journal*, 76(5), pp.785-790.

Rennie, R. J., & Rennie, D. A. (1983). Techniques for quantifying N_2 fixation in association with nonlegumes under field and greenhouse conditions. *Canadian Journal of Microbiology*, 29(8), pp.1022-1035.

Ritchie, J. T. (1991). Specifications of the ideal model for predicting crop yields. R. C. Muchow, J. A. Bellamy (Eds.), *Climatic Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics, Proc. Intnl. Symposium*, St. Lucia, Brisbane, Queensland, Australia. July 2–6, 1990, C.A.B. International, Wallingford, U.K. (1991), pp. 97-122

Rodriguez, D. J. (1997). A method to study competition dynamics using de Wit replacement series experiments. *Oikos*, 78, 411-415.

Sakala, W. D. M. (1998). Nitrogen Dynamics in maize (*Zea mays*) and Pigeonpea (*Cajanus cajan*) intercropping in Malawi. *Doctoral thesis*, Wyne College, University of London

Sartie, A., & Asiedu, R. (2014) Segregation of vegetative and reproductive traits associated with tuber yield and quality in water yam (*Dioscorea alata L.*). *African Journal Biotechnology*. 13 (28): 2807–2818.

Sartie, A., Franco, J., & Asiedu, R. (2012). Phenotypic analysis of tuber yield-and maturity-related traits in white yam (*Dioscorea rotundata*). *African Journal of Biotechnology*. 2012;11(17):3964-75.

Schultz, G. E. (1993). Element Stewardship Abstract for *Dioscorea bulbifera,* Air potato. The Nature Conservancy. June 8, 2007.

Scott, G. J., Rosegrant, M. W., & Ringler, C. (2000). Roots and tubers for the 21st century: Trends, projections, and policy options. *Intl Food Policy Res Inst*. (Vol. 31).

Sharma, D., & Green, J. M. (1980). Pigeonpea. in Hybridization of crop plants. Fehr, Walter R. & Hadley, Henry H. (eds.). *American Society of Agronomy and Crop Science Society of America*. Pg 471-481. Madison, WI, USA.

Simpson, J. A. (1999). Effect of shade on maize and soybean productivity in a tree-based intercrop system. *MSc. Thesis,* The faculty of graduate studies, University of Guelph.

Singh, F., & Oswalt. D. L. (1992). Pigeonpea botany and practices. *Human Resource Development Program, series no. 9.* International Crops Research Institute for the Semi- Arid Tropics (ICRISAT). Patancheru, Andhra Pradesh 502 324, India.

Snapp, S. S. (1998). Soil Nutrient Status of smallholder farmers in Malawi. *Communications in soil sciences and plant analysis* 29(17-18): 2571 – 2588.

Snapp, S. S., Jones, R. B., Minja, E. M., Rusike, J., & Silim, S. N. (2003). “Pigeonpea for Africa: a versatile vegetable—and more,” *Hort-Science*, vol. 38, no. 6, pp. 1073–1079.

Snoeck, D., Zapata, F., Domenach, A. M. (2000). Isotopic evidence of the transfer of nitrogen fixed by legumes to coffee trees. *Biotechnology, Agronomy, Society and Environment,* 4 (2000), pp. 95-100.

Srivastava, A. K. (2010). Management Effects on Yam Production in Benin Republic-Experimental Analysis and Modeling. *Doctoral dissertation*, Faculty of Agriculture, University of Bonn.

Srivastava, A. K., Gaiser, T., Paeth, H., & Ewert, F. (2012). The impact of climate change on Yam (*Dioscorea alata*) yield in the savanna zone of West Africa. *Agriculture, Ecosystems & Environment*, Vol. 153, 15, 2012, Pg 57-64.

Subbarao, G. V., Chauhan, Y. S., & Johansen, C. (2000). Patterns of osmotic adjustment in pigeonpea — its importance as a mechanism of drought resistance. *European Journal of Agronomy*, 12: 239–249.

Sullivan, P. (2003). Intercropping principles and production practice. *Agronomy Systems Guide. Appropriate Technology Transfer for Rural Areas (ATTRA)*. 1-12p.

Tetteh, J. P., & Saakwa, C. (1991). Prospects and constraints to yam production in Ghana. *In Symposium on Tropical Root Crops in a Developing Economy* 380 (pp. 355-359).

Thornton, P. K., & Herrero, M. (2001). Integrated crop–livestock simulation models for scenario analysis and impact assessment. Agricultural Systems, 70(2-3), pp.581-602.

Troedson, R. J., Wallis, E. S., & Singh, L. (1990). Pigeonpea: Adaptation. In: Nene, Y., Hall, S.D., Sheila, V.K. (Eds.), *Pigeonpea*: *adaptation*. CABI, Wallingford, pp. 159–177.

Unkovich, M., Herridge, D., Peoples, M., Cadisch, G., Boddey, R., Giller, K., Alves, B., & Chalk P. (2008). Measuring plant-associated nitrogen fixation in agricultural systems. Australian Centre for International Agricultural Research (ACIAR), *Australia, Monograph No*. 136, 258pp.

Valenzuela, H., & Smith, J. (2002). Pigeonpea. Sustainable Agriculture Green Manure Crops, Aug. 2002. SA-GM-8

Van Delden, A., Schröder, J. J., Kropff, M. J., Grashoff, C., & Booij, R. (2003). Simulated potato yield, and crop and soil nitrogen dynamics under different organic nitrogen management strategies in The Netherlands. *Agriculture, ecosystems & environment*, 96(1-3), pp.77-95.

Van Ittersum, M. K., Leffelaar, P. A., Van Keulen, H., Kropff, M. J., Bastiaans, L., Goudriaan, J. (2003). On approaches and applications of the Wageningen crop models. *European Journal of Agronomy*, 18(3-4), pp.201-234.

Van Ittersum, M. K., Rabbinge, R., van Latesteijn, H. C. (1998). Exploratory land use studies and their role in strategic policy making. *Agricultural systems*, 58(3), pp.309-330.

Vance, C. P. (2001). Symbiotic nitrogen fixation and phosphorus acquisition: Plant nutrition in a world of declining renewable resources. *Plant Physiology*, 127: 390–397.

Vandermeer, J. H. (1990). Intercropping. Intercropping., pp.481-516.

Vavilov, N. I. (1951). The origin, variation, immunity and breeding of cultivated plants. *Chronica Botanica* 13(1-6):1-366.

Vernon Royes, W. (1976). Pigeonpea. in *Evolution of crop plants* (Simmonds, N.W., ed.). Pg 154-156. London, UK: Longmans.

Vessey, J. K. (1994). Measurement of nitrogenase activity in legume root nodules. In: Defense of the Acetylene Reduction Assay. *Plant and Soil* 158: 151–162.

Wahab, A. A., Zahran, H. H., & Abd-Alla, M. H. (1996). Root-hair infection and nodulation of four grain legumes as affected by the form and the application time of nitrogen fertilizer. *Folia microbiologica*, 41(4), pp.303-308.

Wahua, T. A. T., & Miller, D. A. (1978). Effects of Intercropping on Soybean N_2-Fixation and Plant Composition on Associated Sorghum and Soybeans. *Agronomy Journal*, 70(2), pp.292-295.

Wanyera, N. M. W., Asiedu, R., Kapinga, P., & Speijer, R. (1996). Yams (*Dioscorea spp*.) in Tanzania and Uganda. *A survey report*. IITA, Ibadan, Nigeria and IITAESARC, Uganda. 558 Cropping systems: Trends and advances.

Wholey, D. V., & Haynes, P. H. (1971). A yam staking system for Trinidad. Wld. Crops, 23, 123– 126.

Willey, R. (1979). Intercropping-its importance and research needs: Part 1. Competition and yield advantages. In *Field crop abstracts*, vol. 32, pp. 1-10.

Willey, R. (1985). Evaluation and presentation of intercropping advantages. *Experimental Agriculture*, 21(2), pp.119-133.

Willey, R. W. (1990). Resource use in intercropping systems. *Agricultural water management*, 17(1-3), pp.215-231.

Witty, J. F., & Minchin, F. R. (1988). Measurement of nitrogen fixation by the acetylene reduction assay; myths and mysteries. In *Nitrogen fixation by legumes in Mediterranean agriculture* (pp. 331-344). Springer, Dordrecht.

Young, A. (1997). Agroforestry for Soil Management. 2nd edition. CAB International & International Centre for Research in Agroforestry, Wallingford/Nairobi.

Young, N. D., Mudge, J., & Ellis, T. N. (2003). Legume genomes: more than peas in a pod. *Current opinion in plant biology*, 6(2), pp.199-204.

Zapata, F., Danso, F., Hardarson, G., & Fried, M. (1987). Nitrogen Fixation and Translocation in Field-Grown Fababean. *Agronomy Journal*, 79(3), pp.505-509.

Zapata, F., Danso, S. K. A., Hardarson, G., & Fried, M. (1987). Time course of nitrogen fixation in field-grown soybean using nitrogen-15 methodology. *Agronomy Journal*, 79(1), pp. 172-176.

Zeven, A. C., & Zhukovsky, P. M. (1975). Dictionary of cultivated plants. *In the new systematics* (Huxby, J., ed.). Pg. 549-566. London, UK: Oxford University.

Zhang, F., & Li, L. (2003). Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil*. 2003, Vol. 248, Iss. 1–2, pp 305–312

CHAPTER 2

PIGEONPEA (*CAJANUS CAJAN [L] MILLSP*.) -YAM (*DIOSCOREA ROTUNDATA*) CROPPING SYSTEM FOR IMPROVED YAM RESOURCE USE AND PRODUCTIVITY

ABSTRACT

Increasing and sustaining food crop productivity per unit area on the limited land resources is imperative for the world population projected to increase from 7.8 billion to 9 billion by 2050. The objective of this study was to evaluate resource use in pigeonpea-yam cropping systems and implications on yam productivity. Research activities were conducted at Fumesua and Ejura in the forest and forest-savannah transition agroecological zones of Ghana, respectively, through 2017, 2018, and 2019 cropping seasons. The establishment of the pigeonpea either in an alley or as a border was done in the 2017 cropping season. The 2018 and 2019 cropping seasons were used as two seasons to cultivate yam with pigeopea in both locations. A split-plot design with three replications with cropping system (yam planted in alleys of pigeonpea – PA; yam planted in pigeonpea as a border – PB and Sole yam) and fertilizer (0-0-0; 23-23-30; 45-45-60 N-P_2O_5-K_2O kg/ha) was used to arrange the main-plot and subplot treatments respectively. When the competition for sunlight reaching the yam leaves were considered, results revealed that the cropping system had a significant ($P \leq 0.05$) influence on the sunlight reaching the yam leaves on the canopy. Sunlight reaching the mid-canopy (MC) of PB and sole yam fields appeared higher than the sunlight reaching the yam leaves above the canopy (AC) of PA whiles sunlight at the below canopies (BC) of PB, and sole yam was higher than the sunlight reaching the mid-canopy of PA. As such, the PA field resulted in a significant ($P \leq 0.05$) suppression of weeds for both locations and years. The presence of the pigeonpea biomass resulted in a reduction in ridge erosion, improved moisture conservation, improved soil ECEC resulting in a significantly ($P \leq 0.05$) higher and similar tuber yields for the yam planted in pigeonpea with half (23-23-30 kg/ha N-P_2O_5-K_20) and full

(45-45-60 kg/ha N-P_2O_5-K_20) fertilizer rates than the sole yam in both locations and years. As a result of significantly ($P \leq 0.05$) higher pigeonpea biomass produced by PA than PB, corresponding significantly ($P \leq 0.05$) higher tuber yields were observed irrespective of the location and year. The Land Equivalent Ratio indicates about 27-63%, and 34-68% more land area would be needed by the sole yam field to produce similar yam yields as the pigeonpea-yam cropping system at Fumesua and Ejura respectively across the two growing seasons. Therefore, the study, showed that the use of pigeonpea-yam cropping system could sustain soil fertility, improve sprouting of yam, and provide stakes to address the constraint of deforestation and land degradation associated with yam production. However, to encourage the adoption of the pigeonpea-yam cropping system, smallholder farmers with limited access to land would need an alternative livelihood during the 8–12 months lag phase associated with pigeonpea to mature. Also, breeding and improvement on pigeonpea for traits such as erectness, moderate branching, high biomass, and ability to withstand pruning could help produce pigeonpea accessions more suitable for the pigeonpea-yam cropping system.

Keywords: Sustainable yam production, Pigeonpea, Smallholder farmers, Resource use, cropping system

INTRODUCTION AND RATIONALE

The world population is expected to increase from 7.8 billion to 9 billion by 2050 (Roberts, 2011). To keep pace with feeding the growing population, increasing and sustaining food production per unit area on the limited land resources is imperative. The challenge of limited access to resources, soil fertility maintenance, and drought as a result of erratic rainfall, are the main factors contributing to low agricultural productivity in Sub-Saharan Africa (McCann, 2005). Ajayi *et al*., 2007, observed that agriculture innovative technologies accessible and affordable to smallholder farmers especially would be the way forward. Although known for its vital role in rural households, yam production, also serves as food supply and income generation through the consumption and marketing of ware yams. However, yam production faces the challenge of soil fertility maintenance and scarcity of stakes for yams to climb on for sunlight (Ennin *et al*., 2014; Owusu Danquah *et al*., 2014). The cultivation of yam requires nutrient-rich soils. The harvest of a ton of yam from the field is estimated to export N of 3.8-4.0kg N/ha, 0.39-1.1kg P_2O_5/ha, 4.2-5.9 K_2O kg/ha (Le Buanec *et al*., 1972; Ferguson and Haynes, 1970). To cope with the fertile soil demands of the yams, farmers move to new lands every year in search of fertile fields and stakes for yams to climb, resulting in land degradation and deforestation. This shifting cultivation practice, coupled with the increasing human population, has led to pressure on arable lands and forest in the yam growing communities (Ennin *et al*., 2014; Ekanayake and Asiedu, 2003; Asante, 1996). Fallow period and available fertile lands keep reducing whiles distances to yam fields are getting farther and more difficult to access. The Ministry of Food and Agriculture, Ghana (MoFA) report attributed the total loss of about 25% of all forest classes in Ghana to the traditional slash-and-burn method of cultivation, logging, and wildfires (MoFA, 2017). Soil improvement with fertilizer and manure have been suggested to address this situation. However, increasing and high cost of fertilizers are making it difficult for resource-poor farmers to access and use fertilizers on their farms. Also, the use of fertilizer alone has been observed not to promote good soil health (Garrity, 2004; Kotschi *et al*., 1998). The use of traditional organic materials such as crop residue and animal manure has been a cheaper source of nutrition for crop production. However, they are bulky, and availability at reasonable quantities in most cases is also limited to offer a real alternative (Kotschi *et al*., 1998; Young, 1997; Diby *et al*., 2011).

The option of Integrated soil fertility management (ISFM), which combines mineral fertilizer and organic matter for sustainable crop production, is being promoted for intensification of food production (Vanlauwe *et al*., 2010; Giller, 2001). The use of legume crops and shrubs has been identified as a major constituent in sustainable cropping systems due to their Biological Nitrogen Fixation (BNF) and therefore could be adopted in yam production (Ennin and Dapaah, 2008; Asafu-Agyei *et al*., 1997; Kombiok *et al*., 1997; Eze and Orkwor 2010). This study proposes adopting integrated soil nutrient management with the legume shrub – pigeonpea (*Cajanus cajan [L] Millsp.*) for sustainable yam production. Pigeonpea (*Cajanus cajan [L] Millsp.*) is an important grain legume in the semi-arid tropics and an important income source in countries like Tanzania, Malawi, and Myanmar as they export the grain to India (Walker *et al*., 2015; Odeny, 2007). Smallholder farmers in low input, rain-fed systems, generally cultivate the crop as a sole, mixed, intercrop or ratoon crop. In West Africa, pigeonpea is a novel crop species, and it has features that include multipurpose production of biomass above and belowground. This species has shown promise as a means to improve soil aggregation, organic matter, and soil nutrient status (Adu-Gyamfi *et al*., 2007; Snapp *et al*., 2003). Several studies in the semi-arid and sub-humid tropics of East Africa report multiple ecosystem services of pigeonpea including biomass production, replenishing soil fertility, efficient water use, and reduced soil erosion, in addition to the long-term sustainability from diversifying cropping systems with pigeonpea (Kimaro *et al*., 2009; Mafongoya *et al*., 2006; Snapp *et al*., 2002). It fixes more N per unit area from its biomass than other major legumes used in cropping systems (Peoples *et al*., 1995; Giller and Cadisch, 1995). Cropping systems involving pigeonpea in West Africa are rare, even though pigeonpea is found in some home gardens. Few studies have evaluated crop rotation or intercropping of pigeonpea with maize, cowpea, and cassava (*Manihot esculenta*) in Ghana. These have found that pigeonpea returns large quantities of crop residue to the soil, increases yield of subsequent maize crop, and minimizes soil carbon loss (Adiku *et al*., 2009; Adjei-Nsiah *et al*., 2007; Agyare *et al*., 2002). In a farmer-managed trial in Ghana, farmers selected the use of pigeonpea as a soil fertility improvement crop over mucuna (*Mucuna pruriens*) and also because pigeonpea provided immediate benefits both as a food and a cash crop (Adjei-Nsiah *et al*., 2007). Thus, pigeonpea could play a positive role in food security. The grains of pigeonpea can serve as an additional source of income and nutrition to smallholder farmers. The grains are nutritionally well balanced and are an excellent source of protein (20–30%), carbohydrates, and high levels of vitamins A and C (Snapp *et al*., 2003). It can also be used as a cheaper source of fodder for livestock (Saxena *et al*., 2002). However, before introducing pigeonpea into yam production systems in Ghana, it is necessary to evaluate the above and belowground competition that exists between the two plants so appropriate measures can be used to improve productivity. This field study aimed at assisting yam farmers in integrating pigeonpea into yam production in Ghana to improve soil fertility, income, and livelihoods. The specific objectives are to assess the resource use and implication on yam productivity in the pigeonpea-yam cropping system.

MATERIALS AND METHOD

Site description

The study was conducted on a 13 – 15 year continuously cropped field with maize and cowpea in rotation at Fumesua (6^{o} 41’ N, 1^{o} 28’ W) and Ejura (7^{o} 23’ N, 1^{o}21’ W) in the forest and forest-savannah transition zones of Ghana respectively. Fumesua soils are Ferric Acrisols; Asuansi series with greyish brown sandy clay loam topsoil whiles Ejura soils are Ferric Lixisol; Ejura series with a thick top layer of fine sandy loam (Table 2.1, Figures 2.1a & 2.1b).

Table 2.1: Description of the sites used for the studies.

	Location	
Characteristics	Fumesua (6^{o} 41’ N, 1^{o} 28’ W)	Ejura (7^{o} 23’ N, 1^{o}21’ W)
Agro-ecological zone	Humid Forest	Forest-Savannah Transition
Soil type	Ferric Acrisol; Asuasi series upper topsoil consisted of 5cm greyish brown sandy loam topsoil of dark brown gritty clay loam	Ferric Lixisol; Ejura series with a 20-30cm thick top layer of loam soils. Soils are dark brown to brown fine sandy loam
Temperature (Min-Max. ^{o}C) 2017-2019	22-31	21-34
Wet season	Bimodal rainfall pattern	Bimodal rainfall pattern
Major	March –mid August	March –mid- August
Minor	Sept-Nov; peak in Oct	September- Nov; peak in Oct
Total annual rainfall (mm) 2017 -2019	1127-1602 averaging 1442mm/yr	1171-1574; averaging 1311mm/yr

Adopted from Adu, 1992 and Ennin *et al*., 2009

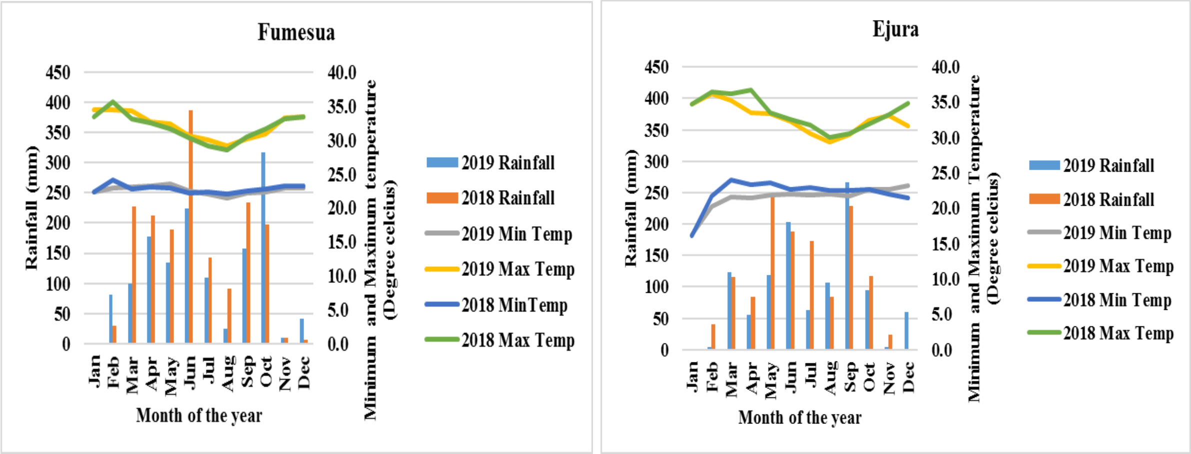

Figure 2.1a: Rainfall, maximum and minimum temperatures for 2018 and 2019 of the study areas (Fumesua and Ejura). *Source: Data from the Ghana Meteorological Agency (GMA), 2019*

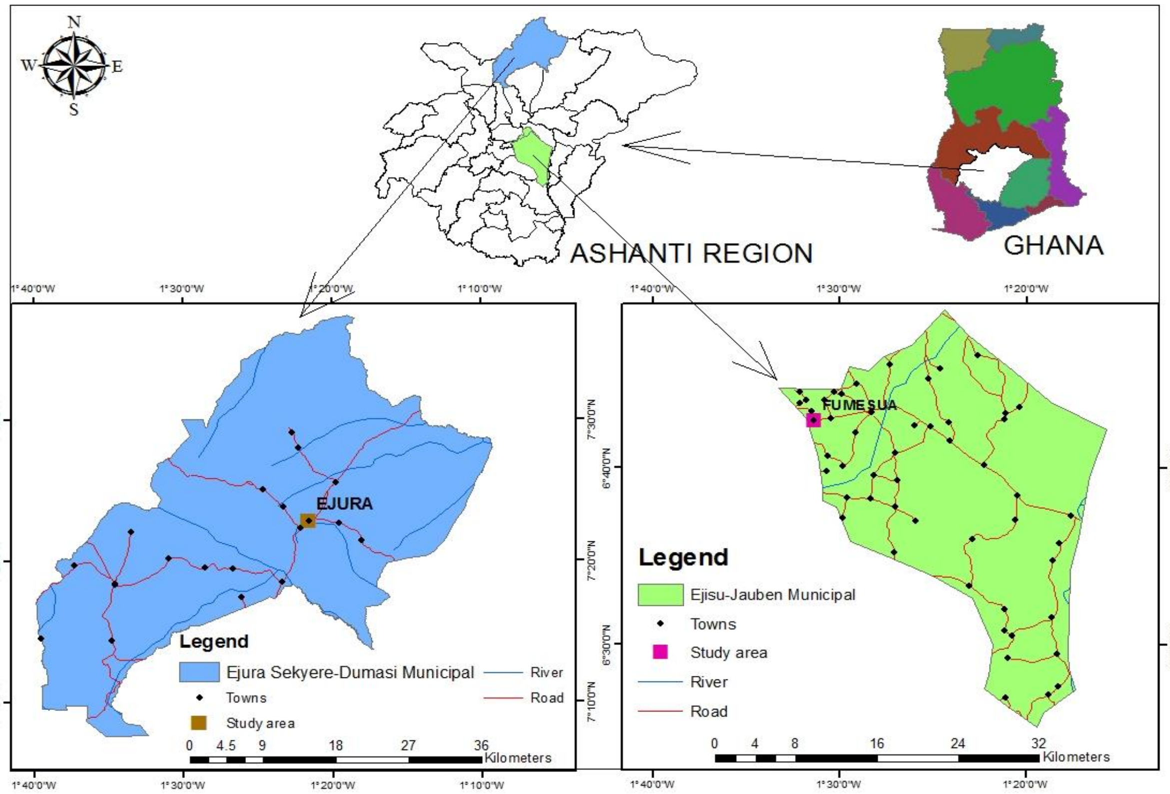

Figure 2.1b: Map showing the study area. *Source: Courtesy of: Enock Bessah with data from the geological survey department, Ghana, 2019.*

Experimental design and data collection

The treatment was arranged in a split-plot design with three replications. Pigeonpea-yam cropping system (yam in an alley of pigeonpea (PA), yam in pigeonpea as a border (PB), and No pigeonpea/sole yam) was the main-plot. The subplot of fertilizer levels consisted of full-rate – 45-45-60 kg/ha N-P_20_5-K_20; half-rate – 23-23-30 N-$P_2$05–$K_2$0 kg/ha and no fertilizer as recommended by CSIR – CRI yam (Ennin *et al*., 2016). Also, a sole pigeonpea/ no yam field established adjacent to each replicate to enable a comparison of the productivity of the systems. The combination of the pigeonpea and yams on the plots followed the replacement/substitutive approach with a row/ridges for yams substituted for pigeonpea either within the yam ridges or around the border of the field for pigeopea in alley and pigeonpea as border plant fields respectively. A total pigeonpea population of 5,931 plants per ha (about 27% of the sole pigeonpea population) planted at one per stand was used on each of the pigeonpea in alley and pigeonpea as border field. The pigeonpea used was a late-maturing (after 8months) whiles "Pona", a premium *Dioscorea rotundata* local accession, was used. Yam sett was treated with 120g Conti-Zeb '5' (mancozeb 80%) a fungicide and 80ml of Dursban (480 g/l chlorpyrifos) an insecticide in 15l of water (Ennin *et al.*, 2016). The fields were tractor plowed, and pigeonpea was planted in the first and second weeks of May 2017 at Fumesua and Ejura, respectively. The yams were planted on ridges in both locations for the pigeonpea in alley and pigeonpea as border/live fence and sole yam (No pigeonpea) during the 2018 and 2019 cropping seasons during the last week of April and first week of May for Fumesua and Ejura respectively. On the pigeonpea in alley fields, pigeonpea was planted at 3.6m and 0.5m inter and intra-row respectively to enable two rows/ridges of yams to be planted within the two rows of the pigeonpea. Two rows/ridges of yams were then planted at 1.2m and 0.8m inter and intra-row respectively to achieve a population of 7,177/ha yam stands within the alleys of pigeonpea with a population of 5,931/ha (Appendix Figures 2.7 & 2.8a; Table 2.2). Pigeonpea biomass was applied on the ridges for each cropping system overtime at both locations and years. The pigeonpea alleys served as live-stakes for yams to climb for sunlight with stake height ranging between 2 – 2.4m. On the pigeonpea as border field, two rows of pigeonpea were planted at three sides of the field at 1.2m and 0.5m inter and intra-row respectively to achieve a population of 5,931 plants per ha. Ridges were constructed in the space within the pigeonpea fence, and yams planted 1.2m and 0.8 inter and intra-row, respectively to achieve a population of 7,177/ha. Stakes were cut from the thick stems of the pigeonpea from the border for staking the yams. Stake height ranged between 0.8 – 1.2m (Appendix Figures 2.7 & 2.8b; Table 2.2). On the sole yam field, yams were planted on ridges at 1.2m X 0.8m inter and intra-rows respectively to achieve a population of 10,416/ha whiles the sole pigeonpea field had pigeonpea planted in rows at 0.9m and 0.5m inter and intra-row to achieve a population of 22,222/ha. Stakes were purchased and transported to the no pigeonpea/sole yam fields for staking. Stake height ranged between 2 – 2.5m (Appendix Figures 2.7 & 2.8c; Table 2.2). Ridges were about 40 – 45 cm high at planting for all treatments. Eight weeks after planting, yam stands were refilled for all treatments to ensure the optimum population. The subplot treatment of fertilizer was formulated from 15-15-15 N-P_205–K_20 (popular fertilizer on the market) with a 15% muriate of potash (MOP) top-up to obtain the 60% K_2O needed. It was split applied using band placement (5 X 5 cm) per yam plant on the ridges at 5-6 and 12 weeks after planting in both locations and years. A sole maize plot of "obatanpa" and 2.31with 105 days to maturity was planted two times in the year adjacent to each replication as a reference crop for N-fixation determination.

Table 2.2: Population of pigeonpea and yam per plot and per hectare designed for the study.

Treatment	Size of plot (m^2)	Number of pigeonpea/plot/ hectare	Number of yam/ plot/ hectare
Yam in PA	200.64	119 / (5,931)	144 / (7,177)
Yam in PB	200.64	119 / (5,931)	144 / (7,177)
Sole yam	200.64	--	209 / (10,416)
Sole pigeonpea	200.64	446 / (22,222)	--

PA – Pigeonpea in alley; PB- Pigeonpea as a border

Soil analysis

Composite soil samples (9 subsamples) were sampled at the planting of pigeonpea, planting of yam, and harvesting of yam at random on the ridges for all cropping seasons. Soil analysis was conducted at the CSIR – Soil Research Institute, Kumasi, for total nitrogen, pH, organic carbon, phosphorus, and potassium measured at 0-20 cm and 20-40 cm on the ridges. Total N was determined using the Kjeldahl method, and soil pH was measured using a pH meter (1:2.5, Soil: H_2O), organic carbon (OC) using the Walkley and Black method (Walkley and Black 1934). Soil available P was determined using the Bray method 1 (Bray and Kurtz, 1945) and available K using flame photometry (Toth and Prince, 1949). Exchangeable cations and Cation Exchange Capacity (CEC) were determined using the ammonium acetate method.

Access tubes installation for soil moisture monitoring

The soil moisture of each cropping system was measured and monitored on a bi-weekly basis using a Time Dorman Reflectometry (TDR) approach with a PR2/6 soil profile probe device from Delta-T Devices (Dalton, 1992; Delta-T Devices Ltd, Cambridge, UK). The soil probe (PR2/6) allowed monitoring of the soil profile to a depth of 1m with six separate rings enabling soil moisture monitoring at 0-100mm, 100-200mm, 200-300mm, 300-400mm, 400-600mm, and 600-1000mm. The probe upon inserting into the tubes emits electromagnetic field around each measuring ring, which penetrates the soil to record moisture readings for each depth (Delta-T Devices Ltd, Cambridge, UK; Dalton, 1992). Two access tubes were inserted at random on ridges of each treatment. The access tubes for each treatment were open, and the PR2/6 probe was inserted on a bi-weekly basis to record the percentage of moisture for the six depths for each cropping system. The soil moisture data were used to evaluate the belowground competition for water and nutrients in each treatment.

Weed biomass determination

A quadrant of 1.2 X 1m was placed at random three times on each field 8 - 9 weeks after planting yam, and the weeds within the area were carefully removed, and fresh weight was taken. Fresh weed samples were then dried in an oven at 75°C until a constant weight was obtained for dry weight determination. Fresh weed weights were converted from the sub-sample fresh weights to dry weights using fresh to dry weight conversion factor.

Determination of Biological N Fixation (BNF) of pigeonpea biomass

Dried leafy biomass of the pigeonpea and maize reference was subsampled and weighed into capsules and sent to the stable isotope facility at UC Davis for determination of %N and δ^{15}N determination. Maize served as the non-N-fixing reference plant. The BNF was calculated using the natural abundance method by Unkovich *et al*. (2008) with the equation 2.1 shown below.

$$\%Ndfa = \frac{(\delta 15N\ reference\ crop - \ \delta 15N\ legume) X\ 100}{(\delta 15N\ reference - B)} \qquad 2.1$$

Where %Ndfa – the percentage of N due to Biological Nitrogen Fixation (BNF); $\delta 15N$ – natural abundance of reference crop or legume (pigeonpea) biomass; B - The smallest weighted value of reference crop (Unkovich *et al*., 2008).

Sunlight and relative chlorophyll monitoring

A photosynQ multispeQ device V1.0 (Kuhlgert *et al*., 2016) was used to monitor photosynthetic related parameters such as light intensity and leaf relative chlorophyll content on a bi-weekly basis on the yam leaves. After the establishment of yam on the stakes (9-10 WAP), fresh and fully developed young yam leaves on the central rows of each treatment were selected bi-weekly on three strata of the stakes (above canopy-AC, mid-canopy-MC and below canopy-BC) for monitoring. The stake height of the yams ranged between 0.8 – 1.2m, 2 – 2.4m, and 2 – 2.5m for pigeonpea as a border, pigeonpea in an alley, and sole yam fields respectively.

These stake heights influenced the position of the mid-canopy (MC) on the stakes used for the monitoring. For the above canopy level, young and fully developed apical yam leaves at the top of the stakes were used. Young and fully developed yam leaves at an average height of 1.1m, 1.2m, and 0.7m were monitored at mid-canopy for pigeonpea in an alley, sole yam, and pigeonpea as border respectively. Young and fully developed yam leaves on the ridges of all the treatments were used for monitoring light, reaching the below canopy. The device also recorded leaf relative chlorophyll content alongside the light intensity. The leaf relative chlorophyll content indicates the health of the plant and N usage in the soil.

Yam yield and Land Equivalent Ratio determination

Yam tuber yields were determined by harvesting the central row of each treatment (8m X 3.6m = 28.8m^2), and adjacent stands were harvested as a replacement in case of loss of stand with-in the central row (Appendix Figure 2.7). For each treatment, both total and sub-sample fresh weights were taken in the field. The fresh tuber sub-samples were oven-dried at 75^{o}C to a constant weight to determine the dry weight. The fresh tuber weights were converted from the sub-sample fresh weights to dry weights, using fresh to dry weight conversion factor. The Land Equivalent ratio was determined following the approach of Willey (1979), equations (2.2, 2.2a and 2.2b) shown below;

$$LER = Partial\ LER\ of\ yam + Partial\ LER\ of\ pigeonpea \qquad 2.2$$

$$Partial\ LER\ of\ yam = \frac{Yield\ of\ yam\ in\ intercrop}{Yield\ of\ yam\ in\ monocrop} \qquad 2.2a$$

$$Partial\ LER\ of\ pigeonpea = \frac{Yield\ of\ pigeonpea\ in\ intercrop}{Yield\ of\ pigeonpea\ in\ monocrop} \qquad 2.2b$$

Data collection and statistical analysis

An analysis of variance at 5% significant level ($P \leq 0.05$) of the SAS, 9.4 version was used to analyze the data collected on sunlight intensity on yam leaves, percentage soil moisture along the soil profile, yam stand establishment, pruned pigeonpea biomass applied on ridges, and the yam yield components. PROC MIXED of Cropping system and Fertilizer level as fixed effects with block, location, and year as random effects were used (SAS inc, 2013). The effect of the Cropping system, location, and year was tested on total pigeonpea pruned biomass, biomass N yield, N-fixation, yam stand establishment, sunlight intensity on yam leaves and weed pressure in a three-way ANOVA. Using the cropping system, fertilizer level as fixed factors and the location, and year as random factors, a four-way ANOVA was used to test the effect on yam yield components and yam leaf chlorophyll content. Where treatment means differ significantly, the Standard Error of the difference between means (SED) at 5% significant level was used in the separation of means.

RESULTS

Soil

Irrespective of the timing of soil sampling, the soils at Ejura showed better indications of fertility (pH and Effective Cation Exchange Capacity (ECEC)) than Fumesua soils (Appendix Table 2.7). Fumesua soils were generally very strongly acidic (pH 4.4-5.2) whiles Ejura soils were closer to neutral (pH 6.6 – 7.9). Ejura soils are lixisols known to be less weathered, have deeper topsoil, and are more fertile than the acidic acrisols found in Fumesua (Lal, 1976). The introduction of the pigeonpea and application of its biomass on the ridges did improve ECEC in the soil of both locations and years. Also, P was high at harvest on Fumesua soils than Ejura soils (Appendix Table 2.7).

Yam stands and establishment

Yam stands, and the establishment was significantly ($P \leq 0.05$) influenced by the cropping system in both locations and years. Irrespective of the location, yam planted in PA (pigeonpea in an alley) had significantly ($P \leq 0.05$) higher number of stand and establishment at the field for both locations and years. Generally, sole yam fields (No pigeonpea field) recorded the worst field establishment in both locations and years (Figure 2.2).

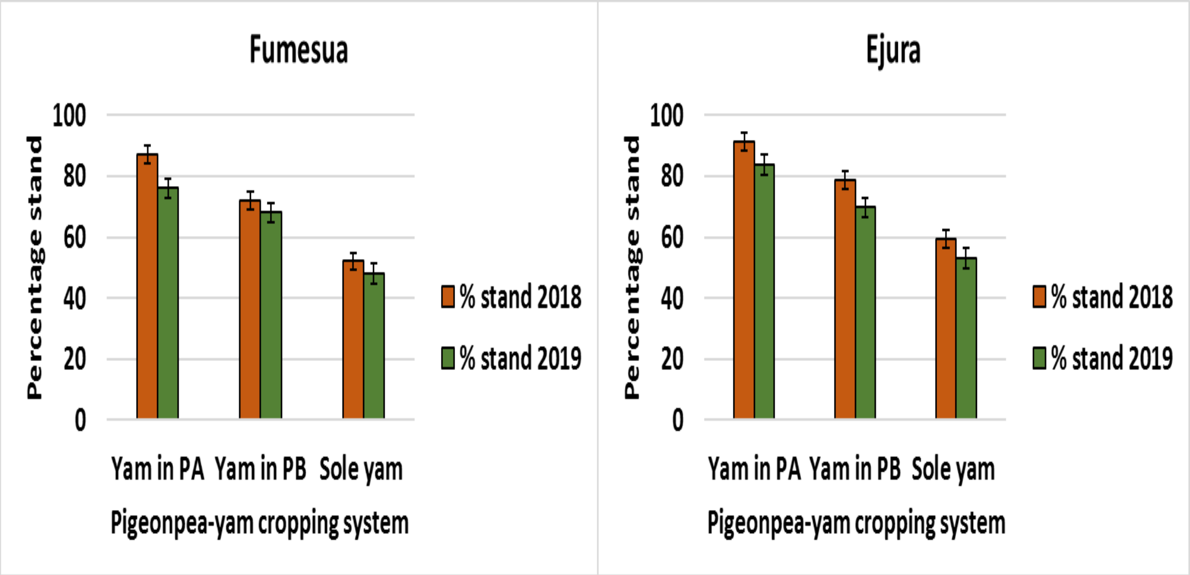

Figure 2.2: Percentage yam stand, two months after planting yam at Fumesua and Ejura for 2018 and 2019 cropping seasons. *PA – Pigeonpea in alley; PB – Pigeonpea as border. Error bars represent SED of cropping system means*

N yield and N – fixation of applied Leafy biomass

The interactions between location, year, and cropping system and their two-way interactions did not significantly ($P \leq 0.05$) influence the N yield and fixation of the applied biomass. However, the cropping system significantly ($P \leq 0.05$) influenced the leafy biomass production of pigeonpea in both locations and years. Pigeonpea stands at harvest was similar for the cropping systems in 2018 but significantly reduced for all the cropping systems in the 2019 cropping season. PA produced significantly ($P \leq 0.05$) higher leafy biomass in 2018 than 2019 cropping seasons irrespective of the cropping system and location. Leafy biomass applied on the PA field resulted in an N yield of 51.10 kg/ha and 76.45 kg/ha at Fumesua and Ejura, respectively, for the 2018 cropping season. In 2019, on PA fields, the N yield reduced significantly ($P \leq 0.05$) to 25.44 kg/ha and 30.05 kg/ha for Fumesua and Ejura, respectively. Similar trends were observed on the PB fields with the applied biomass N yield of 36.08 kg/ha and 65.72 kg/ha at Fumesua and Ejura respectively for the 2018 cropping season compared to N yield of 20.10 kg/ha and 22.86 kg/ha in Fumesua and Ejura respectively for the 2019 cropping season. High N due to fixation of 27.06 kg/ha (52.95%) and 49.2 kg/ha (62.35%)

were observed for Fumesua and Ejura respectively in PA whiles PB had N fixation of 17.99 kg/ha (49.86%) and 34.05 (51.81%) at Fumesua and Ejura respectively in the 2018 cropping season. N due to fixation reduced to 16.30 kg/ha (64.07%) and 19.25 (64.06%) for PA and 10.34 kg/ha (51.44%) and 11.69 kg/ha (51.14%) for PB at Fumesua and Ejura respectively for the 2019 cropping season (Table 2.3).

Table 2.3: Total dry matter of pigeonpea biomass applied on ridges in the cropping system, N yield and N due to fixation as influenced by cropping system for 2018 and 2019 cropping seasons.

Location	Pigeonpea-yam cropping system	Population density at harvest/ha		Total leafy biomass added (t/ha)		N content of biomass (kg/ha)		N due to fixation (kg/ha)	
		2018	2019	2018	2019	2018	2019	2018	2019
Fumesua	Yam in PA	5,910^{a}	4,712^{b}	2.41^{c}	1.06^{c}	51.10^{c}	25.44^{c}	27.06^{c}	16.30^{c}
	Yam inPB	5,871^{a}	4,613^{b}	2.13^{d}	0.91^{d}	36.08^{d}	20.10^{d}	17.99^{d}	10.34^{d}
Ejura	Yam in PA	5,914^{a}	4,837^{a}	3.57^{a}	1.25^{a}	76.45^{a}	30.05^{a}	49.20^{a}	19.25^{a}
	Yam in PB	5,881^{a}	4,638^{b}	3.19^{b}	1.04^{b}	65.72^{b}	22.86^{b}	34.05^{b}	11.69^{b}
SED (5%)		118		0.053		10.61		6.02	
Mean		5,297		1.94		40.98		23.24	
Location (Loc)		0.5192		0.0042		0.1508		0.0811	
Year (Yr)		<.0001		<.0001		0.0088		0.0093	
Cropping system (CS)		0.0018		<.0001		0.0006		0.0005	
Loc*Yr		0.0195		<.0001		0.1574		0.0548	
Loc*CS		0.3032		0.0046		0.7356		0.6519	
Yr*CS		0.6842		<.0001		0.0945		0.0852	
Loc*Yr*CS		0.2446		0.4402		0.4039		0.9647	

PA – Pigeonpea in alley; PB – Pigeonpea as border. Means followed by the same alphabet in each year does not significantly differ from each other

Above ground competition (Competition for sunlight)

There was no significant ($P \leq 0.05$) interaction between location, cropping system, and year and their two-way interactions. Cropping system significantly ($P \leq 0.05$) influenced the light intensity on the yam leaves in both locations and years. Generally, the light intensity observed on yam leaves at mid-canopy (MC) of PB and sole yam was similar to the light intensity on the yam leaves of PA in both locations across the years. Also, the light intensity on yam leaves below the canopy of PB and sole yam were significantly ($P \leq 0.05$) higher than the light intensity on yam leaves at mid-canopy (MC) of PA fields (Figure 2.3).

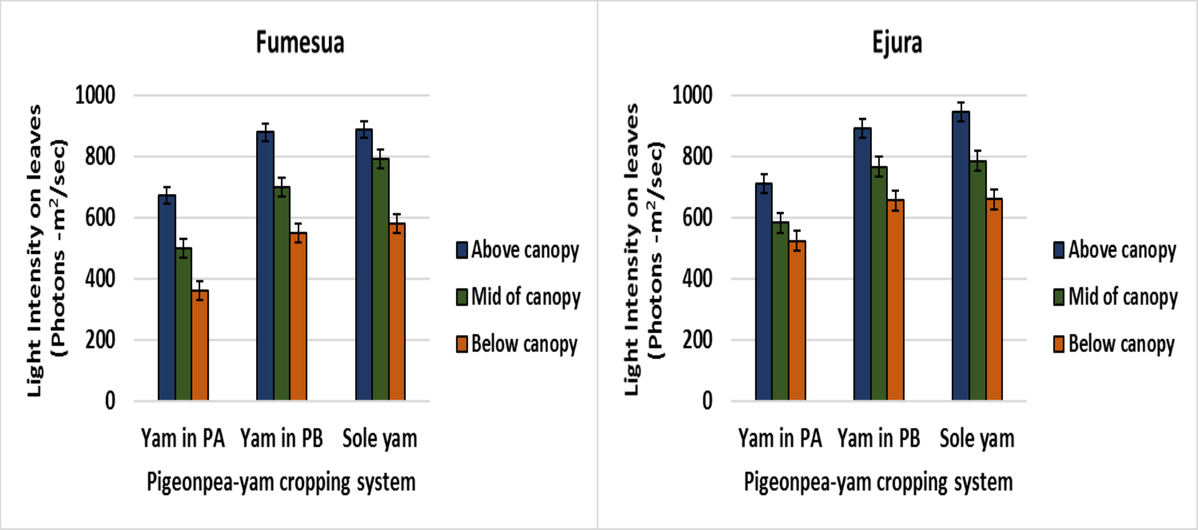

Figure 2.3: Average biweekly (8 – 28 weeks after planting) sunlight photon reaching yam leaves in pigeonpea-yam cropping system at Fumesua and Ejura across 2018 and 2019 cropping seasons. *PA- Pigeonpea in alley; PB – Pigeonpea as border. Error bars represent SED of sunlight reaching a canopy level across seasons.*

Stake and ridge height at harvest

Interaction between location and cropping system significantly ($P \leq 0.05$) influenced the stake height and the ridge height at harvest (Table 2.4). The bamboos used in the sole yam field at both locations and years had an average height of 2.33m and 2.63m in line with the optimum stake height of 2.5m recommended by Rao and Newton (1991), for yam production. The stake height in PA depended on the height of the pigeonpea. Thus, a live-stake pigeonpea with an average height of 2.17m and 2.31m was used at Fumesua and Ejura, respectively. The stake height of the PB field was lowest as a result of shorter pigeonpea stem cuttings used as stakes from the borders with an average height of 0.98m and 1.12m at Fumesua and Ejura, respectively (Table 2.4).

Table 2.4: Stake and ridge height at harvest of yam in cropping systems at Fumesua and Ejura across 2018 and 2019 cropping seasons.

Location	Cropping system	Stake height at harvest (m)	Ridge height at harvest (m)
Fumesua	Yam in PA	2.17^b	0.34^a
	Yam in PB	0.98^c	0.27^b
	Sole Yam	2.33^a	0.20^c
Ejura	Yam in PA	2.31^b	0.38^a
	Yam in PB	1.12^c	0.32^b
	Sole Yam	2.63^a	0.23^c
SED (5%)		0.09	0.01
Mean		1.92	0.29
Location (Loc)		0.0248	0.1465
Cropping system (Cs)		<.0001	<.0001
Loc*Cs		0.0252	0.0005

PA – Pigeonpea in alley; PB – Pigeonpea as border. Means followed by the same alphabet in each location does not significantly differ from each other

Relative chlorophyll content of yam leaves

Significant ($P \leq 0.05$) interaction was observed between pigeonpea-yam cropping system and fertilizer rate on the relative chlorophyll content of yam leaves in both locations and years. The average leaf relative chlorophyll content was significantly ($P \leq 0.05$) higher at Ejura than Fumesua. Generally, at no fertilizer and half fertilizer rate (23-23-30 N-P_2O_5-K_20 kg/ha) leaf chlorophyll content followed the order of PA>PB> sole yam whiles at full rate (45-45-60 N-P_2O_5-K_20 kg/ha) it followed an order of PA=PB>sole yam. The yam leaf chlorophyll content was also similar to the use of half and full fertilizer rate on PA fields (Figure 2.4).

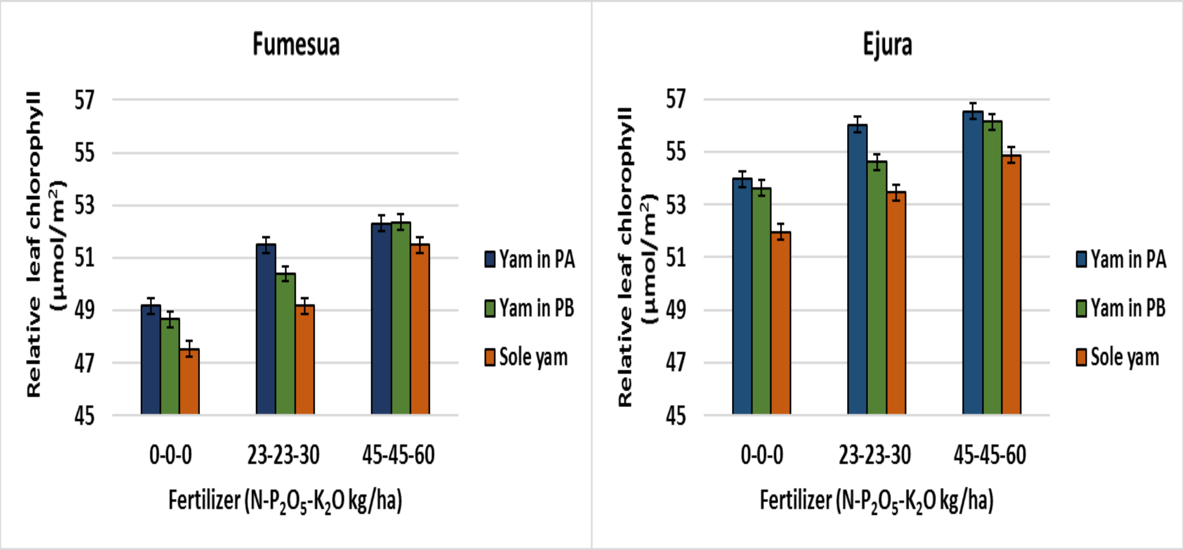

Figure 2.4: Average biweekly relative leaf chlorophyll content of yams in pigeonpea-yam cropping system at Fumesua and Ejura across the 2018 and 2019 cropping seasons. *PA – pigeonpea in alley; PB – Pigeonpea as border. Error bars represent SED of the Cropping system mean across seasons.*

Below ground competition (Competition for water)

The presence of the pigeonpea and biomass on the field influenced the moisture on the ridges (0-40cm). Pigeonpea in alley fields generally had the highest moisture content followed by pigeonpea as a border as a treatment, and the lowest in the sole yam field in both locations and years. Sole yam field had a high percentage of the soil moisture below 400cm as compared to yam planted in PA and PB fields in both locations and years (Figures 2.9a & 2.9b). Thus, soil moisture was available in the ridges for the growth and development of yam during the growing season on PA, followed by PB with worse soil moisture availability on the ridges of the sole yam field for both years and locations.

Weed pressure in the cropping system

Weed pressure was significantly ($P \leq 0.05$) influenced by the pigeonpea-yam cropping system. Weed was significantly ($P \leq 0.05$) suppressed (72 – 73%) in yam planted in PA fields, followed by yam in PB fields (20 – 28%) than sole yam field in both locations and years. Generally, weed pressure was high for all the cropping systems in 2019 than the 2018 cropping season and higher at Ejura than Fumesua for both cropping seasons (Figure 2.5).

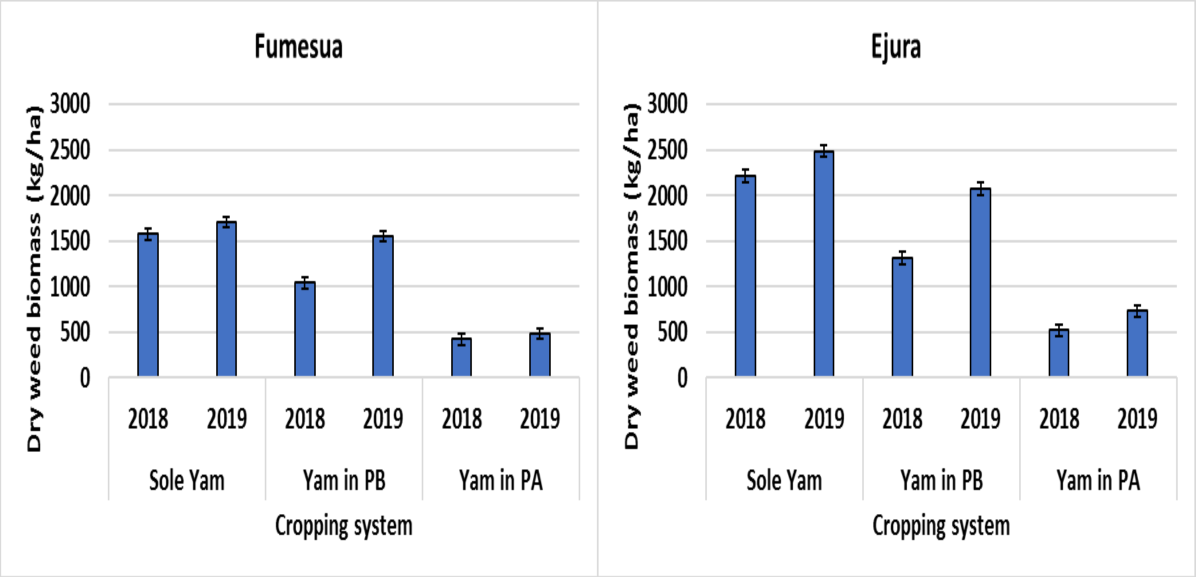

Figure 2.5: Weed pressure 8 weeks after planting in the pigeonpea-yam cropping system at Fumesua and Ejura, for 2018 and 2019 cropping seasons. *PA – pigeonpea in alley, PB – Pigeonpea as border. Error bars represent SED of means of the cropping system.*

Resource use and yam productivity

Significant ($P \leq 0.05$) interactions between location, year, cropping system, and fertilizer was observed on the yam tuber per plant and total tuber yields. Generally, yam productivity was higher at Ejura than Fumesua and in 2018 cropping season than the 2019 cropping season. Also, fertilizer application generally improved yield except in sole yam fields in the 2019 cropping season, where similar yield was observed for no fertilized and half fertilized fields in both locations (Figures 2.6a & 2.6b). Significantly ($P \leq 0.05$) lower per plant yield was observed for the sole yam field irrespective of the fertilizer rate, location, and cropping season (Figure 2.6a). Generally, across locations and years, tuber yields per plant were similar for yam in PA and PB with half fertilizer rate (23-23-30 $N-P_2O_5-K_2O$ kg/ha) and full fertilizer rate (45-45-60 $P_2O_5-K_2O$ kg/ha) than tuber yield per plant on sole yam fields. Also, significantly ($P \leq 0.05$) higher and similar yields were observed for tuber yields of yam in PA with half fertilizer rate (23-23-30 $N-P_2O_5-K_2O$ kg/ha) and full fertilizer rate (45-45-60 $P_2O_5-K_2O$ kg/ha) at both locations and years (Figure 2.6b). The Land Equivalent Ratio (LER) was influenced significantly ($P \leq 0.05$) by the cropping system in both locations and years. The relative yield of yam in all the cropping systems was more than one (1), while that of the pigeonpea was less than 1 for both locations and years. More than 1 LER were recorded for all the intercrop system with yam in PA, recording the highest LER than yam in PB for both locations and years (Table 2.5).

The Pearson correlation indicates the factors that explain the increase in yam tuber components. Total pigeonpea biomass applied and ridge height significantly ($P \leq 0.05$) and directly contributed about R2=77%; R2=53% and R2=66%; R2=54% to yam tuber yield per plant at Fumesua and Ejura respectively across the two cropping seasons. The relative leaf chlorophyll content explains 61% and 30% of the tuber yield per plant at Fumesua and Ejura, respectively. However, a significant ($P \leq 0.05$) inverse relationship was observed between the yam yield components and the total sunlight reaching the yam leaves in both locations across the two seasons (Table 2.6).

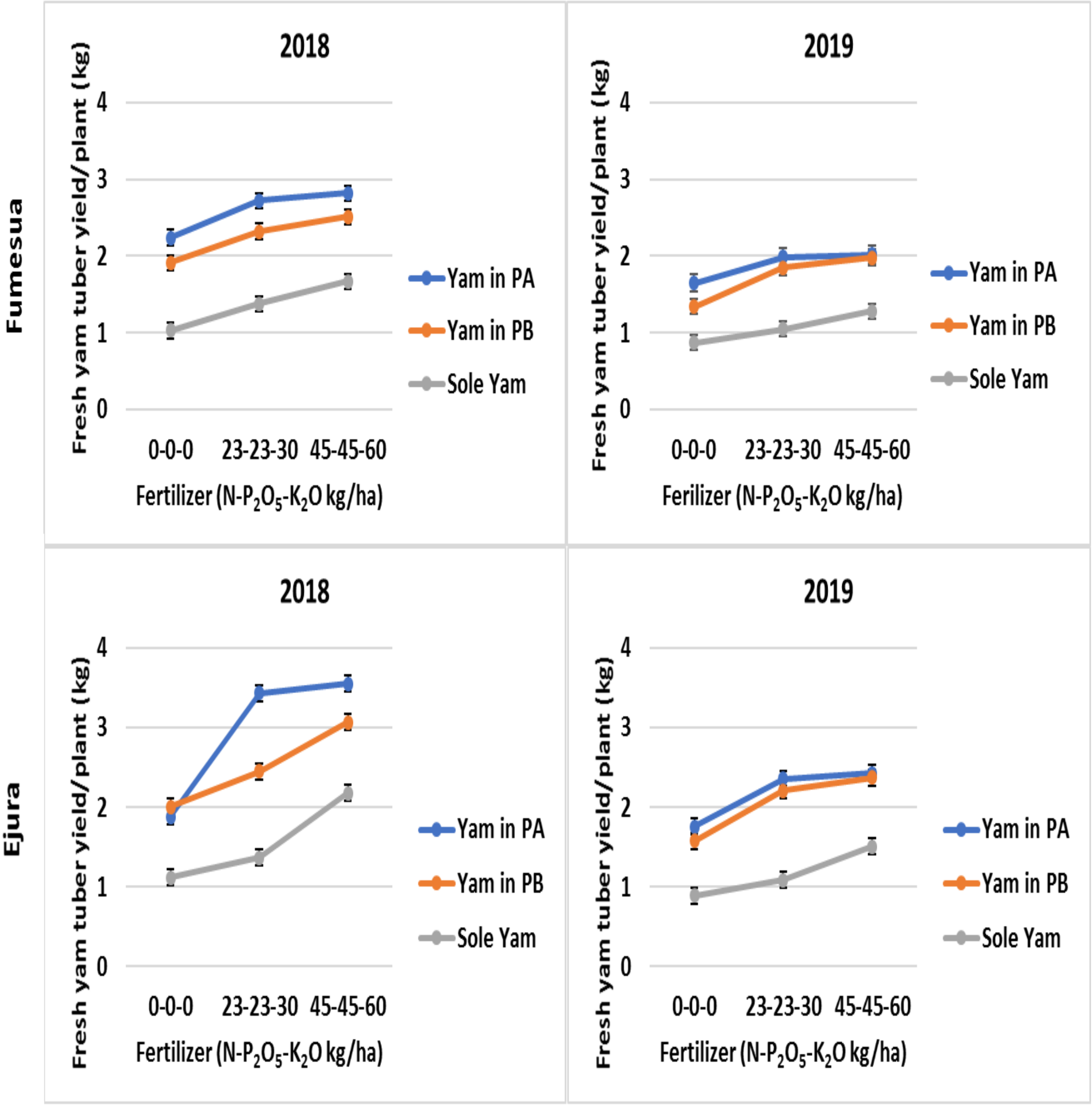

Figure 2.6a: Fresh yam tuber yield per plant in a pigeonpea-yam cropping system at Fumesua and Ejura for 2018 and 2019 cropping seasons. *PA and PB are pigeonpea in alley and pigeonpea as border respectively. Error bars represent the SED of cropping systems.*

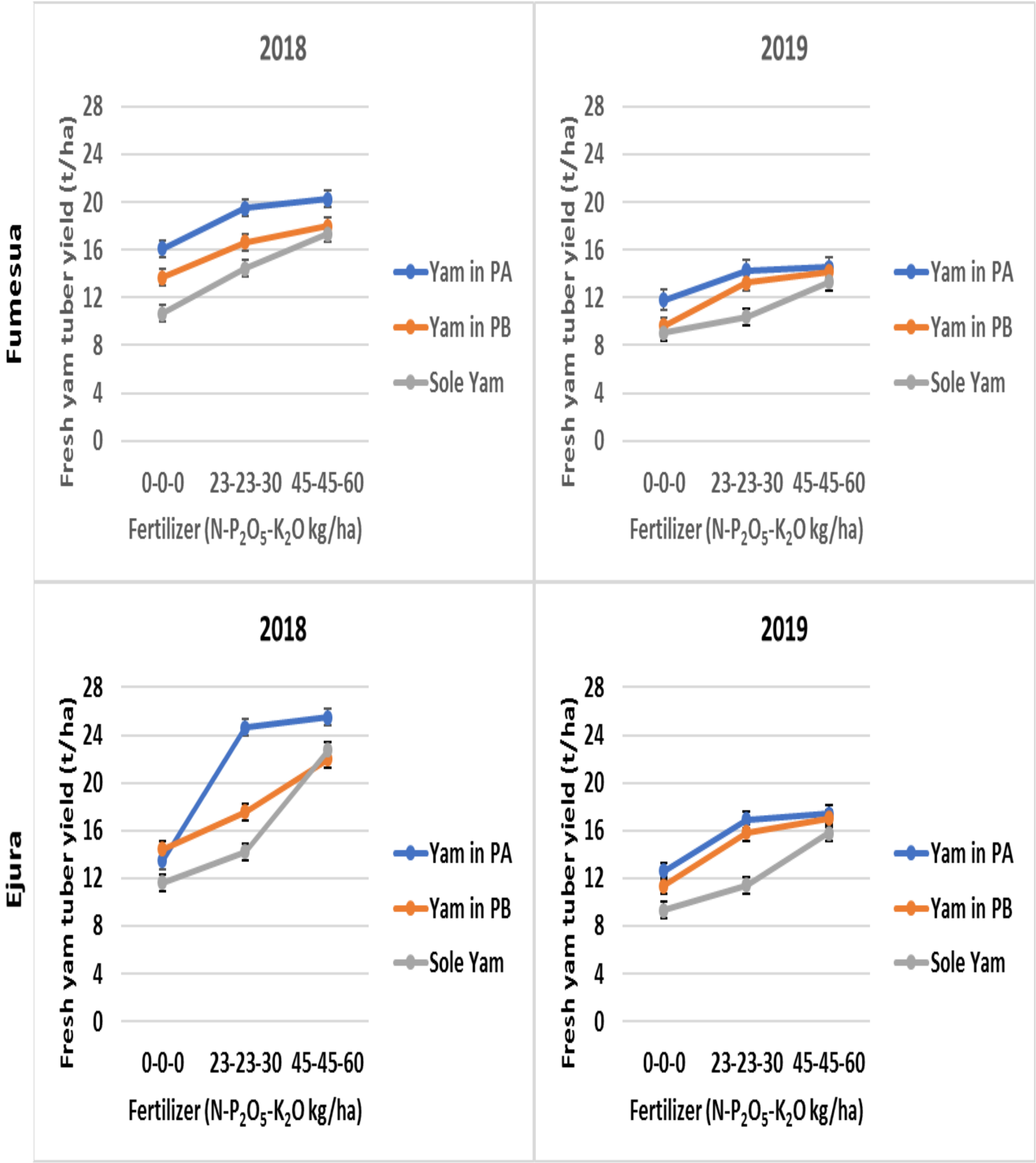

Figure 2.6b: Fresh yam tuber yield in a pigeonpea-yam cropping system at Fumesua and Ejura for 2018 and 2019 cropping seasons. *PA and PB are pigeonpea in alley and pigeonpea as border, respectively. Error bars represent the SED of cropping systems.*

Table 2.5: The land equivalent ratio (LER) of the pigeonpea-yam cropping system at Fumesua and Ejura for 2018 and 2019 cropping seasons.

Location	Cropping System	Relative yield				LER	
		Pigeonpea		Yam			
		2018	2019	2018	2019	2018	2019
Fumesua	Yam in PA	0.30^{a}	0.15^{a}	1.32^{a}	1.24^{a}	1.62^{a}	1.39^{a}
	Yam in PB	0.27^{b}	0.14^{b}	1.14^{b}	1.13^{b}	1.41^{b}	1.27^{b}
Ejura	Yam in PA	0.38^{a}	0.17^{a}	1.31^{a}	1.29^{a}	1.69^{a}	1.46^{a}
	Yam in PB	0.33^{b}	0.14^{b}	1.11^{b}	1.21^{b}	1.44^{b}	1.35^{b}
SED (5%)		0.024		0.059		0.059	
Mean		0.24		1.22		1.46	
Location (Loc)		0.1938		0.5319		0.176	
Year (Yr)		<.0001		0.8691		0.0023	
Cropping system (CS)		<.0001		<.0001		<.0001	
Loc*Yr		0.0028		0.1637		0.4981	
Loc*Cs		0.0004		0.6407		0.4928	
Yr*Cs		0.1625		0.0030		0.0038	
Loc*Cs*Yr		0.4837		0.3432		0.4759	

LER – Land Equivalent ratio; PA – Pigeonpea in alley; PB – pigeonpea as border. Means with the same alphabets within a location indicate no significant (*P≤ 0.05*) differences among treatments.

Table 2.6: Pearson correlation of tuber yield components, sunlight intensity and ridge height at Fumesua and Ejura across 2018 and 2019 cropping seasons.

	Fresh tuber yield/ ha	Fresh tuber yield/ stand	Avg. ridge height	Total sunlight on yam leaf	Rel. leaf chlorophyll content	Applied pigeonpea biomass
Fumesua						
Fresh tuber yield/ ha	1					
Fresh tuber yield/ stand	.891**	1				
Average ridge height	.617**	.812**	1			
Total sunlight on yam leaf	-.605**	-.722**	-.893**	1		
Relative leaf chlorophyll	.930**	.783**	.476**	-.430**	1	
Applied pigeonpea biomass	.648**	.880**	.853**	-.721**	.558**	1
Ejura						
Fresh tuber yield/ ha	1					
Fresh tuber yield/ stand	.911**	1				
Average ridge height	.469**	.727**	1			
Total sunlight on yam leaf	-.421**	-.541**	-.677**	1		
Relative leaf chlorophyll	.701**	.647**	.459**	-.359**	1	
Applied pigeonpea biomass	.508**	.729**	.799**	-.593**	.624**	1

**correlation is significant at the 0.01 level (2-tailed) *correlation is significant at the 0.05 level (2-tailed)

DISCUSSION

Yam sprout rate and establishment

The observed significantly ($P \leq 0.05$) higher stand establishment for planting yam in the PA at Funesua and Ejura for both cropping seasons could be attributed to the shade provided by the pigeonpea and its biomass during the sprouting of the yams. Even in the 2019 cropping season, when pigeonpea biomass reduced significantly for both locations, yam sprouting, and establishment were significantly ($P \leq 0.05$) better on PA and PB fields than the sole yam fields in both locations (Figure 2.2). Thus, shade provided by the pigeonpea canopy and biomass on the ridges resulting in reduced direct heat from the sun and moisture loss from the ridges creating a suitable medium for the yam sprouting and yields. Agbede *et al*., 2013 observed that mulching in yam is essential for the growth and development of yams. Soil nutritional improvement as a result of mulch and the ability of the mulch to control the soil temperature and moisture for the benefit of the yam was demonstrated using *Tithonia* and *Chromoleana* mulch. The use of plant biomass for mulching yam resulted in the reduction of soil temperature between 5 – 7% at 5 – 10 cm depth of the soil for the benefit of the yam (Adeoye 1984). These suggest, to reduce soil temperature and conserve soil moisture, especially in the tropics to prevent seed yam rot and loss after planting, shading, and biomass from the pruning of shrubs such as pigeonpea would play a vital role in yam production.

N and other nutrient contribution of pigeonpea in the system

The generally high pigeonpea biomass production in Ejura than Fumesua, irrespective of the similar stands, could be attributed to the lixisols found at Ejura, which are less weathered and more fertile than the acidic acrisols found at Fumesua (Lal, 1976). Thus, the Ejura fertile soil supported more growth and pigeonpea biomass production at Ejura than Fumesua (Table 2.3). A similar pigeonpea population density was observed for PA and PB in 2018 whiles PA had a higher population density in 2019 and produced significantly ($P \leq 0.05$) higher biomass compared to the PB fields (Table 2.3). This observation could be attributed to the less space and high intra-specific competition for resources by the pigeonpea of the PB field. PB fields had all pigeonpea population crowded at three borders of the field planted at 1.2 X 0.5m, whiles the pigeonpea in an alley field had pigeonpea planted 3.6m X 0.5m. The planting distances imply whiles the intra-specific competition for above ground (Sunlight) and below ground (soil nutrients and water) resources were high among the pigeonpea stands in PB fields, the intra-specific stand competition was minimal in the PA field. As such, the PA would have had almost all resources for growth and accumulation of biomass. Several studies have made similar observations. Kaur and Saini (2018), observed that planting determinate pigeonpea at a wider row spacing of 0.6 m resulted in a significantly high yield attribute than planting at a row spacing of 0.5m and 0.45m. Also, planting pigeonpea at 0.6 X 0.1m resulted in a high yield attribute than planting at 0.45 X 0.1m (Tigga *et al*., 2017). High leafy biomass of the PA field than PB fields contributed to the significantly ($P \leq 0.05$) higher N yield and N-fixation for both locations and years. Significant ($P \leq 0.05$) reduction in the number of stands and leafy biomass in both locations for the 2019 cropping season resulted in significantly lower N yield and N-fixation (Table 2.3). N-fixation depends significantly on the total biomass yield and total N yield of the biomass (Giller, 2001; Peoples *et al*., 2009). Mhango *et al*. (2017) observed that high biomass production of pigeonpea, especially in good rainfall years, resulted in high N-fixation. The significant ($P \leq 0.05$) reduction in the number of stands, leafy biomass, N yield, and N-fixation by PA and PB in both locations in 2019 cropping season might be due to pruning effect from the 2018 cropping season (Table 2.3). Severely pruning of pigeonpea to a height of 25cm significantly reduced the survival and yield of pigeonpea in a pigeonpea-pepper cropping system, although it significantly ($P \leq 0.05$) increased the fruit yield of the associated pepper (Fabunmi et at., 2010). Agyare *et al*. (2002) in managing pigeonpea as a short fallow observed pruning affected biomass production. As such, the control of no pruning treatment recorded significantly ($P \leq 0.05$) higher biomass and seed yields. Thus, the need to further pay attention to the pruning and management of the pigeonpea in the pigeonpea-yam cropping system to ensure sustainable biomass production. Pigeonpea can produce root exudates, enabling it to efficiently take up P from the soil into its biomass for the benefit of associated crops (Ae *et al*., 1990). This observation is in line with the general improvement in phosphorus (P) and cation exchange capacity on the ridges upon applying pigeonpea biomass (Appendix Table 2.7). Dabin, (1980) and Friesen, *et al*. (1997) has indicated high P fixation in tropical soils. Thus, including pigeonpea in the cropping system, especially in the tropics, would be a strategic option for efficient P cycling for the benefit of associated crops.

Resources use and implication on yam productivity in the cropping system

Leaf relative chlorophyll content and tuber yield of yam were influenced significantly ($P \leq 0.05$) by the interaction between cropping system and fertilizer in both locations and years. The generally high leaf relative chlorophyll content and tuber yields at Ejura as compared to Fumesua could be accounted for by the more fertile lixisols at Ejura, which supported plant growth and development than the acidic acrisols found at Fumesua (Lal, 1976) (Figures 2.4, 2.6a & 2.6b). Shiwachi *et al*. (2004) observed that a soil with a pH between 6 and 7, such as in Ejura are suitable for yam production. ECEC improved whiles P reduced at harvest in Ejura soils than Fumesua soils suggesting better uptake of nutrients and P in Ejura soils (pH 6.4 – 6.8) than strongly acidic soils of Fumesua (4.4 – 5.3) (Appendix Table 2.7). The presence of the pigeonpea, especially in yam planted in PA fields, did shade the yam leaves resulting in significantly ($P \leq 0.05$) lower sunlight photons reaching the yam leaves in both locations and years (Figure 2.5), suggesting reduced sunlight on yam leaves as a result of the pigeonpea in the pigeonpea-yam cropping system. However, the shading from the pigeonpea positively resulted in soil moisture conservation, reduced ridge erosion, and reduction in weed pressure (Table 2.4; Appendix Figures 2.9a & 2.9b; Figures 2.6a & 2.6b). Thus, the generally significantly ($P \leq 0.05$) higher tuber yields recorded in 2018 than 2019 cropping season could be attributed to the corresponding high pigeonpea biomass, produced in the 2018 cropping season than 2019 cropping season (Figures 2.6a & 2.6b). Yam in PB fields received similar sunlight photons as the sole yam fields resulting in generally similar sunlight reaching the leaves at various levels of the canopy as compared to sole yam in both locations and years (Figure 2.5). The shading effect of the pigeonpea on the yam in PA, however, did not reduce yam productivity but instead enhanced the yam yields (Figures 2.4, 2.6a & 2.6b; Table 2.6). Significantly ($P \leq 0.05$) higher tuber yields recorded for the yam planted in PA than PB and sole yam in both locations and years indicates the positive effect of the shade and biomass provided by the pigeonpea. Yam as a climber and C3 plant species upon receiving 50% of require light intensity becomes saturated, making yams tolerant to shade and operate under full photosynthetic potential in the moderate shade by increasing their leaf size and chlorophyll content as an adaptation strategy (Coursey and Haynes, 1970; Johnston and Onwueme, 1998).

Also, environmental conditions such as high-temperature results in increased oxygenation reaction along the photorespiratory pathway causing about 25 – 30% losses in carbon fixation especially in C3 plants (Raines, 2011; Sage and Kubien, 2007). Thus, the moderate shading provided by the pigeonpea in the alley might have reduced temperature and improved photosynthetic efficiency resulting in high productivity of yams in PA fields than yam in PB fields and sole yam fields. Improvement in nutrient assimilation and productivity of cocoa under moderate shade have been observed by Isaac *et al*. (2007) and Asare *et al*. (2017) and are in line with this study. Arrangement of agroforestry tree, Flemingia macrophylla in alleys and intercropped with maize – a C4 plant, resulted in similar radiative use efficiency of maize in an alley and sole maize cropping system. The similar radiative use efficiency suggests that shading from the tree component did not significantly affect the quality of photons needed for the maize grain yield (Friday and Fowes, 2002). Stakes for the yam vines to climb are very important for yam productivity (Ennin *et al*., 2014; Owusu Danquah *et al*., 2014). Yam planted in PA and PB had 2.1 – 2.3m live-stake and 0.9 – 1.1m cut stakes respectively from the pigeonpea to climb for enough sunlight (Table 2.4). Pigeonpea has deep root system (Nene and Sheila, 1990 and Akinnifesi *et al*., 2004) and an ability to improve the availability of soil nutrients especially N and P for the benefit of the associated cropping system (Valenzuela and Smith, 2002; Sinclair and Vadez, 2012; Ae *et al*., 1990). These attributes of pigeonpea created a beneficial microenvironment facilitating the use of resources to benefit the yam in the pigeonpea-yam cropping system. Similar relative chlorophyll content of the yams and corresponding similar yam tuber yields for especially yam in PA fields with half fertilizer (23-23-30 kg/ha $N-P_2O_5-K_2O$) and full (45-45-60 kg/ha $N-P_2O_5-K_2O$) fertilizer rates were observed for both locations and years. These results suggest that the half fertilizer rate was able to meet the nutrient requirement of the yam in the presence of the pigeonpea leafy biomass. Even where no fertilizer was applied, yam yields were relatively better with the presence of the pigeonpea biomass on either yam in PA or PB than sole yam fields (Table 2.6). Ennin *et al*. (2013), made a similar observation in a pigeonpea preceding yam cropping system. When pigeonpea preceded yam, tuber yields were higher for 3 t/ha poultry manure and 15-15-20 kg/ha- $N-P_2O_5-K_2O$ and similar to when poultry manure and fertilizer were doubled to 6 t/ha and 30-30-40 kg/ha $N-P_2O_5-K_2O$. The major contributing factor for the significantly ($P \leq 0.05$) higher total tuber yield on the yam pigeonpea intercropped fields (PA and PB) is as a result of the corresponding significantly ($P \leq 0.05$) higher yield per plant compared to the sole yam fields (Figure 2.6a & 2.6b; Table 2.6).

Several studies have observed that the availability of moisture is not only crucial for sprouting and establishment during the early stages of the roots and tuber crops but also vital for bulking larger tubers (Eruola *et al*., 2012; Sunitha *et al*., 2013; Bhattacharjee *et al*. 2011; Ennin *et al*., 2016). Unlike cassava, yam does not penetrate its roots in the soil before bulking, and as such, the tuber expansion, size, shape, and quality are dependent on the soil medium. Mignouna *et al*. (2009) observed that the presence of organic matter on yams would prevent erosion of the medium in which the yam is bulking, increase infiltration and water conservation, and improved microbial activity to enhance yam tuber bulking and yield. Kang and Wilson (1981) found that the size of the bulking medium has a more pronounced influence on yam tuber yield than fertilizer application with significantly higher yields recorded for unfertilized yams on larger size (about 0.30m high) mounds (11.30t/ha) than fertilized yams planted on flat (7.30t/ha) ground.

Although reshaping of the ridges was conducted one and two times for PB and sole yam fields respectively, for this study, no reshaping was needed in the PA fields. The PA fields had a ridge height of 0.34 – 0.38m whiles the PB fields had a ridge height of 0.26 – 0.32m at the time of harvest in comparison to a ridge height of 0.19 – 0.23m in the sole yam fields in both locations and years (Table 2.5). These results suggest that the pigeonpea and biomass on the PA fields protected the ridges from eroding. The significant influence of applied pigeonpea biomass and ridge height on yam tuber yield component (Table 2.3; Figures 2.6a & 2.6b) indicates the vital role pigeonpea could play in a pigeonpea-yam cropping system. Thus, the presence of the pigeonpea would provide shade, reduced erosion of ridges, improve infiltration, conserve moisture, reduce weed pressure, and improve soil nutrition on the ridges resulting in improved yam tuber yield per stand of the associated yam crop.

Yam production along the West African yam belt is far below potential yield, achieving just about 10t/ha yields compared to a potential of about 50t/ha across all yam varieties and increase in yam production are mainly as a result of an increase in the area under yam cultivation (Frossard *et al*., 2017). The Ministry of Food and Agriculture (MoFA), Ghana, had also reported that between 2011 – 2016, when yam production decreased by 6.90%, a correspondent decrease of 5.22% was observed in the area under yam cultivation within the same period (MoFA, 2017). Thus, yam production increase or decrease in Ghana is directly related to increasing the area under yam cultivation. These observations suggest yam would continue to contribute to land degradation and deforestation if improved technologies are not employed to sustain its production on continuously cropped fields, which farmers under normal circumstances would not prefer for yam production. Integrated soil fertility management, along with farmer options and preferences, has been observed to be the way forward (Frossard *et al*., 2017). This study demonstrates that the integration of pigeonpea into the yam cropping system would reduce ridge erosion, improve soil nutrients, and moisture conservation to sustain the productivity of yam even on the continuously cropped fields.

CONCLUSION AND RECOMMENDATIONS

Integrated soil fertility management with pigeonpea biomass and fertilizer is a possible option for sustainable yam production to address the constraint of staking acquisition and soil fertility sustenance resulting in deforestation and land degradation associated with yam production. Apart from the provision of reliable cut-stakes or live-stakes, the pigeonpea biomass and shade reduce ridges erosion, conserves soil moisture, improve yam sprouting, and suppresses weeds. These attributes of the pigeonpea on yam resulted in the facilitation of resources used in the cropping system and enhanced the productivity of yam. Growing yam in an alley of pigeonpea with half fertilizer rate (23-23-30 kg/ha N-P_2O_5-K_2O) resulted in sustained soil fertility, provided live-stake for yam vines and improved yam productivity. Besides, the cultivation of yam with pigeonpea at the borders (equivalent to using about a third of the field for growing pigeonpea) as a reliable source of cut-stakes with half fertilizer rate (23-23-30 kg/ha N-P_2O_5-K_2O) also presents an option better than the sole yam cultivation.

Therefore, integrated soil fertility management of planting yam with pigeonpea with half the recommended fertilizer rate (23-23-30 kg/ha N-P_2O_5-K_2O) has been observed as a way forward for sustainable yam production on continuously cropped fields. However, there would be a need for further studies on the fertilizer rate to ascertain if the half-rate (23-23-30 kg/ha N-P_2O_5-K_2O) can be further reduced without affecting the productivity and returns on the yam. Economic analysis of the pigeonpea-yam cropping system options would be needed to ascertain the profitability of each cropping system option.

Further research work on pruned height and frequency of pruning of the pigeonpea to ensure a sustainable supply of biomass would be needed. Breeding and selecting a more erect, less branching, high biomass, and grain yield would present an ideal pigeonpea accession for the pigeonpea-yam cropping system. The pigeonpea would need about 8 – 12 months to accumulate enough biomass to provide these positive attributes to compliment yam production.

This waiting period may discourage farmers, especially smallholder farmers, with limited access to land to adopt this technology. Therefore, evaluation of the “doubled-up legume” approach of cultivating legumes such as cowpea and groundnut (peanut) during this lag phase (8-12 months) should be pursued for an informed decision on options to make the integrated soil fertility management using pigeonpea-yam for sustainable yam production attractive especially to smallholders.

APPENDIX

APPENDIX

Table 2.7: Physico-chemical properties of the soil at planting of pigeonpea, at planting and harvest of yam at Fumesua and Ejura across 2018 and 2019 cropping seasons.

			% Sand		% Clay		% Silt		Texture		pH 1:2.5		%Total N		ECEC me/100g		Brad P (ppm)	
Location	Cropping system	Fertillizer N-P_2O_5-$K_2$0 kg/ha	0-20cm	20-40cm	0-20cm	20-40cm	0-20 cm	20-40cm	0-20cm	20-40cm	0-20cm	20-40cm	0-20cm	20-40cm	0-20cm	20-40cm	0-20cm	20-40cm
At planting of pigeonpea, May, 2017																		
Fumesua		--	62	58	8	8	30	34	SCL	SCL	4.79	4.43	0.07	0.04	4.05	3.15	38.9	16.0
Ejura		--	76	70	10	10	14	20	SL	SL	7.76	7.88	0.06	0.03	7.24	5.93	36.7	19.9
At planting of yam, May, 2018 & 2019																		
Fumesua	YAP	--	64	66	14	12	22	22	SCL	SCL	5.08	5.09	0.10	0.09	4.80	4.94	260	253
	YPB	--	69	72	10	8	21	20	SCL	SL	4.74	4.88	0.15	0.08	4.87	4.57	235	212
	SY	--	60	66	10	10	30	24	SCL	SCL	4.81	4.86	0.08	0.08	4.21	4.02	163	113
Ejura	YAP	--	74	76	18	17	10	13	SL	SL	6.39	6.39	0.09	0.10	8.12	8.38	264	232
	YPB	--	72	70	18	17	10	13	SL	SL	6.22	6.24	0.09	0.08	6.64	6.34	275	258
	SY	--	74	74	16	15	10	11	SL	SL	6.31	6.08	0.10	0.05	6.38	6.16	228	151
At harvest of yam, December, 2018 & 2019																		
Fumesua	Yam in AP	0-0-0	68	71	10	9	22	20	SCL	SCL	5.12	4.64	0.12	0.13	4.96	3.74	302	337
		23-23-30	72	72	10	10	18	18	SL	SL	4.68	4.52	0.11	0.11	4.32	6.71	268	270
		45-45-60	70	70	9	9	21	21	SCL	SCL	4.44	4.49	0.11	0.10	3.68	4.06	80.1	85.3
	Yam in PB	0-0-0	69	70	10	9	21	21	SCL	SCL	5.05	5.14	0.11	0.11	5.24	5.44	314	342
		23-23-60	73	70	9	9	18	21	SL	SCL	5.26	4.69	0.11	0.44	5.72	4.35	199	133
		45-45-60	69	72	10	9	21	19	SCL	SL	5.16	5.16	0.13	0.12	4.98	5.16	309	304

Table 2.7 (cont’d)

		0-0-0	74	72	8	7	18	21	SL	SL	5.38	5.34	0.10	0.09	5.11	5.28	352	298
	Sole	23-23-30	73	78	9	6	18	16	SL	SL	4.87	5.04	0.10	0.11	4.35	4.06	281	329
	Yam	45-45-60	72	74	7	10	21	16	SCL	SL	5.34	5.75	0.09	0.09	6.38	6.09	119	241
Ejura	Yam	0-0-0	77	74	14	19	9	9	SL	SL	6.68	6.61	0.11	0.11	8.09	7.66	28.3	23.4
	in	23-23-30	81	80	12	13	7	7	SL	SL	6.73	6.87	0.10	0.07	9.17	8.31	82.5	57.9
	PA	45-45-60	73	75	16	19	11	6	SL	SL	6.66	6.67	0.13	0.46	8.44	8.62	71.6	69
	Yam	0-0-0	79	76	13	15	8	9	SL	SL	6.44	6.56	0.09	0.09	6.04	6.59	26.8	35.6
	in	23-23-30	79	78	14	15	7	7	SL	SL	6.46	6.55	0.11	0.09	6.17	6.59	159	32.7
	PB	45-45-60	79	78	12	13	9	9	SL	SL	6.57	6.45	0.10	0.08	7.08	7.03	20.9	20.5
		0-0-0	75	78	15	10	10	12	SL	SL	6.79	6.84	0.10	0.12	7.51	7.15	33.6	20.3
	Sole	23-23-30	81	81	12	12	7	7	SL	SL	6.50	6.49	0.10	0.24	5.97	5.59	44.5	39.5
	Yam	45-45-60	79	77	12	12	9	11	SL	SL	6.43	6.64	0.10	0.08	7.68	7.46	58.0	46.3

SCL – Sandy Clay Loam; SL – Sandy Loam; CS – Cropping System; Y – Yam, S – Sole, PA – Pigeonpea in alley, PB – Pigeonpea as border

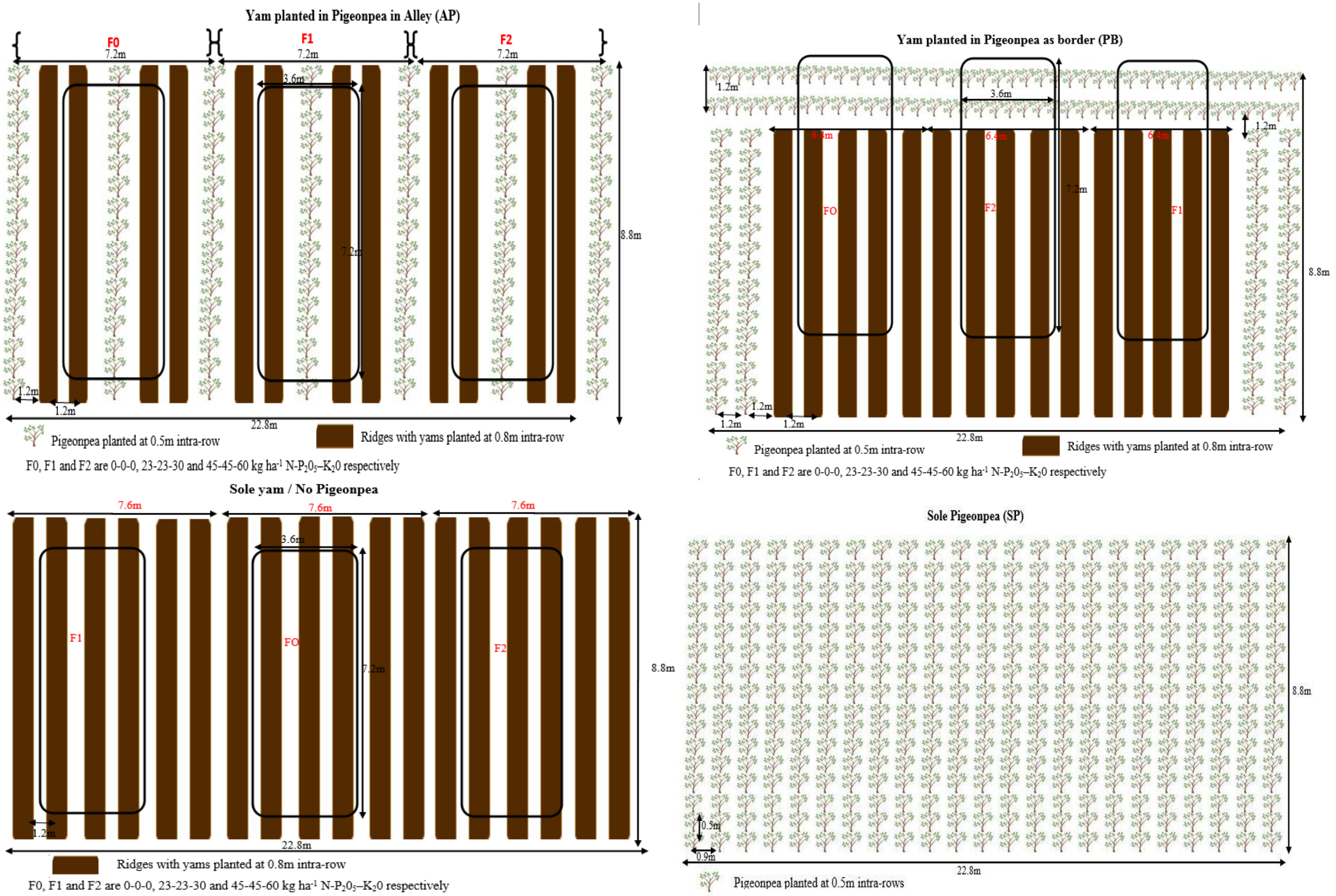

Figure 2.7: Diagrammatic representation and arrangement of treatments on the field

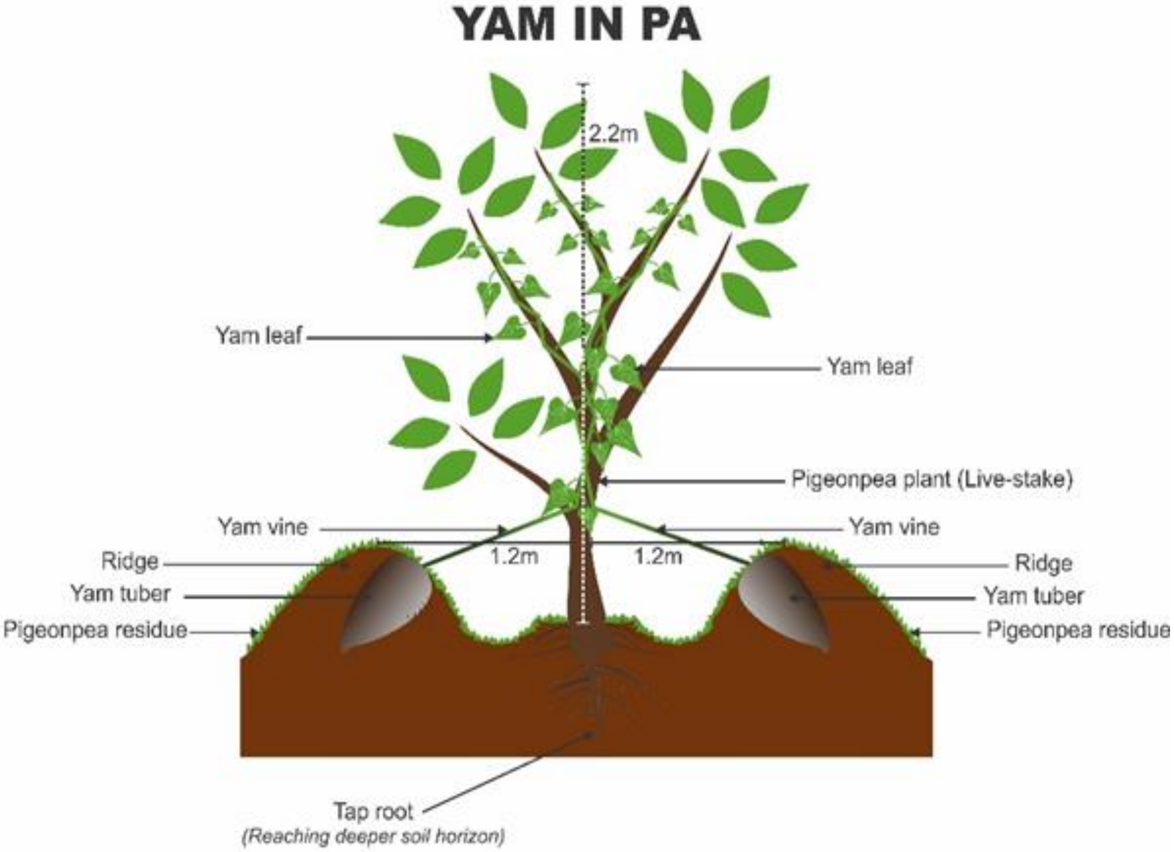

Figure 2.8a: Cross-section pictorial view of the yam in ridges and pigeonpea live- staking option designed for the study. *PA – Pigeonpea in alley*.

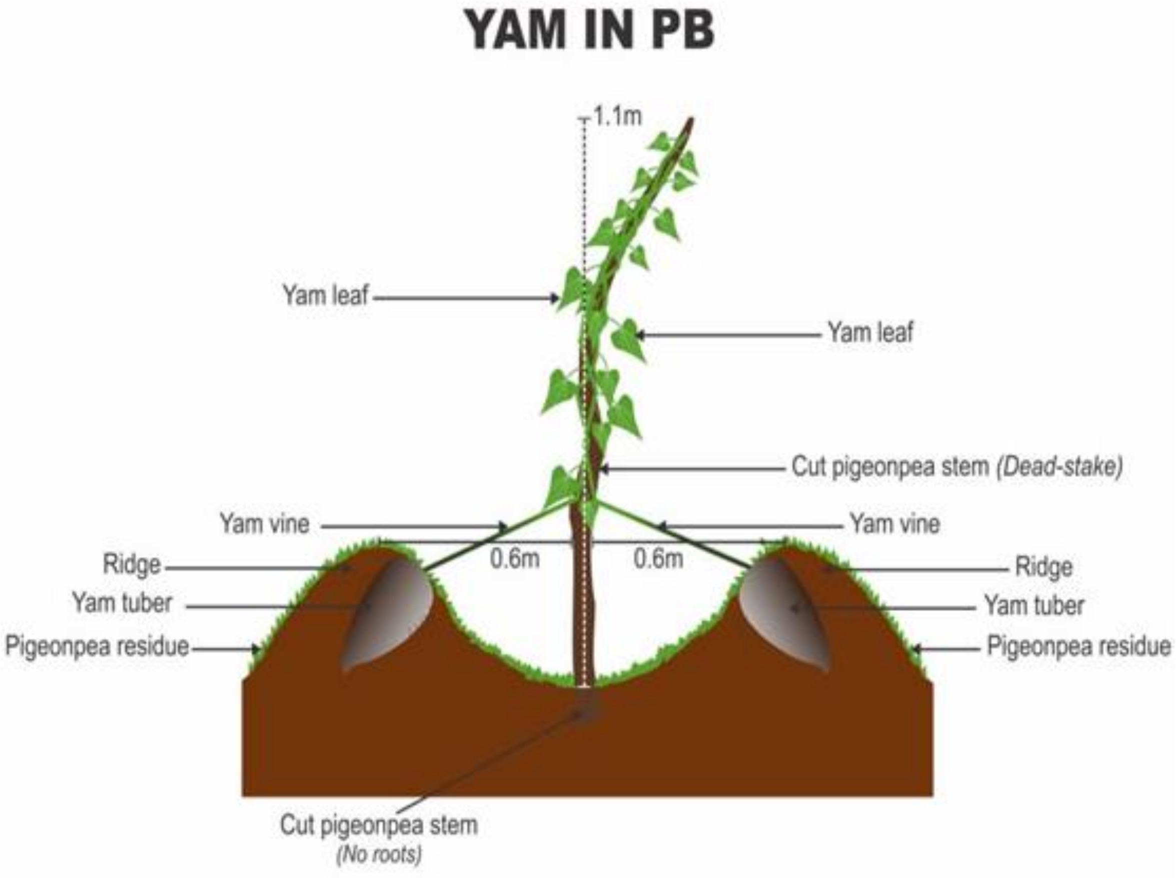

Figure 2.8b: Cross-section pictorial view of the yam in ridges and cut pigeonpea stem staking option designed for the study. *PB – Pigeonpea as a border plant*.

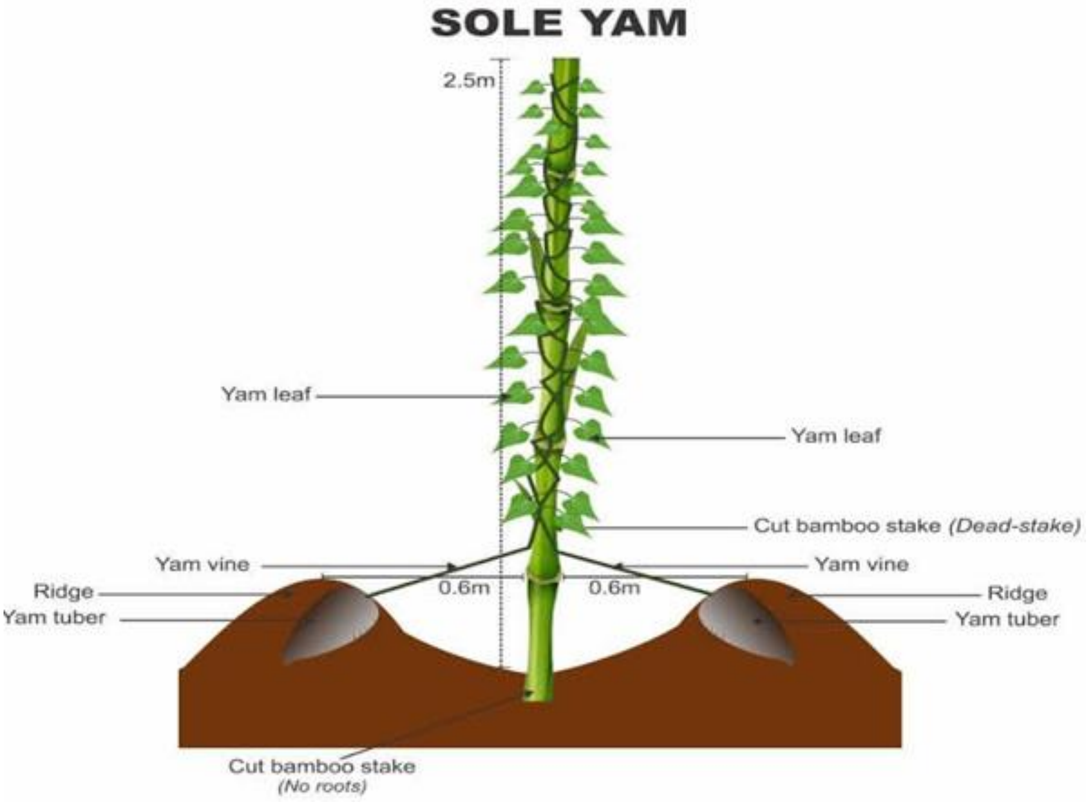

Figure 2.8c: Cross-section pictorial view of the yam in ridges and bamboo staking option designed for the study.

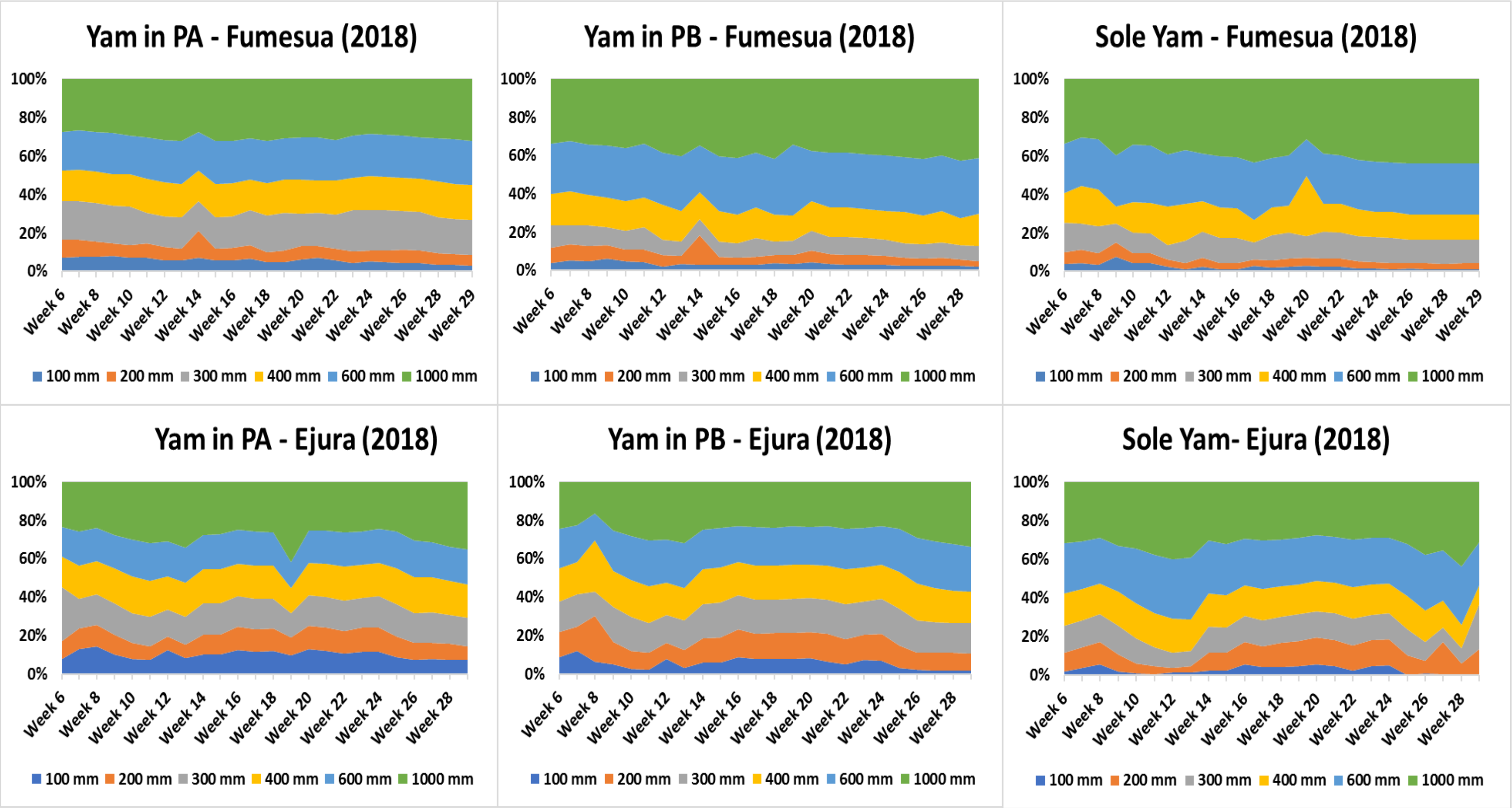

Figure 2.9a: Percentage soil moisture along the soil profile of a pigeonpea-yam cropping system at Fumesua and Ejura 2018 cropping seasons.

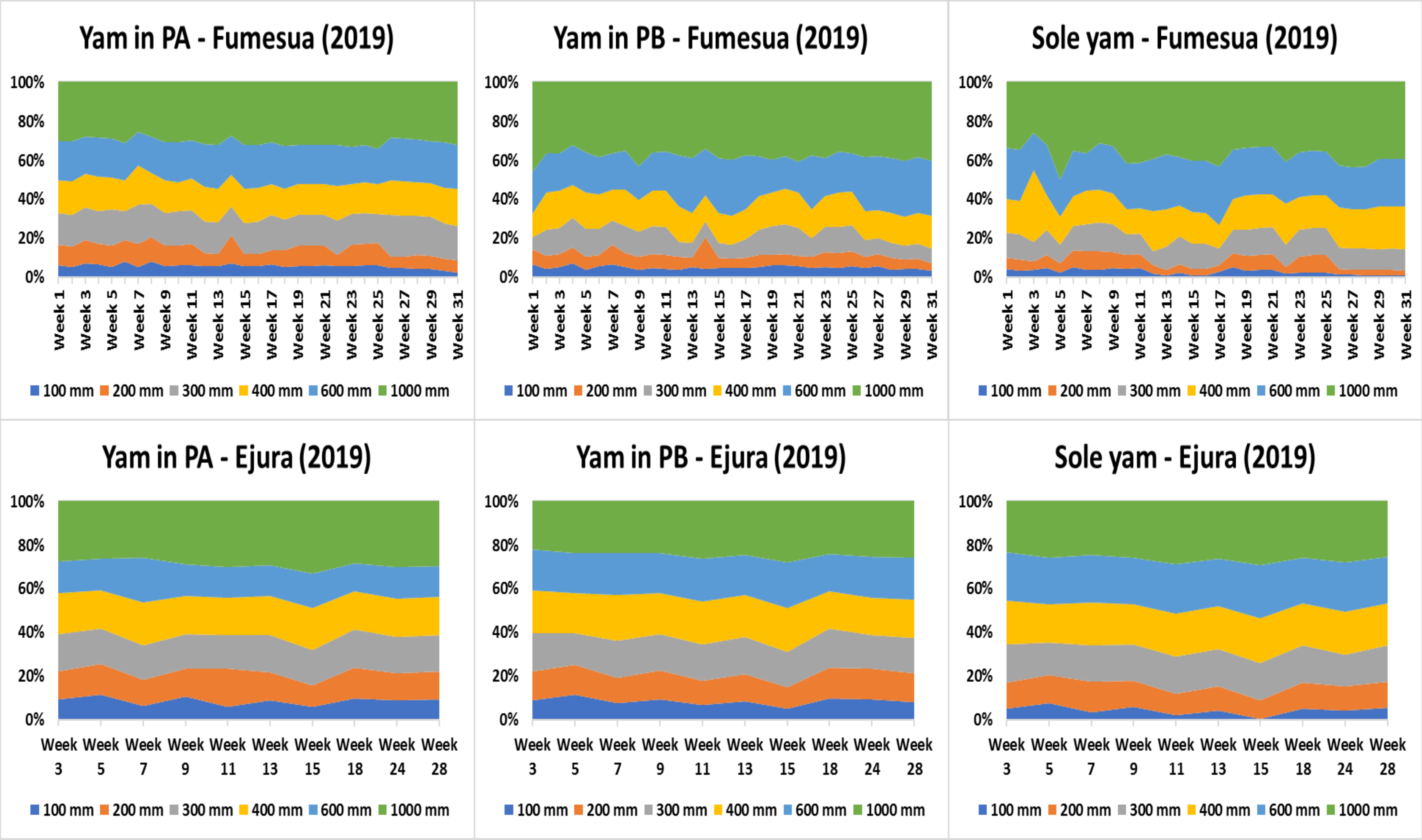

Figure 2.9b: Percentage soil moisture along the soil profile of a pigeonpea-yam cropping system at Fumesua and Ejura, 2019 cropping seasons.

REFERENCES

REFERENCES

Adeoye, K. B. (1984). Influence of grass mulch on soil temperature, soil moisture and yield of maize and gero millet in a savanna zone soil. *Samaru Journal of Agricultural Research* (Nigeria).

Adiku, S. G. K., Jones, J. W., Kumaga, F. K., & Tonyigah, A. (2009). Effects of crop rotation and fallow residue management on maize growth, yield and soil carbon in a savannah-forest transition zone of Ghana. *The Journal of Agricultural Science*, *147*(3), pp.313-322.

Adjei-Nsiah, S., Kuyper, T. W., Leeuwis, C., Abekoe, M. K., & Giller, K. E. (2007). Evaluating sustainable and profitable cropping sequences with cassava and four legume crops: Effects on soil fertility and maize yields in the forest/savannah transitional agroecological zone of Ghana. *Field Crop Research*. 2007;103(2):87–97.

Adu, S. V. (1992). Soils of the Kumasi Region of Ghana. Kwadaso-Kumasi: *Soil Research Institute*.1992.

Adu-Gyamfi, J. J., Myaka, F. A., Sakala, W. D., Odgaard, R., Vesterager, J. M., & Høgh-Jensen, H. (2007). Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize–pigeonpea in semi-arid southern and eastern Africa. *Plant and soil*, 295(1-2), pp.127-136.

Ae, N., Arihara, J., Okada, K., Yoshihara, T., & Johansen, C. (1990). Phosphorus uptake by pigeonpea and its role in cropping systems of the Indian subcontinent. Science, 248(4954), pp.477-480.

Agbede, T. M., Adekiya, A. O., & Ogeh, J.S. (2013). Effects of Chromolaena and Tithonia mulches on soil properties, leaf nutrient composition, growth and yam yield. *West African Journal of Applied Ecology*, *21*(1), pp.15-30.

Agyare, W. A., Kombiok, J. M., Karbo, N., & Larbi, A. (2002). Management of pigeon pea in short fallows for crop-livestock production systems in the Guinea savanna zone of northern Ghana. *Agroforestry Systems*, *54*(3), pp.197-202.

Ajayi, O. C., Akinnifesi, F. K., Sileshi, G., & Chakeredza, S. (2007). Adoption of renewable soil fertility replenishment technologies in the southern African region: Lessons learnt and the way forward. In *Natural resources forum* (Vol. 31, No. 4, pp. 306-317). Oxford, UK: Blackwell Publishing Ltd.

Akinnifesi, F. K., Rowe, E. C., Livesley, S. J., Kwesiga, F. R., Vanlauwe, B., & Alegre, J. C. (2004). Tree root architecture. Below-ground interactions in tropical agroecosystems: concepts and models with multiple plant components". (*Eds M van Noordwijk, G Cadisch, C Ong*) pp. 61-81.

Asafu-Agyei, J. N., Ahenkora, K., Banful, B., & Ennin-Kwabiah, S. (1997). Sustaining food production in Ghana: the role of cereal-legume based cropping systems. Technology options for sustainable agriculture in sub-Saharan Africa, edited by T. Bezuneh, AM Emechebe, J. Sedogo, and M. Ouedraogo. *Semi-Arid Food Grain Research and Development Agency (SAFGRAD) of the Scientific, Technical and Research Commission of OAU, Ouagadougou, Burkina Faso*, pp.409-416.

Asante, A. K. (1996). Use of bast fibre plants as staking materials for yam production in the Guinea Savannah zones of Ghana. *Ghana Journal of Agricultural Science.* National Science of and Technology Press 28-29, 99-103.

Asare, R., Asare, R. A., Asante, W. A., Markussen, B. O & Ræbild, A. (2017). Influences of shading and fertilization on on-farm yields of cocoa in Ghana. *Experimental Agriculture*, *53*(3), pp.416-431.

Bhattacharjee, R., Gedil, M., Sartie, A., Otoo, E., Dominique Dumet, D., Kikuno, H., Kumar, L. P., & Asiedu, R. (2011). *Dioscorea*. In: Wild Crop Relatives: Genomic and Breeding Resources. industrial Crops. C. Kole. *Springer-Verlag Berlin HeIdelberg*; 2011. p. 71–96.

Bray, R. H & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. Soil science, 59(1), pp.39-46.

Coursey, D. G., & Haynes, P. H. (1970). Root crops and their potential as food in the tropics. World Crops, 22, 261–265.

Dabin, B. 1980. Phosphorus deficiency in tropical soils as a constraint on agricultural output. *Priorities for alleviating soil-related constraints to food production in the tropics*, pp.217-233.

Dalton, 1992) F. N. (1992). Development of time-domain reflectometry for measuring soil water content and bulk soil electrical conductivity. Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice, 143–167.

Diby, L. N. G., Tie, B. T., Girardin, O., Sangakkara, R., & Frossard, E. (2011). Growth and nutrient use efficiencies of yams (Dioscorea spp.) grown in two contrasting soils of West Africa. *International journal of agronomy, 2011*.

Ekanayake, I. J., & Asiedu, R. (2003). Problems and perspectives of yam-based cropping systems in Africa. Journal of Crop production, 9(1-2), pp.531-558.

Ennin S. A., Owusu Danquah E., Frimpong F., Akom M., Osei-Adu J., Lamptey J. N. L., Oteng-Darko P., Osei K., Osuman A. S., Aidoo A. K., Adama I., Appiah-Danquah P. HJ. 2016. Yam Production and Marketing Guide. H. Adu-Dapaah, J. N. L. Lamptey, I. S. Baning, B. N. Frimpong JOA and SAE, editor. Kumasi, Ghana: *CSIR-Crops Research Institute*; 2016.

Ennin, S. A., & Dapaah, H. K. (2008). Legumes in Sustainable Maize and Cassava Cropping Systems in Ghana. *Agricultural and Food Science Journal of Ghana*, 2008, 7, 519–540.

Ennin, S. A., Issaka, R. N., Acheampong. P. P., Numafo, M., & Owusu Danquah, E. (2014). Mechanization, Fertilization and Staking Options for Environmentally Sound Yam Production. *African Journal of Agricultural Research*, 2014, 9(29), 2222–2230.

Ennin, S. A., Owusu Danquah, E., and Acheampong, P. P. (2013). "Chemical and integrated nutrient management options for sustainable yam production," in Book of Abstracts of the First Global Conference on Yam (Accra, International Institute of Tropical Agriculture (IITA)), 23.

Eruola, A. O., Bello, N. J., Ufoegbune, G. C., Makinde, A. A. (2012). Application of Rainfall-Potential Evapotranspiration Model for Determining Optimum Planting Date of Yam *(Dioscorea rotundata*) in a Tropical Wet-and-Dry Climate. International Journal of Plant Research 2012, 2(2): 36-40.

Eze, S. C., & Orkwor, G. C. (2010). Studies on effects of mineral fertilizer, organic manure and cultivar on the yield and storability of Yam (*Dioscorea rotundata.* Poir). *African Journal of Food Agriculture, Nutrition and Development*, vol. 10, no. 6, 2010, pp. 2755-2771.

Fabunmi, T. O., Adigbo, S. O., & Odedina, J. N. (2010). Effect of severity of pruning on growth, yield and survivability of pigeon pea (*Cajanus cajan*) in pigeon pea/pepper alley cropping. *J Agricultural Science and Environment*, 10(1), pp.18-26.

Ferguson, T. U., & Haynes, P. H. (1970). The response of yams (*Dioscorea spp.*) to nitrogen, phosphorus, potassium and organic fertilizers. *Tropical Root and Tuber Crops Tomorrow: Proceedings of the 2nd International Symposium on Tropical Root and Tuber Crops*. Plucknett, D. L, (ed.), vol. I, pp. 93-96. Honolulu, Hawaii: College of Tropical Agriculture, University of Hawaii.

Friday, J. B & Fownes, J. H. 2002. Competition for light between hedgerows and maize in an alley cropping system in Hawaii, USA. Agroforestry Systems. Sept. 2002, vol. 55, Iss. 2, pp 125–137.

Friesen, D. K., Rao, I. M., Thomas, R. J., Oberson, A & Sanz, J. I. 1997. Phosphorus acquisition and cycling in crop and pasture systems in low fertility tropical soils. *Plant and soil*, *196*(2), pp.289-294.

Frossard, E., Aighewi, B. A., Aké, S., Barjolle, D., Baumann, P., Bernet, T., Dao, D., Diby, L. N., Floquet, A., Hgaza, V. K., & Ilboudo, L. J. 2017. The challenge of improving soil fertility in yam cropping systems of West Africa. *Frontiers in plant science*, 8, p.1953.

Garrity, D. P. (2004). Agroforestry and the Achievement of the Millennium Development Goals. In: Nair, *et al*. (eds) 2004. *New Vistas in Agroforestry*, Kluwer Academic Publishers, Netherland.

Giller, K. E. (2001). Nitrogen fixation in tropical cropping systems. CABI.

Giller, K. E., & Cadisch, G. (1995). Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant Soil* (1995) 174: 255–277.

Isaac, M., Timmer, V & Quashie-Sam, S. (2007). Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of Theobroma cacao by vector analysis. *Nutrient Cycling in Agroecosystems* 78(2):155–165.

Johnston, M., & Onwueme, I. C. (1998). Effect of shade on photosynthetic pigments in the tropical root crops: yam, taro, tannia, cassava and sweet potato. *Experimental agriculture*, *34*(3), pp.301-312.

Kaur, K., & Saini, K. S. (2018). Performance of pigeonpea (*Cajanus cajan L.*) under different row spacings and genotypes. *Crop Research*, 53(3&4), pp.135-137.

Kang, B. T., & Wilson, J. E., (1981). Effect of mound size and fertilizer on white Guinea yam (*Dioscorea rotundata*) in southern Nigeria. *Plant and soil*, *61*(3), pp.319-327.

Kimaro, A. A., Timmer, V. R., Chamshama, S. A. O., Ngaga, Y. N., & Kimaro, D. A. (2009). Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops. *Agriculture, ecosystems & environment*, 134(1-2), pp.115-125.

Kombiok, J. M., Dogbe, W., & Kanton, R. (1997). Cropping Systems and Long-Term Soil Fertility Management for Sustainable Agriculture in Northern Ghana. In Bezuneh, *et al* (eds.). 1997. Technology options for sustainable agriculture in Sub-Saharan Africa. *Publication of the Semi-Arid Food Grain Research and Development Agency (SAFGRAD) of the scientific, technical and research commission of OAU*, Ouagadougou, Burkina Faso. Pp 417-424

Kotschi, J., Waters-Bayer, A., Adelhelm, R. & Hoesle, U. (1989). Ecofarming in agricultural development (No. 630.2745 E18e). *Tropical Agroecology*. Weikersheim, DE: Margraf.

Kuhlgert, S., Austic, G., Zegarac, R., Osei-Bonsu, I., Hoh, D., Chilvers, M. I., Roth, M. G., Bi, K., TerAvest, D., Weebadde, P. & Kramer, D. M. 2016. MultispeQ Beta: a tool for large-scale plant phenotyping connected to the open PhotosynQ network. *Royal Society open science*, *3*(10), p.160592.

Lal, R. (1976). No-tillage Effects on Soil Properties under Different Crops in Western Nigeria. *Soil science society of America journal*, 40(5), pp.762-768.

Le Buanec, B. (1972). Absorption and uptake of major nutrients by yams. GERDAT. Groupement d'Etudes et de Rechèrche pour le Dévelopment de l'Agronomie Tropicale. IRAT. Institut de Rechèrches Agronomiques Tropicales et des Cultures Vivrières. Nogent-sur-Marne (Côte d'Ivoire) Reunion d'Agronomie de l'IRAT: 1974.

Nene, Y. L. & Sheila, V. K. (1990). Pigeonpea: geography and importance. *Pigeonpea: geography and importance*., pp.1-14.

Mafongoya, P. L., Bationo, A., Kihara, J., & Waswa, B. S. (2006). Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling in Agroecosystems*, 76(2-3), pp.137-151.

McCann, J. (2005). Maize and grace. *Harvard University Press*.

Mhango, W. G., Snapp, S., & Kanyama-Phiri, G. Y. (2017). Biological nitrogen fixation and yield of pigeonpea and groundnut: quantifying response on smallholder farms in northern Malawi. *African Journal of Agricultural Research*, 12(16), pp.1385-1394.

Mignouna, H. D., Abang, M. M., Asiedu, R., & Geeta, R. (2009). Yam (*Dioscorea*) husbandry: Cultivating yams in the field or greenhouse. *Cold Spring Harbor Protocols*, *2009*(11), pp.pdb-prot5324.

Ministry of Food and Agriculture (MoFA). (2017). Agriculture in Ghana; facts and figures. *Statistics, Research and Information Directorate (SRID)*, Ministry of Food and Agriculture, Republic of Ghana.

Odeny, D. A. (2007). The potential of pigeonpea (*Cajanus cajan (L.)* Millsp.) in Africa. Natural Resource Forum. 2007;31: 297–305.

Owusu Danquah, E., Ennin, S. A., Lamptey, J. N. L., & Acheampong, P. P. (2014). Staking Options for Sustainable Yam Production in Ghana. *Sustainable Agricultural Research*. vol. 4 (1):106-113.

Peoples, M. B., Herridge, D. F., & Ladha, J. K., (1995). Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? *In Management of Biological Nitrogen Fixation for the Development of More Productive and Sustainable Agricultural Systems* (pp. 3-28). Springer, Dordrecht.

Peoples, M. B., Brockwell, J., Herridge, D. F., Rochester, I. J., Alves, B. J. R., Urquiaga, S., Boddey, R. M., Dakora, F. D., Bhattarai, S., Maskey, S. L., & Sampet, C. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, 48(1-3), pp.1-17.

Raines, C. A., (2011). Increasing photosynthetic carbon assimilation in C_3 plants to improve crop yield: current and future strategies. *Plant physiology, 155*(1), pp.36-42.

Rao, M. M., and Newton, R. (1991). "A farmer's guide to growing white yam in the Eastern Caribbean." *CARDI*. N.p., May 1991. Web. 20 Feb. 2016.

Roberts, L. (2011). 9 Billion? www.science.sciencemag.org/content/333/6042/540.summary

Sage, R. F & Kubien, D. S. (2007). The temperature response of C3 and C4 photosynthesis. *Plant, cell & environment*, *30*(9), pp.1086-1106.

SAS Institute Inc. Base SAS® 9.4. (2013). Procedures Guide: Statistical Procedures, Second Edition. Cary, NC, USA: SAS Institute Inc.

Saxena, K. B., Kumar, R. V., & Rao, P.V. (2002). Pigeonpea nutrition and its improvement. *Journal of Crop production*, *5*(1-2), pp.227-260.

Shiwachi, H., Okonkwo, C. C., Asiedu R. (2004). Nutrient deficiency symptoms in yams (*Dioscorea spp*). Trop Sci. 44:155–162.

Sinclair, T. R., & Vadez, V. (2012). The future of grain legumes in cropping systems. *Crop and Pasture Science*, *63*(6), pp.501-512.

Snapp, S. S., Rohrbach, D. D., Simtowe, F & Freeman, H. A. (2002). Sustainable soil management options for Malawi: can smallholder farmers grow more legumes?. *Agriculture, Ecosystems & Environment*, 91(1-3), pp.159-174.

Snapp, S. S., Jones, R. B., Minja, E. M., Rusike, J., Silim, S. N. (2003). Pigeonpea for Africa: A Versatile Vegetable - And More. *HortScience*. 2003;38(6):1073–9.

Sunitha, S., Ravi, V., George, J., & Suja, G., (2013). Aroids and water relations: An overview. *Journal of Root Crops*, *39*(1), pp.10-21.

Tigga, B., Chandraker, D. K., Banjara, T. R., Bhagat, S., & Dev, M. (2017). Effect of different genotypes and planting geometry on growth and productivity of rabi season pigeonpea (*Cajanus cajan L*.). *Int. J. Curr. Microbiol. and Appl. Sci*, 6, pp.2188-95.

Toth, S. J. & Prince, A. L. (1949). Estimation of cation-exchange capacity and exchangeable Ca, K, and Na contents of soils by flame photometer techniques. Soil Science, 67(6), pp.439-446.

Unkovich, M., Herridge, D., Peoples, M., Cadisch, G., Boddey, R., Giller, K., Alves, B., & Chalk P. (2008). Measuring plant-associated nitrogen fixation in agricultural systems. Australian Centre for International Agricultural Research (ACIAR), *Australia, Monograph No*. 136, 258pp.

Valenzuela, H., & Smith, J. (2002). Pigeonpea. *Sustainable Agriculture Green Manure Crops, Aug. 2002*. SA-GM-8.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R. E., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E., Woomer, P. L., & Sanginga, N. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*; 2010; vol. 39; Iss. 1; pp. 17 – 24

Walker, T., Silim, S., Cunguara, B., Donovan, C., Parthasarathy, P. R., & Amane, M., Siambi, M. (2015). Pigeonpea in Mozambique: An Emerging Success Story of Crop Expansion in Smallholder Agriculture. *Report. Modernizing Extension and Advisory Services project, University of Illinois at Urbana-Champaign*, Illinois, USA (No. 1098-2016-88859).

Walkley, A. & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science, 37(1), pp.29-38.

Willey, R. (1979). Intercropping-Its importance and research needs.1. Competition and yield advantages. Field Crop Abstracts, 32(1), 1–10.

Young, A. (1997). Agroforestry for Soil Management. 2nd edition. CAB International & International Centre for Research in Agroforestry, Wallingford/Nairobi

CHAPTER 3

EVALUATING LONG-TERM YAM PRODUCTIVITY UNDER INTEGRATED SOIL FERTILITY MANAGEMENT OF PIGEONPEA RESIDUE AND FERTILIZER USING CROP SIMULATION MODEL

ABSTRACT

Integrated Soil Fertility Management (ISFM) for the intensification and sustainable yam production on continuously cropped fields holds the key to addressing deforestation and land degradation associated with yam production along the West African yam belt. The objective of this study was to evaluate the long-term (10 years) implication of integrated soil fertility management of pigeonpea residue and fertilizer on yam tuber yield using the Systems Approach to Land Use Sustainability (SALUS) crop model. The model was calibrated and validated with agronomic data from a three-year pigeonpea-yam evaluation study conducted in the forest and forest-savannah transition zones of Ghana. Six soil fertility management scenarios consisting of factorial of two pigeonpea residue options (yam with pigeonpea residue and sole yam) and three inorganic fertilizer rates (0-0-0; 23-23-30; 45-45-60 N-P_2O_5-K_2O kg/ha) were simulated for their long-term implications on yam tuber yields. The model simulation of the long-term yam yield agreed with the observed results across the two cropping systems, three fertilization rates, and two locations. The root mean square of deviation between the simulated and the observed tuber yield was 0.73 t/ha, mean absolute percentage error was 10.7%, and the coefficient of determination (r^2) was 0.72. Increasing inorganic fertilizer rate from no fertilizer (farmer practice) to half (23-23-30 N-P_2O_5-K_2O kg/ha) and full (45-45-60 N-P_2O_5-K_2O kg/ha) rate on sole yam field in both locations resulted in a dry yam tuber yield range of 1.73-3.15 t/ha, 3.59-4.43 t/ha and 4.83-5.84 t/ha respectively indicating enhanced long-term yam tuber yield with the use of inorganic fertilizer. The use of pigeonpea residue, pigeonpea residue in addition to a half and full recommended inorganic fertilizer rate further increased the range to 4.52-7.26 t/ha, 5.80-8.84 t/ha and 7.0-9.99 t/ha respectively indicating the influence of the pigeonpea biomass in sustaining long-term yam tuber yield. A better probability of long-term yam yield was observed with cultivating yam with only pigeonpea residue (4.52-7.26 t/ha) than planting sole yam with the full recommended fertilizer rate (4.83-5.84 t/ha). These suggest that integrated soil fertility management with pigeonpea residue could be more sustainable than the use of only inorganic fertilizer at any rate for sole yam cultivation. Thus, the use of inorganic fertilizer alone in soil fertility management for yam would not sustain yam production, and at best, would stagnate yam productivity on continuously cropped fields. The study has shown, integrated soil fertility management with legumes such as pigeonpea residue and inorganic fertilizer could sustain soil fertility and yam productivity to address deforestation and land degradation associated with yam production.

Keywords: Modelling, Food Security, Simulation, Sustainability and Deforestation

INTRODUCTION AND RATIONALE

Yam is an essential staple food and food security crop serving as food and income generation to about 60 million people in Ghana and along the West African yam belt (Asiedu and Sartie, 2010; Andres *et al*., 2017). Despite this importance of yam, its production has been dwindling due to many challenges, including declining soil fertility, pests and diseases, and low-quality planting material and thus threatening food security, income, and rural livelihoods (Frossard *et al*., 2017). In Ghana, yam is normally cultivated under monoculture with shifting cultivation in search of fertile land and stakes for yam to climb on (Ennin *et al*., 2014; Owusu Danquah *et al*., 2014). Because yam is a heavy soil nutrient feeder and access to land by smallholder farmers is limiting, it results in continuous cultivation on soils containing less than 1% carbon, which is inadequate to sustain productivity (Benneh *et al.*, 1990; NSFMAP, 1998). Thus, improving soil fertility would increase and sustain yields for smallholder farmers (Diby *et al*., 2011; O'Sullivan *et al*., 2008). The use of biomass and residue of legumes in rotation or intercrop results in increased protection of the soil against erosion, increase soil organic matter, nutrients, and soil water holding capacity (Hayford, 2018; Thierfelder *et al*., 2012; Snapp *et al*., 1998).

Pigeonpea (*Cajanus cajan L*) is a legume shrub identified with high potential of improving N and P cycling for the benefit of associated crops on smallholder farms in the tropics for improved and sustainable crop production (Giller *et al*., 2009; Snapp *et al*., 2010; Ennin *et al*., 2013; Hayford, 2018). Long-term field research involving legumes such as pigeonpea for soil fertility management and productivity of root and tuber crops such as yam is limiting. Also, it takes a longer period to evaluate and monitor productivity and sustainability in cropping systems. Given that, this field study was just for three seasons, and the effect of applied pigeonpea residue on soil fertility and yam productivity may take a longer period than three seasons adds to the multiple questions to be addressed. Can the pigeonpea be managed to play its role of biomass for soil fertility and stakes provision for yams to climb? How much yam productivity improvement could be anticipated in the long-term (10 years) with the use of pigeonpea-yam cropping systems? These questions call for multiple factor field studies over a long period with a major resource commitment. Instead, a process-based cropping system model has been used to offer an efficient and effective option in addressing these research questions within a reasonable time and resource use (Jones *et al*., 2003; Keating, 2003). Process-based crop simulation models such as APSIM, SALUS, and CERES-Maize have been used to explore cropping systems questions resulting in the understanding of the dynamics of crop-soil-climate-management interactions in cropping systems in Africa. These explorations have mostly been conducted for legume-cereal cropping systems (Adiku, 1995; Carberry *et al*., 1996; Whitbread *et al*., 2010; Liu and Basso, 2017; Ollenburger and Snapp, 2014). Not much has been done on the productivity of root & tuber cropping systems with a legume, especially for white yam. This current study explores how integrated soil fertility with pigeonpea biomass residue and fertilizer would sustain yam production on continuously cropped fields using SALUS (System Approach to Land Use Sustainability) model. The SALUS model stimulates and models continuous crop, soil, water, and nutrient conditions under different management approaches for multiple years. The agricultural land use management approaches simulated by SALUS include crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage systems (Basso and Ritchie, 2015). Therefore, using the SALUS, we explore research questions such as: How do integrated soil fertility management impact long-term (10 yrs) yam tuber yields? Are the yam tuber yields on continuously cropped fields sustainable for Long-term (10 yrs)? The simulation's specific objective was to evaluate long-term (10 yrs) yam tuber yield under pigeonpea-yam cropping system management. The specific pigeonpea-yam cropping system options simulated for evaluation include; (a) yam with pigeonpea residue (2t/ha) and full recommended fertilizer rate (45-45-60 N-P_2O_5-K_2O kg/ha) (b) yam with pigeonpea residue (2t/ha) and half recommended fertilizer rate (23-23-30 N-P_2O_5-K_2O kg/ha) (c) yam with pigeonpea residue (2t/ha) and no fertilizer (d) sole yam with full recommended fertilizer rate (45-45-60 N-P_2O_5-K_2O kg/ha) (e) sole yam with half recommended fertilizer rate (23-23-30 N-P_2O_5-K_2O kg/ha) (f) sole yam with no fertilizer. These management approaches were taken to reflect the current yam production practices and the proposed integrated soil fertility management approach for adoption. The sole yam with no fertilizer would represent the baseline scenario and the current practice where farmers with limited access to land do continuous cropping on the same land year after year. The sole yam with full fertilizer option was an intervention approach released to farmers by the CSIR – Crops Research Institute of Ghana (Ennin *et al*. 2016). The integrated soil fertility management options of cultivating yam with pigeonpea residue are being tested as an Integrated Soil Fertility Management (ISFM) option for release to farmers.

MATERIALS AND METHOD

Study site and field experiment for model validation

The field study was conducted on-station at the CSIR – Crops Research Institute at Fumesua (6^{o} 41’ N, 1^{o} 28’ W) and Ejura (7^{o} 23’ N, 1^{o}21’ W) in the forest and forest-savannah transition zones of Ghana respectively (Figure 3.1) from 2017 through 2018 and 2019 cropping seasons. The fields were about 13 – 15 years continuously cropped fields with a rotation of maize and cowpea/groundnut. Ejura soils are Ferric Lixisol; Ejura series with a thick top layer of fine sandy loam whiles Fumesua soils are Ferric Acrisols; Asuasi series with a greyish brown sandy clay loam topsoil (Adu, 1992; MoFA, 2017). Both locations have a bimodal rainfall pattern with rainfall between March – mid-August, and September – November as the major and minor rainfalls, respectively. Minimum and maximum temperatures range between 22 – 31^{o}C and 21 – 34^{o}C at Fumesua and Ejura, respectively, as shown in chapter 2 (Figure 3.1).

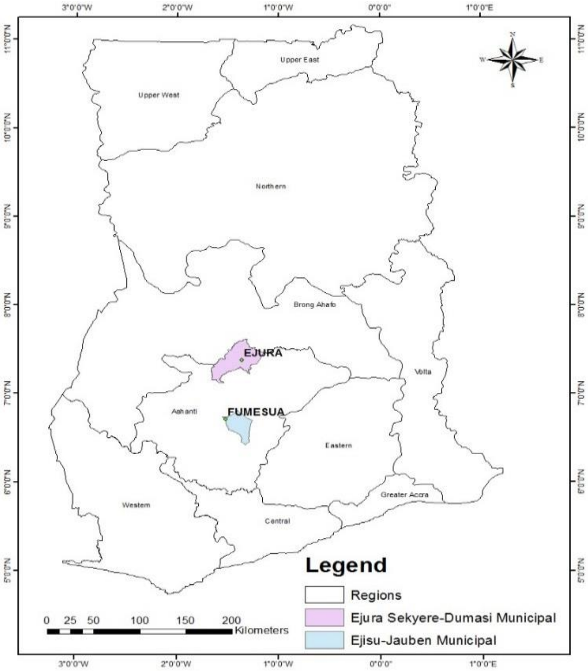

Figure 3.1: Map showing the study area. *Source: Drawn by the author with data from the geological survey department, Ghana, 2019*

The treatments were arranged in a split-plot with three replications. The two main plots were yam in pigeonpea as a border (PB) and No pigeonpea/sole yam. The subplot treatments were variations in fertilizer levels as recommended by CSIR – Crops Research Institute of Ghana for yam production as full-rate – 45-45-60 kg/ha N-P_20_5-K_20; half-rate – 23-23-30 N-P_20_5–K_20 kg/ha and no fertilizer (Ennin *et al.*, 2016). The pigeonpea and yams on the plots followed the replacement/substitutive approach with a row/ridges for yams substituted for pigeonpea around the border of the field for pigeonpea as a border plant. In all locations and years, pigeonpea biomass was pruned and applied on the ridges whiles stems were cut and used as stakes for the yams to climb (Table 3.1). Pigeonpea were planted in 2017 cropping season while the yams were planted, and fertilizer applied in the 2018 and 2019 cropping seasons in both locations. Yam in PB had stakes cut from the border whiles bamboo stakes were procured and transported to the sole yam field for staking.

Table 3.1: Population of pigeonpea, yam and total pigeonpea biomass applied in the study.

Cropping system	Size of the plot (m^2)	Number of pigeonpea/ ha	Number of yam/ ha	Dry biomass kg/ha applied	
				Fumesua	Ejura
Yam in PB	200.64	5,931	7,177	1521.44	2113.06
Sole yam	200.64	--	10,416	--	--

NB- PB had two rows of PP & yam planted at inter and intra-row of 1.2X 0.5m along three sides of the field and 1.2X 0.8m, respectively. Whiles sole yam had 1.2 X 0.8m of the only yam. PB – Pigeonpea as a border plant

A local pigeonpea accession and the "Pona" variety of white yam (*Dioscorea rotundata*) were used. Ridges were constructed manually on all treatments. After being treated with a fungicide and insecticides, yam sets were planted in April and May at Fumesua and Ejura respectively for both seasons. The fertilizer was split applied at 5-6 and 12 weeks after planting in both locations and years. Weeds were controlled manually 4 and 5 times on the PB and sole yam fields respectively in both locations and years. Re-shaping of ridges took place one and two times for PB and sole yam fields. Yam tubers were harvested in December in all locations and years. Soil sampling was conducted at planting and harvesting on the ridges at 0 - 20cm and 20 – 40cm for all treatments, locations, and years.

Overview of the Systems Approach to Land Use Sustainability (SALUS) model

SALUS model is a process-based cropping system model that simulates the interaction between climate-soil-crop-management and their implications on soil water & nutrient cycling and crop growth & development (Figure 3.2). The SALUS model was derived from the Crop Environment Resource Synthesis (CERES) with improved modifications to soil nutrient, and water-cycle growth cycle (Basso and Ritchie, 2015; Basso *et al*., 2016). SALUS runs on a daily time step for multiple years using a minimum input dataset of daily weather data, the soil at each layer, crop genetics parameters, and field management data. The daily weather data consist of minimum and maximum temperatures, precipitation, and solar radiation. The soil layer data consist of layer depth, drained upper limit, lower limit, bulk density, and organic carbon. The field management data includes details of planting date, fertilizer use and rate, and date of harvesting. It uses two main approaches; simple and complex, in the analysis of the development and growth of crops. The simple approach is based on the generic crop-specific curve of leaf area index (LAI), to the thermal time for crop development (crop durations) and potential biomass accumulation (harvest index) in the face of the prevailing stresses such as temperature, water, N on the plant development in the season (Liu and Basso, 2017; Dzotsi *et al*., 2013). The complex approach is similar to CERES, where genetic coefficients are used. Leaf area, ability to use radiation efficiently, and the ability of the crop to grow in the presence of nutrient and water stresses are vital for biomass accumulation. The SALUS soil nutrient cycling model was adapted from the century (Parton *et al*., 1988) with temperature, clay, and water functions modified. Soil organic matter (SOM) goes through the process of decomposition, mineralization of N, N immobilization, and transformation into gaseous N. The model uses three pools of phosphorus and three soil organic carbon pools; active, slow and passive. Also, turnover rate and C: N ratio are factored in the model for the simulation SOM, N mineralization, and immobilization. Fresh crop residue such as pigeonpea biomass is split into two pools of structural and metabolic using their N and lignin content. SOC goes through a dynamic process starting with residue and root decomposition, mineralization in the soil, immobilization, and loss to the atmosphere in gaseous form. The SOC initialization process follows the method used by Basso *et al*., 2011, and an example of the SOC decomposition process shown by Senthilkumar *et al*. (2009). The water balance followed the method used by Ritchie for simulating infiltration, drainage, evapotranspiration, runoff, and water redistribution (Basso and Ritchie 2012; Suleiman and Ritchie 2003). K cycle was not considered in the model. SALUS, however, does not simulate weed, pests, and diseases.

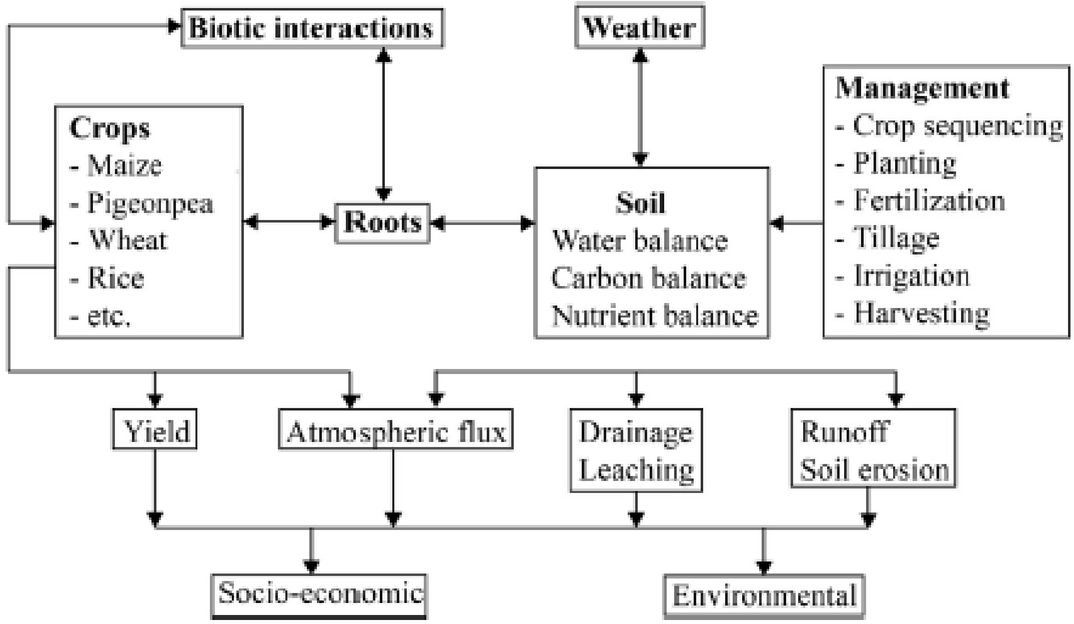

Figure 3.2: Overview of the System Approach to Land Use Sustainability (SALUS). *Source: Basso et al., 2006)*

SALUS model validation

SALUS has been tested for simulation of cropping systems under different climates. Simulated cereal gain yields match observed yields in Italy with a Mediterranean climate (Basso *et al*., 2011; Pezzuolo *et al*., 2014), in Argentina with a humid subtropical climate (Albarenque *et al*., 2016) and in the warm, humid climate of the US (Basso and Ritchie, 2015). It has been used successfully to simulate spatial variability in maize-pigeonpea cropping system's productivity in the humid subtropical and tropical savannah climates of Malawi (Liu and Basso, 2017). Also, grain yield, evapotranspiration, drainage and SOC dynamics in cropping systems under various management has been tested and simulated (Basso and Ritchie, 2015; Basso *et al*., 2015; Basso *et al*., 2006; Senthilkumar *et al*., 2009; Basso and Ritchie, 2012). In this study, the SALUS model was parameterized to represent the growth and development of the white yam (*Dioscorea rotundata*) variety "Pona" in Ghana. SALUS model was tested against observed yam tuber yield under two cropping systems (sole yam and yam in pigeonpea as border plant) with three fertilizer application levels (0-0-0, 23-23-30 and 45-45-60 N-P_20_5–K_20 kg/ha) for two years (2018-2019) in two locations, Fumesua and Ejura (Chapter 2). The soil and management input for model validation was collected during field experiments, discussed in Chapter 2. The weather input for SALUS validation was derived from two sources. Daily rainfall, minimum and maximum temperatures were obtained from weather stations near the two study sites, provided by the Ghana Meteorological Agency. The daily solar radiation was obtained from the grided, Prediction Of Worldwide Energy Resources (POWER) Agroclimatology dataset (https://power.larc.nasa.gov).

The accuracy of the model was assessed using Root Mean Square of Deviation (RMSD), the Mean Absolute Percentage Error (MAPE) between simulated and observed tuber yield, and the Coefficient of Determination (r^2) of a linear regression model with simulated yam tuber yield as the independent variable and observed yam tuber yield as the dependent variable (Figure 3.4). The Root Mean Square of Deviation (RMSD) (Eqn. 3.1) indicates the magnitude of the mean difference between observed and simulated results (Pineiro *et al*., 2008). The mean absolute percentage error (MAPE) (Eqn. 3.2) indicates the percentage of the relative difference between simulated and observed data (Chipanshi *et al*., 2015; Kumar *et al*., 2013). When $\text{MAPE} < 10\%$, $10\% \leq \text{MAPE} \geq 20\%$, and $\text{MAPE} > 20\%$, it means the performance of the model is highly accurate, good accuracy, and low accuracy prediction, respectively (Ramasamy *et al*., 2015). The Coefficient of Determination (r^2) indicates the strength of correlation between the observed and simulated yields. The r^2 ranges from 0 and 1. r^2 of 1 indicates a perfect correlation between observed and simulated yield, and r^2 of 0 means no correlation between the two yields (Chipanshi *et al*., 2015; Johnson, 2014).

$$\text{RMSD} = \left[\, (n-1)^{-1} \Sigma\, (\text{simulated} - \text{observed})^2 \,\right]^{0.5} \tag{3.1}$$

Where n is the number of observations

$$\text{MAPE} = \left[\, n^{-1} \Sigma\, (|\text{observed} - \text{simulated}|)/(|\text{observed}|)\right] \text{X } 100 \tag{3.2}$$

where n is the number of observations,

Simulation experiment

We used the validated SALUS model to evaluate the effect of integrated soil fertility management of pigeonpea biomass and fertilizer on long-term (10 years) yam tuber yield. Two cropping systems consisted of yam in pigeonpea as the border (Yam in PB) and sole yam cultivation. Each cropping system was split into three, where the recommended fertilizer rate of full rate-45-45-60 N-P_2O_5-K_2O kg/ha, half rate – 23-23-30 N-P_2O_5-K_2O kg/ha and no fertilizer were applied (Table 3.2). Simulations were carried out for 2010-2019. The long-term weather record was derived from NASA POWER. In simulations, 2 t/ha of dried pigeonpea leafy biomass (average leafy biomass produced in the experiments for two years) was added annually for the PB cropping system.

Table 3.2: Agronomic management evaluated for long-term (10 yrs) yield implication on yam in the study.

Cropping system	Fertilizer (N-P_2O_5-K_2O kg/ha)	Agronomic management description
Sole yam	No fertilizer	Yam cultivated continuously in 2010-2019 on ridges with no fertilizer. Only yam tubers harvested and exported from the field.
	23-23-30	Yam cultivated continuously in 2010-2019 on ridges with half recommended fertilizer rate. Only yam tubers harvested and exported from the field.
	45-45-60	Yam cultivated continuously in 2010-2019 on ridges with full recommended fertilizer rate. Only yam tubers harvested and exported from the field
Yam in PB	No fertilizer	Yam cultivated continuously in 2010-2019 on ridges with pigeonpea as the border plant. Average dry pigeonpea residue of 2t/ha with no fertilizer applied on ridges. Only yam tubers harvested and exported from the field.
	23-23-30	Yam cultivated continuously in 2010-2019 on ridges with pigeonpea as the border plant. Average dry pigeonpea residue of 2t/ha and half recommended fertilizer rate applied on ridges. Only yam tubers harvested and exported from the field.
	45-45-60	Yam cultivated continuously in 2010-2019 on ridges with pigeonpea as the border plant. Average dry pigeonpea residue of 2t/ha and full recommended fertilizer rate applied on ridges. Only yam tubers harvested and exported from the field.

Statistical analysis

To compare the integrated soil fertility management treatment options, the dry tuber yields for all the ten years (2010 – 2019) of each treatment were presented in line and empirical cumulative distribution function graphs.

RESULTS

SALUS model evaluation

SALUS model was able to reproduce yam cultivation in Ghana with good accuracy. The root means square of deviation (RMSD), and the mean absolute percentage error (MAPE) between the simulated and observed yam tuber yield was 0.73t/ha and 10.73%, respectively. Overall, the simulated tuber yield matched with the observed yield, with a coefficient of determination (r^2) of 0.72 (Figure 3.3).

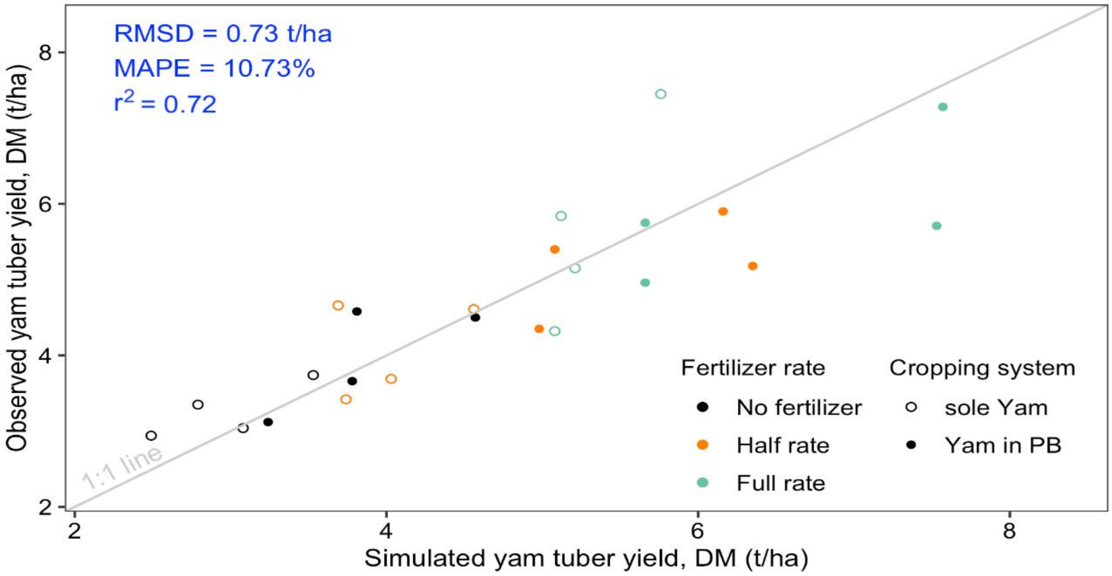

Figure 3.3: Comparisons between simulated and observed yam tuber dry matter yield across two cropping systems under three fertilizer rates in 2018-2019 at two sites. *DM – Dry Matter; No fertilizer, Half rate, and Full rate are 0-0-0, 23-23-30, and 45-45-60 N-*P_2O_5*-*K_2O *kg/ha, respectively.*

Effect of cropping system and inorganic fertilizer on long-term yam tuber yield

For cultivating sole yam without fertilizer input on continuously cropped fields (farmers practice) for ten (10) years, the dry tuber yield ranged from 2.31 to 2.92 t/ha and 1.73 to 3.15 t/ha at Fumsua and Ejura respectively. The probability of exceeding 2.5 t/ha is 50% and 40% at Funesua and Ejura respectively (Figures 3.4 & 3.5). When sole yam was fertilized with half and recommended full fertilizer rate, yam tuber yield improved to 3.59-4.43 t/ha and 4.83-5.65 t/ha, respectively, at Fumesua. At Ejura, the use of half and full fertilizer rates on the sole yam field resulted in an improved yam tuber yield range of 3.73-4.16 t/ha and 5.03-5.84 t/ha respectively. At Fumesua, yam tuber yield would not exceed 4.0 t/ha and 5.4 t/ha under half and full fertilizer rate, respectively, when given a 70% probability. Given 60% probability, yam tuber yield would not exceed 4.0 t/ha and 5.4 t/ha under half-rate and full-rate fertilizer input, respectively at Ejura. (Figures 3.4 & 3.5). Incorporation of pigeonpea leaf residue further enhanced yam tuber yields in both locations. At Fumesua, cultivating yam with pigeonpea residue alone, pigeonpea residue with half fertilizer rate, and pigeonpea with full fertilizer rate resulted in yam tuber yield range of 4.52-6.02 t/ha, 5.80-7.74 t/ha and 7.0-8.38 t/ha respectively. At Ejura, pigeonpea residue alone, pigeonpea residue with half fertilizer rate, and pigeonpea residue with full fertilizer rate resulted in a yield range of 5.81-7.26 t/ha, 6.92-8.84 t/ha and 7.91-9.99 t/ha respectively (Figure 3.4). There is a 30% and 100% chance of exceeding 5t/ha tuber yield at Fumesua and Ejura respectively, upon using pigeonpea residue without fertilizer. The use of half recommended fertilizer rate in addition to the pigeonpea residue improved the chances of exceeding 6 t/ha to 70% and 100% at Fumesua and Ejura respectively. Yam tuber yield is further enhanced exceeding 7.5 t/ha at a probability of 30% and 100% for Fumesua and Ejura respectively when full recommended fertilizer rate is used in addition to pigeonpea residue (Figure 3.5). The range and chance of improving yam tuber yield were better when yam was cultivated with only pigeonpea residue than when sole yam was cultivated with full fertilizer rate (Figures 3.4 & 3.5).

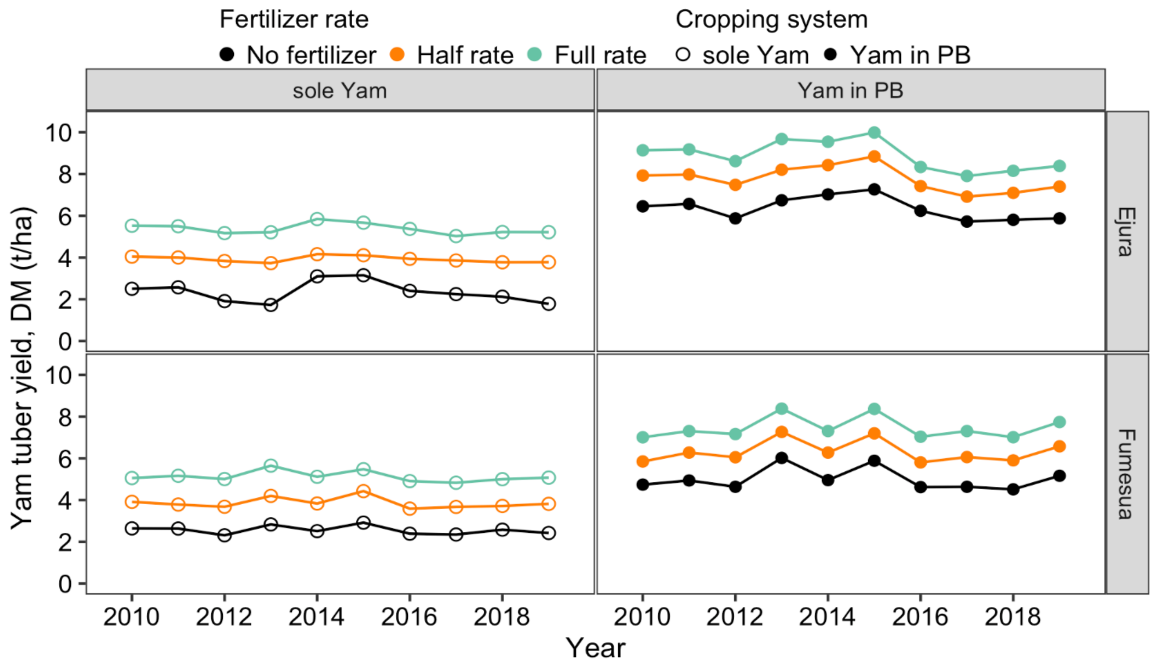

Figure 3.4: Simulated long-term (10 yrs) yam yield, dry tuber yield (DM), under two cropping systems, and three inorganic fertilizer rates at two sites. *DM – Dry Matter; No fertilizer, Half rate, and Full rate are 0-0-0, 23-23-30, and 45-45-60 N-P_2O_5-K_2O kg/ha, respectively.*

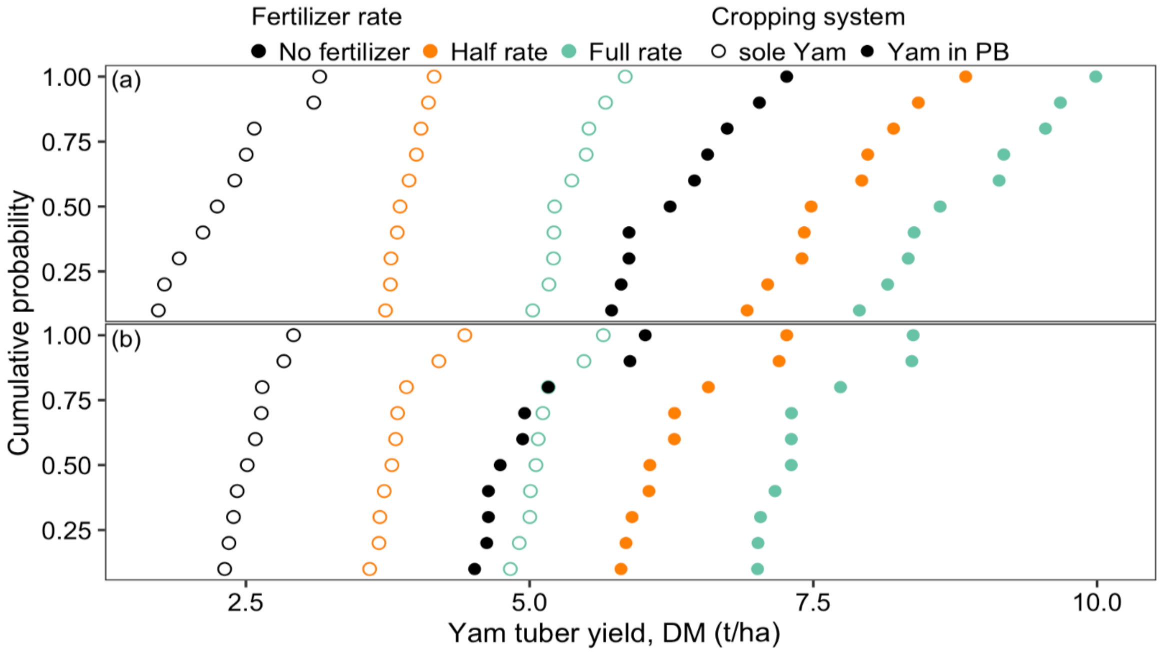

Figure 3.5: Cumulative probability of yam tuber yield, dry matter (DM), under two cropping systems and three inorganic fertilizer rates at two sites: (a) Ejura and (b) Fumesua. *No fertilizer, Half rate, and Full rate are 0-0-0, 23-23-30, and 45-45-60 N-P_2O_5-K_2O kg/ha, respectively.*

DISCUSSION

Models are simplified, formal representations of relationships between defined quantities or qualities in physical and mechanical terms developed to assist in making informed decisions in the management of agricultural systems (Jeffers, 1982: Basso and Ritchie, 2015; Oteng-Darko *et al*., 2013). SALUS evaluated ISFM of pigeonpea and inorganic fertilizer implication on the long-term (10 yrs) yam tuber yield on the continuously cropped fields. The generally better yield range and the chance of improving long-term tuber yields recorded at Ejura than the Fumesua could be attributed to the more fertile soil (Lixisols) with almost neutral pH (6.6 – 7.9) at Ejura than acidic acrisols with very strong acid pH (4.4-5.2) at Fumesua (Chapter 2; Lal, 1976). This soil condition favored yam growth and yield at Ejura than Fumesua. The better chance of sustaining long-term yields on the PB field than the use of sole yam irrespectively of the tested fertilizer rates and location (Figure 3.4 & 3.5) indicates the impact of the pigeonpea residue on soil fertility and yam yield on continuously cropped fields. The pigeonpea residue improved nitrogen (N), phosphorus, and the exchangeable cation capacity (ECEC) of the soil. Also, the presence of the pigeonpea residue improved soil moisture and reduced erosion of the ridges favoring bulking and tuber yield (Chapter 2).

Several studies have noted the integration of leguminous shrub such as pigeonpea (*Cajanus cajan*), *gliricidia sepium* into yam cropping system did improve on soil N, nutrient cycling and yam tuber yields (Ennin *et al*., 2013; Maliki *et al*., 2012a; Maliki *et al*., 2012b; Liu *et al*., under review). The better chance of sustaining long-term yam yields upon planting yam with pigeonpea residue without fertilizer than planting yam as a sole crop with any inorganic fertilizer rate (Figures 3.4 & 3.5), indicates that the use of only inorganic fertilizer in soil fertility management on continuously cropped fields is not sustainable. This is in line with the observation that the use of only inorganic fertilizer for long-term resulted in a faster loss of soil organic matter on yam producing fields across Ghana than integrating with pigeonpea (Liu *et al*., under review). The reduced or no fallow periods, slash and burn land preparation and intensive soil preparation medium (mound) for yam cultivation, has resulted in a loss of soil organic matter and soil microbial communities. This loss has resulted in yam producing areas of West Africa having low soil organic matter (about 1%) (Nwaga *et al*., 2010; Tchabi *et al*., 2008 & 2009). The low soil organic matter leads to low soil moisture infiltration, retention, and increased erosion of the bulking medium (mound) (Frossard 2017; chapter 2). As a result of these soil conditions, O'Sullivan *et al*. (2008) noted that yam yields did not respond to N, P and K application on some soils whiles Hgaza *et al*., (2012) observed a maximum of just 30% N recovery in yam tuber indicating more loss of N to the environment. These conditions, alongside limited land resources and climate change in sub-Saharan Africa, are hampering yam and other food crop production (FAO, 2017; Montanarella *et al*., 2016). The use of leguminous shrubs in sustaining soil fertility, especially at the yam producing belt of West Africa, is imperative for sustainable yam production and food security. Using the EPIC (Environmental Policy Integrated Climate) crop growth simulation model, Srivastava *et al*. (2012) evaluated the impact of climate change on yam (*Dioscorea alata*) yield in Benin. The study projected a 27 – 48 % reduction in yam yields resulting from weather variability, especially temperature and rainfall. Also, Cornet *et al*. (2016), using the Bayesian network model, found that, the emergence date of the yam sett was the major direct cause of plant yield variability in both white (*D. rotundata)* and water yam *(D. alata*). The study recommended agronomic practices, which improve early and uniform sprouting, to be very important in improving yam yields in West Africa. Thus, plant biomass residue, especially from the leguminous shrub, is vital in addressing soil fertility challenges and climate change impact mitigation. However, producing reasonable quantities of leguminous shrub biomass for an ISFM for crop production is a major challenge for soil fertility maintenance and yam production (Frossard *et al*., 2017). Planting yam with pigeonpea as a border plant has shown to be an option in addressing this challenge in yam production. Three border sides or a third of the field, when used for growing and provision of pigeonpea residue and stakes, could sustain the yam on the two-thirds of the remaining field. Even when farmers have no access to inorganic fertilizer, the use of pigeonpea residue alone results in a better chance of long-term tuber yield than the use of full (45-45-60 N-P_2O_5-K_2O kg/ha) fertilizer rates on sole yam fields (Figures 3.4 & 3.5). This indicates, integration of pigeonpea into yam cropping systems by planting yam in alleys of pigeonpea, or planting yam with pigeonpea as border plants described here as pigeonpea-yam cropping system, presents options for sustainable yam production on continuously cropped fields.

CONCLUSION AND RECOMMENDATIONS

The study has indicated that the provision of pigeonpea residue for ISFM with inorganic fertilizer for sustainable yam production on continuously cropped fields is possible with the pigeonpea-yam cropping system. The chances of sustaining long-term (10yrs) yam tuber yields improved significantly on pigeonpea residue treated fields than sole yam fields. When a farmer has no access to inorganic fertilizer, planting yam with pigeonpea residue alone resulted in an improved chance of sustaining long-term tuber yields than sole yam cultivation with full (45-45-60 N-P_2O_5-K_2O kg/ha) recommended inorganic fertilizer rate.

Thus, suggesting ISFM of pigeonpea residue and inorganic fertilizer could improve and sustain yam yield on continuously cropped fields than using only inorganic fertilizer. However, further simulation of the long-term changes in soil carbon, N, P, and other nutrients resulting from the pigeonpea residue and their correlation with yam productivity in the pigeonpea-yam cropping system would be needed. Also, simulation for long-term pigeonpea residue production in a pigeonpea-yam cropping system, and implications on yam productivity should be pursued. These would provide a guide on ISFM of pigeonpea residue and fertilizer for sustainable yam production on continuously cropped fields to address the search for fertile lands yearly, resulting in deforestation in the yam producing areas of West Africa.

REFERENCES

REFERENCES

Adiku, S. G. K, Carberry, P. S, Rose, C. W, McCown, R. L, & Braddock, R. (1995). A maize (*Zea mays*)-cowpea (*Vigna unguiculata*) intercrop model. In: Sinoquet, H., and Cruz, P. (Ed.), *Ecophysiology of tropical intercropping* (INRA, pp. 397–406). Paris, France.

Adu, S. V. (1992). Soils of the Kumasi Region of Ghana. Kwadaso-Kumasi: *Soil Research Institute*.1992.

Albarenque, S. M., Basso, B., Caviglia, O. P., & Melchiori, R. J. M. (2016). Spatio-temporal nitrogen fertilizer response in maize: field study and modeling approach. *Agron. J*. 108, 2110–2122.

Andres, C., AdeOluwa, O. O., & Bhullar, G. S. (2017). Yam (*Dioscorea spp*.), in Encyclopedia of Applied Plant Sciences, Vol 3, eds. B. Thomas, B. G. Murray, and D. J. Murphy (Waltham, MA, Academic Press), 435–441.

Asiedu, R., & Sartie, A. (2010). Crops that feed the World 1. Yams. Yams for income and food security. Food Security. 2, 305-315.

Basso, B., & Ritchie, J. T. (2012). Assessing the impact of management strategies on water use efficiency using soil-plant–atmosphere models. Vadose Zone Journal, 11.

Basso, B., & Ritchie, J. T. (2015). Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model. In: The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability. (eds Hamilton SK, Doll JE, Robertson GP) pp. 252–274. New York, NY, USA, *Oxford University Press*.

Basso, B., Gargiulo, O., Paustian, K., Robertson, G. P., Porter, C., & Grace, P. R. (2011) Procedures for initializing soil organic carbon pools in the DSSAT-CENTURY model for agricultural systems. *Soil Science Society of America Journal*, 75, 69–78.

Basso, B., Hyndman, D. W., Kendall, A. D., Grace, P. R., & Robertson, G. P. (2015). Can impacts of climate change and agricultural adaptation strategies be accurately quantified if crop models are annually re-initialized? *PLoS One* 10, e0127333.

Basso, B., Liu, L., & Ritchie, J. T. (2016). A comprehensive review of the CERES-wheat, -maize and -rice models' performances. In: Donald, L.S. (Ed.), *Advances in Agronomy*. Academic Press, pp. 27–132.

Basso, B., Ritchie, J. T., Grace, P. R., & Sartori, L. (2006). Simulation of tillage systems impact on soil biophysical properties using the SALUS model. *Ital. J. Agron.* 1, 677–688.

Benneh, G., Agyepong, G. T. & Allotey, J. A. (1990). Land degradation in Ghana. *Commonwealth Secretariat*, London and University of Ghana, Legon.

Carberry, P. S., Adiku, S. G. K., McCown, R. L., Keating, B. A. (1996). Application of the APSIM cropping systems model to intercropping systems. Japan International Research Center for Agricultural Sciences.

Chipanshi, A., Zhang, Y., Kouadio, L., Newlands, N., Davidson, A., Hill, H., Warren, R., Qian, B., Daneshfar, B., Bedard, F., & Reichert, G. (2015). Evaluation of the Integrated Canadian Crop Yield Forecaster (ICCYF)model for in-season prediction of crop yield across the Canadian agricultural landscape. Agricultural and Forest Meteorology 206 (2015) 137–150.

Corneta, D., Sierra, J., Tournebize, R., Gabrielle, B., & Lewise, F. I., (2016). Bayesian network modeling of early growth stages explains yam interplant yield variability and allows for agronomic improvements in West Africa. *Europ. J. Agronomy* 75 (2016) 80–88.

Diby, L. N., Sangakkara, R, Tie, B. T., Girardin, O., & Frossard, E. (2011). Growth and Nutrient Use Efficiencies of Yams (*Dioscorea spp*.) Grown in Two Contrasting Soils of West Africa. *Hindawi Publishing Corporation International Journal of Agronomy*.

Dzotsi, K. A., Basso, B. & Jones, J. W. (2013). Development, uncertainty, and sensitivity analysis of the simple SALUS crop model in DSSAT. *Ecol. Model*. 260, 62–76.

Ennin, S. A., Issaka, R. N., Acheampong. P. P., Numafo, M., & Owusu Danquah, E. (2014). Mechanization, Fertilization, and Staking Options for Environmentally Sound Yam Production. *African Journal of Agricultural Research*, 2014, 9(29), 2222–2230.

Ennin, S. A., Owusu Danquah, E., Acheampong, P. P. (2013). Chemical and Integrated Nutrient Management options for sustainable Yam production. Yams 2013. *First global conference on yams*. 3-6 Oct 2013, Accra-Ghana.

Ennin, S. A., Owusu Danquah, E., Frimpong, F., Akom, M., Osei-Adu, J., Lamptey, J. N. L., Oteng-Darko, P., Osei, K., Osman, A. S., Aidoo, A. K., Adama, I., Appiah-Danquah, P., & Haleegoah, J. (2016). Yam Production and Marketing Guide. Eds. H. Adu-Dapaah, J. N. L. Lamptey, I. S. Banning, B. N. Frimpong, J. Osei-Adu, and S. A. Ennin. *CSIR – Crops Research Institute*. Kumasi, Ghana.

FAO (2017). The future of food and agriculture – Trends and challenges. Rome.

Frossard, E., Aighewi, B. A., Ake, S., Barjolle, D., Baumann, P., Bernet, T., Daouda, D., Diby, L., Floquet, A., Hgaza, V. K., Ilboudo, J. L., Kiba, D. I., Mongbo, R, L., Nacro, H. B., Nicolay, G. L., Oka, E., Florence, O. Y., Pouya, N., Six, J., Isabelle Orokya Traore, I. O. (2017). The challenge of improving soil fertility in yam cropping systems of West Africa. *Frontiers in plant science*, 8, p.1953.

Giller, K. E., Witter, E., Corbeels, M., &Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* 114, 23-34.

Hayford, P. (2018). Evaluating water-use efficiency in Sorghum-Pigeonpea (*Sorghum bicolor l. moench-Cajanus cajan [l] millsp.*) diversified cropping systems in marginal areas of Ghana and Mali. *Ph.D. Thesis*, Department of Plant, Soil and Microbial Sciences, Michigan State University.

Hgaza, V. K., Diby, L. N., Oberson, A., Tschannen, A., Tié, B. T., Sangakkara, U. R., Aké, S., & Frossard, E. (2012). Nitrogen use by yam as affected by mineral fertilizer application. *Agron. J.* 104, 1558-1568.

Jeffers, J. N. R. (1982). Modeling. New York: Chapman and Hall. 80 p.

Johnson, D. M. (2014). An assessment of pre- and within-season remotely sensed variables for forecasting corn and soybean yields in the United States. *Remote Sens. Environ.* 141 (0), 116–128.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T., (2003). The DSSAT cropping system model. *European journal of agronomy*, 18(3-4), pp.235-265.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargrea, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., & Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18(3-4), pp.267-288.

Kumar, A., Agrawal, R., & Chattopadhyay, C. (2013). Weather based forecast models for diseases in mustard crop. MAUSAM, 64, 4 (October 2013), 663-670

Lal R, Kimble J. M., & Follett B. (1997). Land use and soil C pools in terrestrial ecosystems. In: Lal R *et al*. (eds) Management of carbon sequestration in soil. CRC Press, Boca Raton, pp 1–9

Liu, L., & Basso, B. (2017). Spatial evaluation of maize yield in Malawi. *Agricultural Systems* 157 (2017) 185–192.

Liu, L., Owusu Danquah, E., Weebadde, C., Bessah, E., Basso, B. (under review). Modeling soil organic carbon and yam yield under different agronomic management in Ghana. Under review, Field Crops Research.

Maliki, R., Sinsin, B., & Floquet, A. (2012b). Evaluating yam-based cropping systems using herbaceous leguminous plants in the savannah transitional agroecological zone of Benin. *J.Sustain. Agr.* 36, 440-460.

Maliki, R., Toukourou, M., Sinsin, B., and Vernier, P. (2012a). Productivity of yam-based systems with herbaceous legumes and short fallows in the Guinea-Sudan transition zone of Benin. *Nutrient Cycl. Agroecosys*. 92, 9-19.

Ministry of Food and Agriculture (MoFA). (2017). Agriculture in Ghana; facts and figures. *Statistics, Research and Information Directorate (SRID),* Ministry of Food and Agriculture, Republic of Ghana.

Montanarella, L., Pennock, D. J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Singh Aulakh, M., Yagi, K., Young Hong, S., Vijarnsorn, P., Zhang, G. L., Arrouays, D., Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henriquez, C. R., de Lourdes Mendonça-Santos, M., Taboada, M., Espinosa-Victoria, D., AlShankiti, A., AlaviPanah, S. K., Elsheikh, E. A. E. M., Hempel, J., Camps Arbestain, M., Nachtergaele, F., &Vargas, R. (2016). World's soils are under threat. *SOIL* 2, 79-82. doi:10.5194/soil-2-79-2016.

NSFMAP- National Soil Fertility Management Action Plan. 1998. Gov. of Ghana- *Ministry of Food and Agriculture*. Pp 32-35.

Nwaga, D., Jansa, J., Abossolo Angue, M., & Frossard, E. (2010). The Potential of Soil Beneficial Microorganisms for Slash-and-Burn Agriculture in the Humid Forest Zone of Sub-Saharan Africa. In *Soil Biology and Agriculture in the Tropics*, ed P. Dion (Springer), Chapter 5: 81-107.

O'Sullivan, J. N., Ernest, J., Melteras, M., Halavatau, S., Holzknecht, P., & Risimeri, J. (2008). Yam nutrition and soil fertility management in the pacific, *Project final report*. ACIAR, Canberra, Australia.

Ollenburger, M., & Snapp, S. (2014). Model Applications for Sustainable Intensification of Maize-Based Smallholder Cropping in a Changing World. 5, 375–398.

Oteng-Darko, P., Yeboah, S., Addy, S. N. T., Amponsah, S. K., & Owusu Danquah. E. (2013). Crop modeling: A tool for agricultural research – A review. *E3 Journal of Agricultural Research and Development* Vol. 2(1). pp. 001-006.

Owusu Danquah, E., Ennin, S. A., Lamptey, J. N. L., & Acheampong, P. P. (2015). Staking Options for Sustainable Yam Production in Ghana. *Sustainable Agricultural Research*. vol. 4 (1):106-113.

Parton, W. J., Stewart, J. W., & Cole, C. V. (1988). Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5, 109–131.

Pezzuolo, A., Basso, B., Marinello, F., & Sartori, L. (2014). Using SALUS model for medium and long-term simulations of energy efficiency in different tillage systems. *Appl. Math. Sci*. 8, 6433–6445.

Pineiro, G., Perelman, S., Guerschmanb, J. P., & Parueloa, J. M. (2008). How to evaluate models: Observed vs. predicted or predicted vs. observed? *ecological modelling*. 2 1 6 (20 0 8) 316–322.

Ramasamy, P., Chandel, S.S. & Yadav, A.K. (2015). Wind speed prediction in the mountainous region of India using an artificial neural network model. Renewable Energy, 80, pp.338-347.

SAS Institute Inc. Base SAS® 9.4. (2013). Procedures Guide: Statistical Procedures, Second Edition. Cary, NC, USA: SAS Institute Inc.

Senthilkumar, S., Basso, B., Kravchenko, A. N., Robertson, G. P. (2009). Contemporary evidence of soil carbon loss in the US corn belt. *Soil Science Society of America Journal*, 73, 2078–2086.

Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R., & Kanyama-Phiri, G.Y., (2010). Biodiversity can support a greener revolution in Africa. *Proceedings of the National Academy of Sciences of the United States of America* 107, 20840-20845.

Snapp, S. S., Mafongoya, P. L., & Waddington, S. (1998). Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agriculture Ecosystems & Environment* 71, 185-200.

Srivastava, A K., Gaiser, T., Paeth, H., Ewert, F. (2012). The impact of climate change on Yam (*Dioscorea alata*) yield in the savanna zone of West Africa. *Agriculture, Ecosystems and Environment* 153 (2012) 57– 64

Suleiman, A. A., Ritchie, J. T. (2003). Modeling soil water redistribution during second-stage evaporation. *Soil Science Society of America Journal*, 67, 377–386.

Tchabi, A., Burger, S., Coyne, D., Hountondji, F., Lawouin, L., Wiemken, A & Oehl, F. (2009). Promiscuous arbuscular mycorrhizal symbiosis of yam (*Dioscorea spp*.), a key staple crop in West Africa. Mycorrhiza 19, 375–392.

Tchabi, A., Coyne, D., Hountondji, F., Lawouin, L., Wiemken, A & Oehl, F. (2008). Arbuscular mycorrhizal fungal communities in sub-Saharan Savannas of Benin, West Africa, as affected by agricultural land-use intensity and ecological zone. *Mycorrhiza* 18, 181–195.

Thierfelder, C., Cheesman, S & Rusinamhodzi, L. (2012). A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Research* 137, 237-250.

Whitbread, A. M., Robertson, M. J., Carberry, P. S. & Dimes, J. P. (2010). How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa. *European Journal of Agronomy* 32, 51-58.

CHAPTER 4

ECONOMIC ANALYSIS OF A PIGEONPEA-YAM CROPPING SYSTEM OPTIONS

ABSTRACT

Economic analysis is a vital process for determining the benefits and attractiveness of technologies and the costs associated with those interventions to inform better decision-making on adoption. An investigation into the cashflows and profitability was conducted as part of a larger study to compare the effects of integrating pigeonpea into yam cropping system with different fertilizer rates to sole yam (SY) with different fertilizer rates replicating the farmer practice. The integration of pigeonpea into yam described as a pigeonpea-yam cropping system consists of; yam planted with pigeonpea in alleys (PA) and as a border (PB). PA, PB, and SY plots are further divided into sub-plots, which are subjected to three treatments of N-P_2O_5-K_2O in kg/ha at 0-0-0, 23-23-30, 45-45-60 as no, half and full fertilizer rate respectively. The study was conducted in Fumesua and Ejura in the Forest and Forest-Savannah transition zones, during the 2018 – 2019 cropping seasons. The income advantage of each cropping system and fertilizer combination was estimated using Income Equivalent Ratio (IER) and Cost-Benefit Analysis (CBA) to complement the agronomic trials. The IER was evaluated under three farmer-practiced scenarios of 1) when a farmer has no access to fertilizer; 2) when a farmer can apply half the recommended fertilizer rate; 3) when a farmer can apply the full recommended fertilizer rate. A significant interaction was observed between the pigeonpea-yam cropping system and the fertilizer rate. Planting yam in PA with half and full fertilizer rates resulted in a significantly ($P \leq 0.05$) higher and similar IER than sole yam for all three scenarios in both locations and seasons. Also, planting yam with pigeonpea (PA and PB) without fertilizer was observed to have better IER than planting sole yam with full fertilizer rate in both locations. The total cost of production (TCP) was higher for sole yam across fertilizer rates in both locations, mainly due to the cost of stakes and labor costs for staking. The total cost of implementing a PA cropping system with no fertilizer was the cheapest option for farmers in the two locations. The cash inflows and outflows discounted at 7.43% were based on the social opportunity cost of capital observed; planting yam in pigeonpea (PA and PB) with half fertilizer rate was only slightly lower than the use of full fertilizer rate. A maximum Internal Rate of Return (IRR) ranging from 6.38% – 6.36% and 6.12% – 6.11% for planting yam in PA with full and half fertilizer rates respectively were observed between the two locations. Interestingly, planting yam in PA with half and full fertilizer rates resulted in similar Benefit-Cost Ratio (BCR) of 2.14 and 2.13 respectively for Fumesua whiles the same treatments recorded 2.38 and 2.36 for Ejura suggesting that estimated benefits from adopting the proposed technologies will be more than double for each Gh₵ 1.00 spent. Even when yams were planted without fertilizer, the presence of the pigeonpea (PA and PB) resulted in a better IER, IRR, and BCR than when half and full fertilizer rates were used for sole yam in both locations. With these results and in consideration of the environmental pollution caused by excessive and unregulated fertilizer usage, doubling the fertilizer rate would result in marginal income gains and not worth the environmental and cost implications. Pigeonpea-yam cropping system can be promoted as a viable option for soil fertility management and a source of readily available stakes for sustainable yam production. Adoption by farmers would address deforestation and land degradation issues associated with yam production whiles improving productivity and income of smallholder yam farmers.

Keywords: Benefit-cost Ratio; Income Equivalent Ratio; Cost of Stakes; Present Net Value, Internal Rate of Return; Cost of Production

INTRODUCTION AND RATIONALE

Agriculture has a critical role in improving the income and livelihoods of smallholder farmers of the African continent since the bulk of the labor force is employed by the agriculture sector (Hawkins *et al*., 2009). The situation is similar in Ghana, where the agriculture sector is the largest source of employment (Darfour and Rosentrater, 2016). The Medium-Term Agricultural Sector Investment Plan (METASIP) and the Comprehensive African Agricultural Development Program (CAADP) program targeting 6% annual agricultural growth were thus introduced to promote agricultural development for improved income and food security (Ministry of Food and Agriculture (MoFA), 2010; National Development Planning Commission (NDPC), 2010). Despite the importance of agriculture and the programs introduced, the agriculture sector is still challenged with low productivity and inadequate processing and storage facilities, resulting in the decline of product quality (NDPC, 2010). This fact has reduced the contribution of the agriculture sector to Gross Domestic Product (GDP) and has risen poverty amongst smallholder farmers (NDPC, 2010; Ghana Statistical Services (GSS), 2014). One of the primary reasons for this outcome is the low adoption of improved technologies for sustainable crop production (MoFA, 2010).

New and improved technologies are critical to boost agricultural productivity to meet the growing demand, enhance food security and stimulate economic growth (Fuglie *et al*., 2019). According to Jain *et al*. (2009), "improved techniques and practices which affect the growth of agricultural output" are referred to as agricultural technologies. As such, better soil and fertility management and input reduction techniques fall under new or improved technologies. They help boost yields and reduces the average cost of production while reducing the negative impacts on the environment leading to substantial productivity and socioeconomic gains by farmers. Pinstrup-Andersen (1982) observed that the adoption of agricultural technology is driven by their usability and ability to meet the farmers' needs, which in the case of smallholder farmers, mainly includes food and income. Moreover, the adoption of technologies and delivering technical assistance will be more effective when there is a better understanding of the farmers' social and cultural background (Crane, 2014). Other attributes, such as affordability, accessibility, safety, and scale neutrality, also play a pivotal role in technology uptake (Fischer, 2016). Despite the best intentions to assist smallholders and resource-poor farmers, socioeconomic, and environmental benefits from new agricultural technologies do not benefit these groups (Loevinsohn *et al.*, 2012).

Yam is an essential staple food and cash crop produced and consumed along the yam belt of West Africa. In Ghana, yam is one of the most important root and tuber crops cultivated for food and income generation predominantly by smallholder farmers (Babaleye, 2005). It contributes about 16% to the National Agricultural Gross Domestic Product (Anaadumba, 2013). As the second-largest global producer, and the leading exporter of yams, Ghana exported about US$ 33 million worth of yam in 2017 (Ghana Export Promotion Authority (GEPA), 2018). Despite this importance of yam, its production is challenged with the regeneration of soil fertility and scarcity of stakes for staking (Akwag *et al*., 2000; Ennin *et al*., 2014; Owusu Danquah *et al*., 2014). Yam is an input-intensive crop that is a heavy nutrient feeder. Farmers are constantly pressed to source or maintain fertile fields and move to a new field each year. As a result, farmers clear forest areas in search of new fertile lands and stakes, leading to deforestation and other detrimental environmental impacts (Owusu Danquah *et al.*, 2014; Ennin *et al*., 2014). Despite these efforts, the yam yields are still low, and farmers cannot maximize productivity and profitability.

Given that Ghana is a top exporter of yam, cost-effective and sustainable cultivation of yam would help sustain the livelihoods for thousands of smallholder farmers and generate export revenues. Thus, technologies that can improve soil fertility and minimize the need for stakes can address two major constraints faced by farmers (Acheampong *et al*., 2019). Research shows that intercropping nutrient-intensive crops with leguminous plants have agronomic (Ege and Idoko, 2009; Ngwira *et al.* 2012; Chapter 2) and economic benefits (Egbe *et al.*, 2012; Mutegi and Zingore, 2014) for farmers in Africa. Intercropping with pigeonpea is particularly suited for drought-prone areas with degraded soils (Egbe *et al.*, 2009; Kiwia *et al*., 2019). A multipurpose and drought-tolerant leguminous shrub such as pigeonpea (*Cajanus cajan*) is well suited for the climate in Ghana. It can help address the soil fertility and staking problems and provide several other benefits. Pigeonpea adds Nitrogen to the soil, and its biomass, when incorporated into the soil, can increase soil organic matter and conserves moisture. A mature pigeonpea tree trunk provides a sturdy and durable stake for the yam vines to climb on, eliminating the need to procure and install stakes (Chapter 2). Seran and Brintha (2010) noted complimentary benefits such as input use efficiencies, weed control, pest and disease management, erosion control, and grain yield when pigeonpea was intercropped with maize.

METHODOLOGY

Experimental design and treatments

The fieldwork to evaluate the performance of the pigeonpea-yam cropping system was conducted in Fumesua and Ejura during the 2018 and 2019 cropping season. Fumesua and Ejura are in the forest and forest-savannah transition agroecological zones of Ghana, respectively. Fumesua has a mean temperature range of 22-31^{o}C, while Ejura's mean temperature ranges from 21 to 34^{o}C. Both agroecological zones have a bimodal rainfall pattern with the major rainy season starting from March and continue through to August and the minor rainy season starting from September and continues through to November. Annual rainfall ranges between 1027-1322mm for Fumesua and 1171-1574mm for Ejura (Adu, 1992). As described in a previous chapter, the field study was conducted in a split-plot design with three replications. The main plot was divided into three consisting of 1) sole yam (SY); 2) yam with pigeonpea in alleys (PA); 3) yam with pigeonpea as a boarder (PB). The SY plot replicated the farmer scenario. The three subdivided plots were further divided into sub-plots with three N-P_2O_5-K_2O kg/ha fertilizer treatments - no fertilizer (0-0-0); half fertilizer rate (23-23-30); and full fertilizer rate (45-45-60). The fertilizer rate recommended for yam production by the Council for Scientific and Industrial Research – Crop Research Institute (CSIR-CRI) in Ghana was used as the full fertilizer rate for this research (Ennin *et al*., 2016). The pigeonpea variety used was a long duration (6-8 months) accession sourced locally and planted a year ahead (May 2017) in both locations before planting the yam in April-May 2018. "*Pona*," a premium white yam (*Dioscorea rotundata*) variety was used in the study. The fertilizer rates were split applied at 5-6 weeks after planting (WAP), and 12WAP on the yam stands on the ridges for all treatments. The combination of the pigeonpea and the yams on the PA and PB field followed the substitutive/replacement approach. In the PA field, pigeonpea was planted 3.6m apart between rows and 0.5m apart within a row to enable planting two ridges/rows yams in-between 1.2m apart and 0.8m apart within a ridge (described with diagrams in Chapter 2). A total plant population of 5,931 pigeonpea plants/ha and 7,177 yam plants/ha with one plant per stand were achieved for pigeonpea and yam in fields at both locations. In PB fields, two rows of pigeonpea were planted in the margins on three sides of the field 1.2m apart and 0.5m intra-row. Yam was planted in the middle at a recommended spacing of (1.2m X 0.8m) (Ennin *et al.*, 2016). With this spacing, a population of 5,931 pigeonpea plants/ha and 7,177 yam plants/ha was achieved. The SY field had yams planted on ridges at 1.2m X 0.8m inter and intra-rows respectively to achieve a population of 10,416 plants/ha. Biomass was pruned from the pigeonpea and applied on ridges as green manure to add nutrients to the soil to benefit the yams crop. The woody trunks of pigeonpea grown in alleys served as live stakes in the PA treatments and stakes cut from the surrounding pigeonpea was used as stakes in the PB treatments. In the case of SY fields, stakes were purchased and transported to the field for staking. Data from two cropping seasons reveal that the integration of pigeonpea into the yam production system helped improve and sustain soil fertility through the fixing of atmospheric nitrogen and provide readily available stakes for yam production. There were substantial productivity gains when yam was intercropped with pigeonpea compared to sole yam with different fertilizer rates in both locations (Chapter 2, figure 2.6b). It would be useful to estimate the potential costs and/or benefits to producers associated with each technology to make more informed recommendations to farmers. This study aims to quantify several economic measures used to determine the profitability of the pigeonpea-yam cropping systems. The combined economic impacts of each cropping system and fertilizer combination will complement the agronomic data and aid in decision making. Access to this information will enable research in the technology dissemination process and empower farmers with evidence to make more rational decisions. The analysis was conducted using yam and pigeonpea productivity data from field evaluation of pigeonpea-yam and SY from Fumesua and Ejura during the 2018 and 2019 cropping seasons (Chapter 2).

Income Equivalent Ratio and Cost-Benefit Calculation

The profitability of the cropping systems was estimated using Income Equivalent Ratio (IER). To better understand the implications of the various cost components of yam in PA, PB, and sole yam cropping systems, a Cost-Benefit Analysis (CBA) was conducted, taking into account variation in fertilizer rate. Discounted cash inflows and outflows were used to calculate the Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR). When calculating these different parameters, three possible scenarios that could apply in the farmers' context of continuous crop production were considered: scenario 1: when there is no access to fertilizer; scenario 2: when a farmer can apply half recommended fertilizer rate (23-23-30 N-P_2O_5-K_2O kg/ha); and scenario 3: when a farmer can apply full recommended fertilizer rate 45-45-60 N-P_2O_5-K_2O kg/ha). All parameters were computed on a per hectare basis. The costs were classified into fixed costs (FC) and variable costs (VC). Costs reported under FC included expenses incurred during the production process that did not change with the volume of output and initial investments made towards establishing the pigeonpea-yam cropping system. The costs of land preparation and pigeonpea establishment were classified as FC since these costs were investments made only in 2017. Variable costs (VC) included recurring costs that varied with production. The costs of various inputs such as seed yam, fertilizer, labor costs (for ridging, fertilizer application, weeding, and harvesting), cost of stakes, were categorized under VC. Total Cost of Production (TCP) is the sum of FC and VC. It was assumed that in the case of SY, the land is undergoing a fallow period in year 1. In the case of the PA and PB fields, yam cultivation did not begin until the second year because the pigeonpea plants needed to reach a certain level of maturity before they can be used as stakes in PB or replace the stakes in PA.

Therefore, no harvesting of pigeonpea or yam was done during year 1. The revenue generation begins in year 2 with the 1st season of yam and pigeonpea harvesting. The amount of yam and pigeonpea harvested was adjusted by 10% to account for post-harvest losses. This adjusted value was adopted from Ennin *et al*. (2014) to account for extrapolation from smaller plots to a hectare. Total revenue was estimated for SY and intercropped systems based on the average market price of yam and pigeonpea for years 2018 and 2019, assuming the sale of the total adjusted harvest of yam and pigeonpea is possible.

Income equivalent ratio

The Income Equivalent Ratio (IER) is a concept similar to the Land Equivalent Ratio (LER), which uses gross income instead of yields. In this case, gross income from sole yam and pigeonpea systems was used to calculate IER to compare the income for the three cropping systems (PA, PB, and SY) factored in the partial IER for sole pigeonpea. The IERs for the three scenarios described earlier were calculated following the approach used by Ghaffarzadeh (1997). Equation 4.1 was modified to reflect the different scenarios and fertilizer rates on the sole yam fields. Equations 4.1a and 4.1b were used to calculate the IER for scenario 1, and equations 4.1c and 4.1d were used to calculate IER for scenario 2. Equations 4.1e and 4.1f were used for calculating the IER of scenario 3.

$$IER = Partial\ IER\ of\ yam + Partial\ IER\ of\ pigeonpea \qquad 4$$

Scenario 1: Farmer has no access to fertilizer (sole yam without fertilizer)

$$Partial\ IER\ of\ yam = \frac{Gross\ income\ of\ yam\ in\ intercrop\ without\ fertilizer}{Gross\ income\ of\ yam\ in\ monocrop\ without\ fertilizer} \qquad 4.1a$$

$$Partial\ IER\ of\ pigeonpea = \frac{Gross\ income\ of\ pigeonpea\ in\ intercrop}{Gross\ income\ of\ pigeonpea\ in\ monocrop} \qquad 4.1b$$

Scenario 2: Farmer has access to half fertilizer rate (sole yam with half rec. fertilizer rate)

$$Partial\ IER\ of\ yam = \frac{Gross\ income\ of\ yam\ in\ intercrop\ with\ half\ rec. fert. rate}{Gross\ income\ of\ yam\ in\ monocrop\ with\ half\ rec. fert. rate} \qquad 4.1c$$

$$Partial\ IER\ of\ pigeonpea = \frac{Gross\ income\ of\ pigeonpea\ in\ intercrop}{Gross\ income\ of\ pigeonpea\ in\ monocrop} \qquad 4.1d$$

rec. – recommended; fert - fertilizer

Scenario 3: Farmer has access to full fertilizer rate (sole yam with full rec. fertilizer rate)

$$Partial\ IER\ of\ yam = \frac{Gross\ income\ of\ yam\ in\ intercrop\ with\ full\ rec. fert. rate}{Gross\ income\ of\ yam\ in\ monocrop\ with\ full\ rec. fert. rate} \qquad 4.1e$$

$$Partial\ IER\ of\ pigeonpea = \frac{Gross\ income\ of\ pigeonpea\ in\ intercrop}{Gross\ income\ of\ pigeonpea\ in\ monocrop} \qquad 4.1f$$

rec. – recommended; fert – fertilizer

Cost-Benefit Analysis

The approach proposed by Gittinger (1982) was used for the Cost-Benefit Analysis (CBA). It was assumed that the smallholders would receive an incremental net benefit from their investment in the SY and pigeonpea-yam cropping systems. This analysis attempts to identify and estimate the net present value (NPV) of stream discounted cash inflows (benefits) and outflows (costs) resulting from the crop production operations under three types of cropping systems (SY, PA, and PB) with alternative fertilizer rates. It enables the comparison of net cashflows with the adoption of PA or PB to SY, representing the typical production system executed by the smallholder yam farmers in Ghana. The CBA conducted here entails several steps involving NPV (equation 4.3), IRR (equation 4.4), and BCR (equation 4.5). First, farm budgets were developed for each location, taking into account the cropping systems and the three levels of fertilizer treatments. A discount rate (*i*) of 7.43% was used to convert all benefits (gross revenues) and costs into their present value (equation 4.2). The discount rate used in this analysis was based on the opportunity cost of capital, considering the next best option for the farmer is to invest his/her money in a savings account. The average savings interest rate published by the current Bank of Ghana formed the basis for selecting this value (Bank of Ghana (BoG), 2020). Next, the NPV was calculated using equation 4.3 to estimate of the net incremental benefit from implementing the various cropping systems. An NPV higher than zero is considered to be a good investment (Gittenger, 1982). The IRR is the discount rate at which the present value of total benefit equals the present value of total cost (equation 4.4) or when NPV equals zero. Thus, IRR represents the maximum interest that a cropping system could yield based on the resources used if the cropping system recuperates its investment and operating costs and still breaks even (Vawda *et al*., 2001). The IRR will facilitate the ranking of the cropping systems evaluated in this research based on its return rate. The cropping systems with IRR greater than or equal to the savings interest rate will be most attractive. BCR is calculated by dividing the present value of benefit by the present value of cost (equation 4.5). A BCR ratio of one (1) indicates costs and benefits breakeven, a ratio of greater than one (1) indicates a profitable venture where returns accrued is more than the costs incurred, and a ratio of less than one (1) indicates non-profitable venture as costs outweigh the benefits (Vawda *et al*., 2001). In this evaluation of multiple cropping systems with different fertilizer rates, the cropping system with the highest NPV, IRR, and BCR would be selected. All these different profitability analysis approaches provide potential investors; in this case, farmers with feasible options to make informed decisions on profit-maximizing cropping systems.

$$Present\ value\ of\ cash\ flows\ (PV) = \frac{FV_t}{(1+i)^t} \qquad 4.2$$

Where FV = future value of cash flows; i = discount rate; and t = number of years (1, 2, 3, …. n).

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t} - INV \qquad 4.3$$

Where: C_t = cost in year t; B_t = benefits in year t; i = discount rate; t = number of years (1, 2, 3, …. n); and INV is the initial investment.

$$IRR\ = NPV = 0, when \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} - \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} = \ 0 \qquad 4.4$$

Where: C_t = cost in year t; B_t = benefits in year t; i = discount rate; and t = number of years (1, 2, 3, …. n)

$$BCR = \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} \div \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \qquad 4.5$$

Where: C_t = cost in year t; B_t = benefits in year t; i = discount rate; and t = number of years (1, 2, 3,…. n)

Data analysis

Data analysis for this study was subjected to analysis of variance (ANOVA) at a 5% significance level using statistical analysis software (SAS) version 9.4. With the cropping system and fertilizer level as fixed factors and block, location, and year as random factors, a four-way ANOVA was used to test the effect of the cropping system, and fertilizer on IER under the three scenarios described earlier. The Standard Error of the difference between means (SED) at 5% significant level was used in the separation of means, where treatment means differed significantly. Microsoft Excel and Simple descriptive statistics were also used to estimate various economic measures and results presented in tables.

RESULTS

Income equivalent ratio

The IER of all the three scenarios of farmers' practice was significantly ($P \leq 0.05$) influenced by the interaction between cropping system, fertilizer rate, location, and year. Generally, planting yam in PA and PB with half fertilizer or no fertilizer rates present a better IER than planting yam in PA and PB with full fertilizer rates in both locations and seasons. Also, sole yam presented the worse IER under all three scenarios (Tables 4.1a, 4.1b & 4.1c). When a farmer has no access to fertilizer (Scenario 1), planting yam in PA presents a significantly higher ($P \leq 0.05$) IER for both 2018 (1.81) and 2019 (1.46) seasons at Fumesua. For Ejura, planting yam in PA resulted in similar IER values compared to plating yam in PB (1.55 and 1.57 respectively) for the 2018 cropping season. However, PA presented the best option for the 2019 cropping season with IER values of 1.53 for PA and 1.36 for PB (Table 4.1a). When a farmer has access to half the recommended fertilizer rate (Scenario 2), planting yam in PA was still the best option at Fumesua for both seasons. However, at Ejura planting yam in PA was observed as the best option in 2018 and similar to planting yam in PB in 2019 (Table 4.1b). In Ejura, when a farmer has access to full fertilizer rate planting yam in PA recorded the best IER for the 2018 cropping season while a similar IER was observed for plating yam in PA and PB for the 2019 cropping season (Table 4.1c).

Across cropping seasons (2018 – 2019), planting yam in PA with no, half, and full fertilizer rate resulted in an average IER of 1.54, 1.88, and 1.39, respectively, at Ejura. However, planting yam in PA with no, half, and full fertilizer rates resulted in an average IER of 1.64, 1.59, and 1.36 at Fumesua across seasons. Thus, whiles planting yam in PA with half fertilizer rate improves IER at Ejura, planting yam in PA with half fertilizer rate resulted in a decreased IER at Fumesua (Tables 4.1a, 4.1b, and 4.1c). Planting yam in PB with no, half, and full fertilizer rate resulted in an average

IER across seasons of 1.38, 1.42, and 1.26, respectively, at Fumesua. Whiles, an average across seasons IER of 1.47, 1.55, and 1.26, were recorded for planting yam in PB with no, half, and full fertilizer rate respectively at Ejura (Tables 4.1a, 4.1b & 4.1c). Although planting yam in PB did result in a significantly ($P \leq 0.05$) higher IER than planting yam in PA for both locations and seasons, it presented a similar IER as planting yam in PA in Ejura during 2018 and 2019 cropping seasons when a farmer has no access, half access and full access to fertilizer respectively. At Fumesua, similar IER was observed for planting yam in PB and PA for the 2019 cropping seasons when a farmer had access to full fertilizer rate (Tables 4.1a, 4.1b, and 4.1c). The largest average income advantage (2018 – 2019) for Fumesua was between the SY and PA without fertilizer amounting to 63.5% more income (Table 4.1a) and for Ejura between SY and PA with half the fertilizer rate increasing income by 87.5% (Table 4.1b). If all the produced yams from 2018 and 2019 are marketable, the maximum potential average gross income from just the sale of yams harvested from the intercropping system where pigeonpea is grown in alleys is Gh₵ 11,640 for Fumesua and Gh₵ 19,3730 for Ejura with half the recommended fertilizer rate (Table 4.2).

Table 4.1a: Income Equivalent Ratio (IER) of the pigeonpea-yam cropping system under different inorganic fertilizer levels compared with sole yam with no fertilizer at Fumesua and Ejura for the 2018 and 2019 cropping seasons.

Location	Cropping system	Partial Income Equivalent Ratio				IER	
		Yam		Pigeonpea			
		2018	2019	2018	2019	2018	2019
Fumesua	Sole Crop	1.00^{c}	1.00^{b}	0.00^{b}	0.00^{b}	1.00^{c}	1.00^{c}
	Yam in PA	1.51^{a}	1.31^{a}	0.30^{a}	0.15^{a}	1.81^{a}	1.46^{a}
	Yam in PB	1.28^{b}	1.07^{b}	0.27^{a}	0.14^{a}	1.55^{b}	1.20^{b}
SED (5%)		0.02	0.06	0.03	0.01	0.02	0.06
Ejura	Sole Crop	1.00^{c}	1.00^{c}	0.00^{c}	0.00^{c}	1.00^{b}	1.00^{c}
	Yam in PA	1.16^{b}	1.36^{a}	0.38^{a}	0.17^{a}	1.55^{a}	1.53^{a}
	Yam in PB	1.24^{a}	1.22^{b}	0.33^{b}	0.14^{b}	1.57^{a}	1.36^{b}
SED (5%)		0.01	0.07	0.02	0.01	0.02	0.06
Location (Loc)		0.2093		0.0264		0.8533	
Year (Yr)		0.0879		<.0001		0.0008	
Cropping System (CS)		<.0001		<.0001		<.0001	
Loc*Yr		0.0043		0.0142		0.0082	
Loc*CS		<.0001		0.0011		0.0001	
Yr*CS		0.0031		<.0001		<.0001	
Loc*Yr*CS		<.0001		0.0321		0.0002	

PA – Pigeonpea in an alley; PB – pigeonpea as a border. Means with the same alphabets within a location indicate no significant ($P \leq 0.05$) differences among treatments.

Table 4.1b: Income Equivalent Ratio (IER) of the pigeonpea-yam cropping system under different inorganic fertilizer levels compares with sole yam with half fertilizer rate (23-23-30 N-P$_2$O$_5$-K$_2$O kg/ha) at Fumesua and Ejura for the 2018 and 2019 cropping seasons.

Location	Cropping system	Partial Income Equivalent Ratio				IER	
		Yam		Pigeonpea			
		2018	2019	2018	2019	2018	2019
Fumesua	Sole Crop	1.00^{c}	1.00^{c}	0.00^{c}	0.00^{c}	1.00^{c}	1.00^{b}
	Yam in PA	1.35^{a}	1.38^{a}	0.30^{a}	0.15^{a}	1.65^{a}	1.53^{a}
	Yam in PB	1.15^{b}	1.28^{b}	0.27^{b}	0.14^{b}	1.42^{b}	1.42^{a}
SED (5%)		0.09	0.07	0.02	0.007	0.011	0.07
Ejura	Sole Crop	1.00^{c}	1.00^{b}	0.00^{c}	0.00^{c}	1.00^{c}	1.00^{b}
	Yam in PA	1.72^{a}	1.48^{a}	0.38^{a}	0.17^{a}	2.10^{a}	1.65^{a}
	Yam in PB	1.23^{b}	1.39^{a}	0.33^{b}	0.14^{b}	1.56^{b}	1.53^{a}
SED (5%)		0.08	0.13	0.02	0.01	0.10	0.15
Location (Loc)		0.0440		0.0215		0.0373	
Year (Yr)		0.6062		<.0001		0.0213	
Cropping System (CS)		<.0001		<0.001		<.0001	
Loc*Yr		0.1691		0.0099		0.0974	
Loc*CS		0.0036		0.0004		0.0022	
Yr*CS		0.0022		<.0001		0.0009	
Loc*Yr*CS		0.0392		0.0169		0.0501	

PA – Pigeonpea in an alley; PB – pigeonpea as a border. Means with the same alphabets within a location indicate no significant (P ≤ 0.05) differences among treatments.

Table 4.1c: Income Equivalent Ratio (IER) of the pigeonpea-yam cropping system under different inorganic fertilizer levels compares with sole yam with full fertilizer rate (45-45-60 N-P_2O_5-K_2O kg/ha) at Fumesua and Ejura for the 2018 and 2019 cropping seasons.

Location	Cropping system	Partial Income Equivalent Ratio				IER	
		Yam		Pigeonpea			
		2018	2019	2018	2019	2018	2019
Fumesua	Sole Crop	1.00^{b}	1.00^{b}	0.00^{b}	0.00^{b}	1.00^{c}	1.00^{b}
	Yam in PA	1.17^{a}	1.09^{a}	0.30^{a}	0.15^{a}	1.47^{a}	1.24^{a}
	Yam in PB	1.03^{b}	1.07^{ab}	0.27^{a}	0.14^{a}	1.30^{b}	1.21^{a}
SED (5%)		0.10	0.08	0.03	0.01	0.13	0.09
Ejura	Sole Crop	1.00^{c}	1.00^{c}	0.00^{c}	0.00^{c}	1.00^{c}	1.00^{b}
	Yam in PA	1.12^{a}	1.10^{a}	0.38^{a}	0.17^{a}	1.50^{a}	1.27^{a}
	Yam in PB	0.97^{b}	1.08^{a}	0.33^{b}	0.13^{b}	1.30^{b}	1.22^{a}
SED (5%)		0.05	0.05	0.02	0.01	0.06	0.10
Location (Loc)		0.5398		0.0264		0.6570	
Year (Yr)		0.7047		<.0001		0.0126	
Cropping System (CS)		0.0007		<.0001		<.0001	
Loc*Yr		0.3494		0.0143		0.9187	
Loc*CS		0.8710		0.0011		0.8533	
Yr*CS		0.0702		<.0001		0.0055	
Loc*Yr*CS		0.7555		0.0321		0.9948	

PA – Pigeonpea in an alley; PB – pigeonpea as a border. Means with the same alphabets within a location indicates no significant ($P \leq 0.05$) differences among treatments.

Table 4.2: Revenue effects from yam yield gains for PA and PB intercropping system at Fumesua and Ejura for the 2018 and 2019 cropping seasons.

Location	Cropping system	Fertilizer ($N\text{-}P_2O_5\text{-}K_20$ kg/ha)	Gross revenue gain (‘000)		Avg. gross rev. gain (Gh₵)
			2018	2019	
Fumesua	Yam in PA	0-0-0	13.50	7.56	10,530
		23-23-30	12.75	10.53	11,640
		45-45-60	7.25	3.24	5,245
	Yam in PB	0-0-0	7.50	1.62	4,560
		23-23-30	5.50	7.83	6,665
		45-45-60	1.50	2.43	1,965
Ejura	Yam in PA	0-0-0	4.56	8.42	6,488
		23-23-30	24.72	14.03	19,373
		45-45-60	6.72	4.08	5,400
	Yam in PB	0-0-0	6.72	5.36	6,038
		23-23-30	7.92	11.22	9,570
		45-45-60	-1.68	3.06	690

PA – Pigeonpea in an alley; PB – pigeonpea as a border.

Cost of production and Cost-Benefit Analysis

The results of the CBA provided a more comprehensive understanding of costs and benefits. The TCP in 2017 was mainly associated with the establishment and maintenance of pigeonpea for subsequent yam cultivation in the 2018 and 2019 cropping season. Generally, the TCP was higher on the sole yam fields followed by yam planted in PB and yam planted in PA fields for both seasons and locations. The use of half or full fertilizer rate on each cropping system further increased production cost for both locations and years with SY with a full fertilizer costing the most. High net income was recorded for planting yam in PA, followed by yam in PB with sole yam being the least profitable for both locations and cropping seasons. Generally, planting yam in PA with half recommended fertilizer rate (23-23-30 $N\text{-}P_2O_5\text{-}K_2O$ kg/ha) resulted in closer Net income to planting yam in PA with a full fertilizer rate (45-45-60 $N\text{-}P_2O_5\text{-}K_2O$ kg/ha) (Tables 4.4a and 4.4b). The NPV and IRR of planting yam in PA with half fertilizer rate were only slightly lower than planting yam in PA with a full fertilizer rate. The NPV values further reinforce that the integration of pigeonpea is beneficial not only for yam productivity and soil health but also to increase the profitability of yam cultivation by 0.1 to nearly five folds in Ejura and 0.42 to 23 folds in Fumesua under different fertilizer rates. Planting yam in PA with half and full fertilizer rates resulted in a maximum IRR of 5.67 and 5.90 respectively at Fumesua and 5.66 and 5.88 respectively at Ejura Generally, higher benefit-cost ratios (BCR) were observed for all cropping systems at Ejura than Fumesua. Compared to all cropping systems, planting yam in PA with half fertilizer rate resulted in a higher and similar BCR in both locations and seasons (Table 4.3). Thus, doubling the fertilizer to 45-45-60 N-P_2O_5-K_2O kg/ha in pigeonpea-yam cropping system had marginal effects on income for both locations. Even when yams were planted without fertilizer, the presence of the pigeonpea resulted in better profit and BCR than when half and full fertilizer rates were used on sole yam fields for both locations (Tables 4.3).

Table 4.3: Cost-benefit analysis for pigeonpea-yam cropping system with savings deposit rate 7.43% as a discount.

		Fumesua			Ejura		
Cropping System	Fertilizer rate (N-P_2O_5-K_2O kg/ha)	Net Present Value (NPV)	Internal Rate of Return (IRR)	Benefit-Cost Ratio (BCR)	Net Present Value (NPV)	Internal Rate of Return (IRR)	Benefit-Cost Ratio (BCR)
Yam in PA	0-0-0	25.49	4.21	1.87	17.73	1.96	1.57
	23-23-30	35.13	5.67	2.14	44.62	5.66	2.38
	45-45-60	36.08	5.90	2.13	46.23	5.88	2.36
Yam in PB	0-0-0	13.12	2.46	1.40	13.93	1.69	1.41
	23-23-30	24.14	3.86	1.70	26.23	2.84	1.73
	45-45-60	27.63	4.42	1.78	35.68	4.18	1.96
Sole yam	0-0-0	1.05	*	1.03	3.09	*	1.09
	23-23-30	9.13	*	1.23	9.95	*	1.26
	45-45-60	19.65	*	1.49	32.81	*	1.84

*-IRR was not able to be calculated due to no cash flow on the 1st year of the project.

DISCUSSION

Profitability of the pigeonpea-yam cropping system

Several studies have used IER as a basis for estimating the gross returns from the cropping system in comparison to sole cropping (Bantie, 2014; Tetteh, 2019; Yang *et al*., 2018; Dudhade *et al*., 2009; Yusuf *et al*., 2016). Further, the CBA helps quantify the monetary value of costs and benefits of a project's or system's inputs and outputs to guide decision making. Thus, it indicates the long-term profitability of the cropping system when the fixed cost is accounted for (Vawda *et al*., 2001). These two analyses were used to evaluate the economic aspects of the PPY cropping system and were used to make decisions and recommendations. Across the cropping seasons (2018 -2019), the average partial IER of the yam in the pigeonpea fields (PA and PB) in both locations for all the scenarios were better than the pigeonpea, indicating high returns on the yams in the intercrop than the pigeonpea. The partial IER of the pigeonpea would mean an additional income to farmers if they chose to integrate pigeonpea into the yam cropping system (Tables 4.1a, 4.1b & 4.1c). The generally better IER on yam production in Ejura than Fumesua could be attributed to the more fertile lixisols at Ejura, which supported yam growth and tuber yields than the acid acrisols found in Fumesua (Lal, 1976; Ennin *et al*., 2009). Also, the higher IER in PA and PB systems in 2018 compared to 2019 cropping season could be attributed to the high quantity of pigeonpea biomass productivity and the resulting N – fixation in 2018 than 2019 (Chapter 2). The observed improved and reduced IER for planting yam with half fertilizer rate at Ejura and Fumesua, respectively, could be attributed to the soil conditions at both locations (Tables 4.1a, 4.1b). Ejura soils were slightly alkaline (pH 7.76 – 7.88) whiles Fumesua soils were very strongly acidic (4.43 – 4.79). The slightly alkaline soil at Ejura might have resulted in better nutrient use efficiency than the strongly acidic soil at Fumesua, resulting in higher productivity and returns capable of offsetting the half fertilizer cost introduced at Ejura. At Fumesua, due to the very strongly acidic soil condition, the improved productivity was not capable of offsetting the half fertilizer cost introduced, resulting in low IER. The significantly ($P \leq 0.05$) higher IER in PA than SY and similar values between half and full fertilizer rates further suggests that a higher fertilizer application does not substantially increase yam productivity and farmers' income (Tables 4.1a, 4.1b & 4.1c). This finding reinforces that even with limited access to inputs, farmers will have the potential to improve their income with the presence of pigeonpea than by proportionately increasing fertilizer use leading to detrimental environmental and health outcomes. For continuously cropped fields, this provides a more sustainable and economical option that helps enhance livelihoods and help produce safe food with a reduced impact on the environment. The comparison of average IER from planting yam in PA without fertilizer, which amounted to 1.64 and 1.54 at Fumesua and Ejura, respectively, implies better revenues for farmers than applying full fertilizer rate for 1.36 and 1.39 at Fumesua and Ejura. Planting yam in PB with no fertilizer also resulted in higher IER of 1.38 and 1.47 at Fumesua and Ejura compared to an IER of 1.26 for both locations for planting yam in PB with full fertilizer rate (Tables 4.1a, 4.1b & 4.1c). The generally low IER and gross profit of yam on sole yam fields irrespective of fertilizer rate for both locations and seasons could mainly be attributed to the low yam tuber yields, the cost of stakes, and the labor cost for staking on sole yam fields. The cost of stakes was eliminated by planting yam with pigeonpea in PA and PB fields, where live-stake and cut trunks of the pigeonpea replaced purchased stakes. Also, the incorporation of pigeonpea biomass helped to improve and sustain soil fertility and productivity.

Several studies highlighted staking to be a major issue influencing productivity and profitability of yam production and suggested reduced or live staking as an alternative to farmers' practice (Obiazi, 1995; Owusu Danquah *et al*., 2014; Ekanayake and Asiedu, 2003; Behera *et al*., 2010). The pigeonpea-yam cropping system proposed in this study help address this major constraint in yam production. The observations by Otu and Agboola (1991) showed that the use of *Gliricidia sepium* live-stake resulted in a 16% increase in yam productivity than when yam is cultivated with bamboo stakes. With pigeonpea, yam productivity gains of 51% for Fumesua, and 50% for Ejura without fertilizer, are in line with this study. Also, Bantie, (2014) observed a significantly higher IER of 1.91 when potatoes were intercropped with maize in a ratio of 1:1 than when produced as sole potatoes or sole maize. Thus, intercropping, especially with legumes such as pigeonpea, would sustain and increase yam productivity and income while lessening the burden on smallholder farmers by reducing the need to search for fertile lands to improve yam yields periodically. This outcome enhances food and income security and lowers the cost of production, freeing up revenues for family use or investing in other income generation activities. The NPV values for Ejura and Fumesua revealed that the net cash flows for SY were very low unless treated with a full dose of fertilizer. Also, the generally less IRR for the cropping systems than the opportunity cost of capital observed at both locations indicates the real situation of smallholder farming in many contexts resulting in low returns. Planting yam in PA with half fertilizer rate resulted in a better NPV than SY with different fertilizer levels but a similar NPV and BCR as with a full fertilizer rate in both locations and seasons. Planting yam in PA with half and full fertilizer rate resulted in a similar BCR of 2.14 and 2.13, respectively, at Fumesua whiles the same treatments had 2.38 and 2.36, respectively, at Ejura (Table 4.3). That is if yam is planted in PA with the half fertilizer rate, more than double the benefits would be expected for every GhȻ 1.00 invested in both locations. Even when a farmer has no fertilizer access, the returns with the use of pigeonpea in an alley or as a border plant would be better than cultivating yam as a monocrop with fertilizer (Table 4.2).

Thus, the economic analysis with IER and CBA suggests the integration of pigeonpea into yam cropping systems would improve and sustain yam production. However, planting yam in alleys of pigeonpea (PA) with half fertilizer rate resulted in the highest returns and profit in both locations and years. This result is because N, P, and other nutrient contributions, and moisture conservation of the pigeonpea in the yam cropping systems resulted in the use of the half-recommended fertilizer rate enough for the yam (Chapter 2). Similar profits recorded for half and full fertilizer rates with pigeonpea biomass in PA fields for both locations implies the use of full fertilizer rate with pigeonpea biomass has little to no economic benefit. It only increases production cost without a corresponding increase in yam productivity and profit. Even with the initial investment and the loss of a cropping year to establish pigeonpea, the farmers have NPV greater than zero with pigeonpea-yam systems. This results is in line with the observation by Ennin *et al.* (2013), that it is more profitable to precede yam with pigeonpea and thus would require half recommended poultry manure rate (3t/ha) and a third (15-15-20 N-P_2O_5-K_2O kg/ha) recommended fertilizer rate for sustainable yam production. As a result of a search for fertile land and stakes for staking, yam production contributes to deforestation and land degradation (Akwag *et al*., 2000; Otoo *et al*., 2008; Owusu Danquah *et al*., 2014; Ennin *et al*., 2014).

The study has indicated that the integration of pigeonpea into the yam cropping system would address the constraint of stake acquisition and high labor cost for staking on the field. In addition to this, the moisture conservation and soil fertility amelioration provided by the pigeonpea biomass would further enhance the yields and the profit margin than planting yam as a sole crop.

Profitability and environmental sustainability

Evaluation of long (10 years) term yields of yam using crop model SALUS, indicated that yam yields could be sustained in the long-term with integrated soil fertility management (ISFM) of pigeonpea biomass with recommended fertilizer rate than with just the use of fertilizer application for yam production (Chapter 3). The SALUS results suggest that both yam productivity and profitability can be sustained in the long-term. As such, the smallholder farmers can continue to reap benefits from the integration of pigeonpea into yam cultivation in West Africa. It also incentivizes and motivates farmers to invest in land and yam production activities. Given that yam farmers are vulnerable to various uncertainties from finding land to timely rainfalls to market fluctuation, this system offers more stability to farming activities and a reliable flow of income over time. As noted earlier, planting yam with pigeonpea (PA and PB) with full fertilizer (45-45-60 N-P_2O_5-K_2O kg/ha) rate presented a slightly higher NPV and IRR than planting yam with pigeonpea (PA and PB) with half fertilizer rate, the difference in values were very close (Tables 4.3).

In the face of global calls for reducing environmental and ecosystem pollution as a result of increased agricultural input use, such as fertilizer use and application, a balance between environmental and productivity sustainability is required (Zhang *et al*., 2018; Abler and Shortle, 1995). Basso *et al*. (2016), using the SALUS crop model, observed that, instead of a blanket uniform application, applying variable N in response to variability in soil and landscape of a field would result in higher profit and less nitrate leaching to the environment. Thus, planting yam with pigeonpea and half fertilizer rate would be more environmentally friendly and profitable than doubling the fertilizer at the expense of the environment. One limitation of this study is that the profitability indicators used in this study (IER and CBA) all measure the cost and benefit of the various yam production systems with explicit monetary values. It does not take into account the costs and benefits resulting from social and environmental variables (Senkondo, 2004).

Thus, in this study, environmental services/benefits such as carbon sequestration rendered by the pigeonpea and the implications of reducing fertilizer rate to half instead of full were not factored into the CBA. Quantification and inclusion of these environmental services/benefits of integrating pigeonpea would provide a more precise estimate of the economic returns from the pigeonpea-yam cropping system against the sole yam cropping system.

CONCLUSION AND RECOMMENDATIONS

The study has demonstrated, integrated soil fertility management (ISFM) for sustainable yam production with half recommended fertilizer and pigeonpea would provide live-stakes or readily available stakes for yam in the cropping system. Even if a farmer has no access to fertilizer, planting yam with pigeonpea (PA and PB) presents a better option in terms of profitability, and environmentally beneficial than the use of full recommended fertilizer for yam production. Thus, the soil moisture conservation, soil fertility maintenance, and provision of stakes from the pigeonpea makes it a profitable option on continuously cropped fields than the current practice of yam production.

Sensitivity analysis of changes in crop produce price and interest rates over time would be needed to provide a short and long-term guide to yam farmers interested in investing in yam production using the pigeonpea-yam cropping system. One valuable lesson learned from this research is that it is important to carry out the pruning of the pigeonpea at appropriate timing and intensity to ensure a continuous and sustainable supply of pigeonpea green manure each year while ensuring the health of pigeonpea trees. A further study on this would be pursed and made an integral component of this technology dissemination to farmers. Further studies would also be needed to quantify the environmental returns/benefit associated with pigeonpea (As carbon sink, N, and other nutrients added to the soil) in the yam cropping system. Breeding and Introducing farmers to pigeonpea with improved biomass, erect stems, and high grain yield would make the pigeonpea-yam cropping system attractive for adoption by farmers. These findings give researchers, farmers, and stakeholders more insights and data to guide and support decisions on the use of pigeonpea-yam cropping systems for profitable and sustainable yam production.

APPENDIX

APPENDIX

Table 4.3a: Partial budgeting and cost-benefit analysis of pigeonpea-yam cropping system at Fumesua for 2017, 2018 and 2019 cropping seasons.

CS	Yam in PA							Yam in PB							Sole yam					
Yr	2017	2018			2019			2017	2018			2019			2018			2019		
Fertilizer level		NF	½ rate	FR	NF	½ rate	FR		NF	½ rate	FR	NF	½ rate	FR	NF	½ rate	FR	NF	½ rate	FR
Yam yld. (t/ha)	0.0	16	20	20	12	14	15	0.0	14	17	18	10	13	14	11	14	17	9.0	10	13
Adj yam yld. (t/ha)	0.0	15	18	18	11	13	13	0.0	12	15	16	8.6	12	13	9.6	13	16	8.1	9.4	12
Yam GI (₵/ha) (in 000)	0.0	36	44	46	29	35	35	0.0	31	37	41	23	32	35	24	32	39	22	25	32
PP yld. (t/ha)	0.0	0.3	0.3	0.3	0.1	0.1	0.1	0.0	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Adj. PP yld (t/ha)	0.0	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
PP GI (₵/ha) (in 000)	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRCS (₵/ha) (in 000)	**0.0**	**36**	**44**	**46**	**29**	**35**	**35**	**0.0**	**31**	**37**	**41**	**23**	**32**	**35**	**24**	**32**	**39**	**22**	**25**	**32**

Table 4.3a (cont'd)

LC (₵/ha) (in 000)	1.8	0.4	0.4	0.4	0.4	0.4	0.4	1.8	0.4	0.4	0.4	0.4	0.4	0.4	1.8	1.8	1.8	0.5	0.5	0.5
Cost of PP Est. (₵/ha) (in 000)	1.5	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TFC (₵/ha) (in 000)	3.3	0.4	0.4	0.4	0.4	0.4	0.4	3.3	0.4	0.4	0.4	0.4	0.4	0.4	1.8	1.8	1.8	0.5	0.5	0.5
CPPH (₵/ha) (in 000)	0.0	0.6	0.6	0.6	0.7	0.7	0.7	0.0	0.6	0.6	0.6	0.7	0.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0
PP biom. spread (₵/ha)(in 000)	0.0	0.7	0.7	0.7	0.7	0.7	0.7	0.0	0.8	0.8	0.8	0.9	0.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0
FC (₵/ha) (in 000)	0.0	0.0	0.6	1.2	0.0	0.6	1.2	0.0	0.0	0.6	1.2	0.0	0.6	1.2	0.0	0.6	1.2	0.0	0.6	1.2
FAC (₵/ha) (in 000)	0.0	0.0	0.5	0.5	0.0	0.6	0.6	0.0	0.0	0.5	0.5	0.0	0.6	0.6	0.0	0.5	0.5	0.0	0.6	0.6
CRC (₵/ha) (in 000)	0.0	1.6	1.6	1.6	1.7	1.7	1.7	0.0	1.6	1.6	1.6	1.7	1.7	1.7	2.0	2.0	2.0	2.2	2.2	2.2

Table 4.3a (cont'd)

CSY (ℂ) (in 000)	0.0	6.1	6.1	6.1	6.3	6.3	6.3	0.0	6.1	6.1	6.1	6.3	6.3	6.3	6.7	6.7	6.7	7.0	7.0	7.0
CPY (ℂ/ha) (in 000)	0.0	1.8	1.8	1.8	1.9	1.9	1.9	0.0	1.8	1.8	1.8	1.9	1.9	1.9	2.2	2.2	2.2	2.3	2.3	2.3
CRY (ℂ/ha) (in 000)	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.7	0.7	0.7	0.9	0.9	0.9	1.6	1.6	1.6	1.8	1.8	1.8
CSY (ℂ/ha) (in 000)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	1.5	1.6	1.6	1.6
LCS (ℂ/ha) (in 000)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.6	0.6	0.6	1.0	1.0	1.0	1.1	1.1	1.1
WCPP (ℂ/ha) (in 000)	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WCY (ℂ/ha) (in 000)	0.0	1.5	1.5	1.5	1.6	1.6	1.6	0.0	2.0	2.0	2.0	2.1	2.1	2.1	2.5	2.5	2.5	2.6	2.6	2.6
CRR (ℂ/ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.6	0.6	0.6	1.2	1.2	1.2	1.3	1.3	1.3
CYH (ℂ/ha) (in 000)	0.0	1.5	1.5	1.5	1.6	1.6	1.6	0.0	1.5	1.5	1.5	1.6	1.6	1.6	2.0	2.0	2.0	2.0	2.0	2.0

Table 4.3a (cont'd)

TVC (in000)	**0.7**	**14**	**15**	**16**	**15**	**16**	**17**	**0.7**	**16**	**17**	**18**	**17**	**18**	**19**	**21**	**22**	**22**	**22**	**23**	**24**
TCP (₵/h) (in000)	**4.0**	**15**	**16**	**16**	**16**	**17**	**17**	**4.0**	**17**	**18**	**18**	**18**	**19**	**19**	**23**	**24**	**24**	**22**	**23**	**24**
GP (₵/h) (in000)	**-1**	**22**	**29**	**30**	**14**	**19**	**19**	**-1**	**15**	**20**	**23**	**6.0**	**14**	**16**	**3.4**	**11**	**17**	**0.1**	**2.4**	**8.8**
NI (₵/ha) (in000)	**-4**	**22**	**28**	**29**	**13**	**18**	**18**	**-4**	**14**	**20**	**22**	**5.7**	**14**	**15**	**1.6**	**8.8**	**15.0**	**-0.4**	**1.9**	**8.3**

NB: *Average yield adjusted 10%; NF (No fertilizer), ½ rate and (FR) full fertilizer rates are 0-0-0, 23-23-30 and 45-45-60 N-P_2O_5-K_2O kg/ha, respectively, Farm-gate prices per kg of white yam tubers (Pona) in 2018 and 2019 were Gh cedis 2.5 and Gh cedis 2.7, respectively. Farm-gate price per kg of pigeonpea grains in 2018 and 2019 were Gh cedis 0.48 and Gh cedis 0.49, respectively. Weeds were controlled 3, 4, and 5 times in yam planted in PA, PB and sole yam, respectively. Re-shaping of mounds was done 0, 1, 2 times for PA, PB, and sole yam, respectively. PA – yam planted in pigeonpea in an alley; PB – yam planted in pigeonpea as a border; Est. – Establishment; PP – Pigeonpea, CS – Cropping System; Yr – Year; yid – Yield; LC – Land clearing; TFC – Total Fixed Cost; TCP – Total Cost of Production, FC – Fertilizer Cost; FAC – Fertilizer Application Cost; CSY – Cost of Seed Yam; CPY – Cost of Planting Yam; CRC – Cost of Ridges Construction; CRR – Cost of Reshaping of Ridges; WCY – Weeding Cost in Yam; WCPP – Weeding Cost in PP; CSY – Cost of Staking Yam; LCS – Labor Cost for Staking; CYH – Cost of Yam Harvest; Cost of PP Harvest; GI – Gross Income; NI – Net Income; GP – Gross Profit; TVC – Total Variable Cost.

Table 4.3b: Partial budgeting and cost-benefit analysis of pigeonpea-yam cropping system at Ejura for 2017, 2018 and 2019 cropping seasons.

CS	Yam in PA							Yam in PB							Sole yam					
Yr	2017	2018			2019			2017	2018			2019			2018			2019		
Fertilizer level		NF	½ rate	FR	NF	½ rate	FR		NF	½ rate	FR	NF	½ rate	FR	NF	½ rate	FR	NF	½ rate	FR
Yam yld. (t/ha)	0.0	14	25	26	13	17	17	0.0	14	18	22	11	16	17	12	14	23	9.3	11	16
Adj yam yld. (t/ha)	0.0	12	22	23	11	15	16	0.0	13	16	20	10	14	15	10	13	20	8.4	10	14
Yam GI (₵/ha) (in 000)	0.0	29	53	55	29	39	40	0.0	31	38	48	26	36	39	25	31	49	21	26	36
PP yld. (t/ha)	0.0	0.3	0.3	0.3	0.1	0.1	0.1	0.0	0.3	0.3	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Adj. PP yld (t/ha)	0.0	0.3	0.3	0.3	0.1	0.1	0.1	0.0	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
PP GI (₵/ha) (in 000)	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRCS (₵/ha) (in 000)	**0.0**	**29**	**53**	**55**	**29**	**39**	**40**	**0.0**	**31**	**38**	**48**	**26**	**36**	**39**	**25**	**31**	**49**	**21**	**26**	**36**

Table 4.3b (cont’d)

LC (₵/ha) (in 000)	1.7	0.4	0.4	0.4	0.0	0.0	0.0	1.8	0.4	0.4	0.4	0.0	0.0	0.0	1.7	1.7	1.7	0.0	0.0	0.0
Cost of PP Est. (₵/ha) (in 000)	1.4	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TFC (₵/ha) (in 000)	3.1	0.4	0.4	0.4	0.0	0.0	0.0	3.3	0.4	0.4	0.4	0.0	0.0	0.0	1.7	1.7	1.7	0.0	0.0	0.0
CPPH (₵/ha) (in 000)	0.6	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0
PP biom spread (₵/ha) (in 000)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
FC (₵/ha) (in 000)	0.0	0.0	0.6	1.2	0.0	0.6	1.2	0.0	0.0	0.6	1.2	0.0	0.6	1.2	0.0	0.6	1.2	0.0	0.6	1.2
FAC (₵/ha) (in 000)	0.0	0.0	0.5	0.5	0.0	0.6	0.6	0.0	0.0	0.5	0.5	0.0	0.6	0.6	0.0	0.6	0.6	0.0	0.7	0.7

Table 4.3b (cont'd)

CRC (₵/ha) (in 000)	0.0	1.5	1.5	1.5	1.6	1.6	1.6	0.0	1.5	1.5	1.5	1.6	1.6	1.6	2.0	2.0	2.0	2.0	2.0	2.0
CSY (₵) (in 000)	0.0	5.9	5.9	5.9	6.1	6.1	6.1	0.0	5.9	5.9	5.9	6.1	6.1	6.1	6.5	6.5	6.5	6.9	6.9	6.9
CYP (₵/ha) (in 000)	0.0	1.8	1.8	1.8	1.9	1.9	1.9	0.0	1.8	1.8	1.8	1.9	1.9	1.9	2.2	2.2	2.2	2.3	2.3	2.3
CRR (₵/ha) (in 000)	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.7	0.7	0.7	0.8	0.8	0.8	1.6	1.6	1.6	1.7	1.7	1.7
CSY (₵/ha) (in 000)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	1.5	1.8	1.8	1.8
LCS (₵/ha) (in 000)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.2	1.2	1.2
WCPP (₵/ha) (in 000)	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WCY (₵/ha) (in 000)	0.0	1.4	1.4	1.4	1.4	1.4	1.4	0.0	1.8	1.8	1.8	1.9	1.9	1.9	2.3	2.3	2.3	2.3	2.3	2.3
CRR (₵/ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.1	1.1	1.1
CYH (₵/ha) (in 000)	0.0	1.4	1.4	1.4	1.5	1.5	1.5	0.0	1.4	1.4	1.4	1.5	1.5	1.5	2.0	2.0	2.0	2.1	2.1	2.1

Table 4.3b (cont’d)

TVC (in 000)	**2.0**	**14**	**15**	**15**	**14**	**15**	**16**	**2.0**	**15**	**16**	**17**	**16**	**17**	**18**	**20**	**21**	**22**	**21**	**23**	**23**
TCP (₵/ha) (in000)	**5.1**	**14**	**15**	**16**	**14**	**15**	**16**	**5.3**	**16**	**17**	**17**	**16**	**17**	**18**	**22**	**23**	**23**	**21**	**23**	**23**
GP (₵/ha) (in 000)	**-2.0**	**16**	**39**	**40**	**15**	**23**	**24**	**-2.0**	**16**	**22**	**31**	**10**	**19**	**21**	**5.2**	**9.8**	**27**	**0.1**	**3.6**	**13**
NI (₵/ha) (in 000)	**-5.1**	**15**	**38**	**40**	**15**	**23**	**24**	**-5.3**	**16**	**21**	**30**	**10**	**19**	**21**	**3.5**	**8.1**	**26**	**0.1**	**3.6**	**13**

NB: *Average yield adjusted 10%; NF (No fertilizer), ½ rate and (FR) full fertilizer rates are 0-0-0, 23-23-30 and 45-45-60 N-P_2O_5-K_2O kg/ha, respectively, Farm-gate prices per kg of white yam tubers (Pona) in 2018 and 2019 were Gh cedis 2.4, and Gh cedis 2.55, respectively. Farm-gate price per kg of pigeonpea grains in 2018 and 2019 were Gh cedis 0.48 and Gh cedis 0.49, respectively. Weeds were controlled 3, 4 and 5 times in yam planted in PA, PB, and sole yam, respectively. Re-shaping of mounds was done 0, 1, 2 times for PA, PB, and sole yam, respectively. PA – yam planted in pigeonpea in an alley; PB – yam planted in pigeonpea as a border; Est. – Establishment; PP – Pigeonpea, CS – Cropping System; Yr – Year; yid – Yield; LC – Land clearing; TFC – Total Fixed Cost; TCP – Total Cost of Production, FC – Fertilizer Cost; FAC – Fertilizer Application Cost; CSY – Cost of Seed Yam; CPY – Cost of Planting Yam; CRC – Cost of Ridges Construction; CRR – Cost of Reshaping of Ridges; WCY – Weeding Cost in Yam; WCPP – Weeding Cost in PP; CSY – Cost of Staking Yam; LCS – Labour Cost for Staking; CYH – Cost of Yam Harvest; Cost of PP Harvest; GI – Gross Income; NI – Net Income; GP – Gross Profit; TVC – Total Variable Cost.

REFERENCES

REFERENCES

Abler, D. G. and Shortle, J. S. (1995). Technology as an agricultural pollution control policy. *American Journal of Agricultural Economics*, *77*(1), pp.20-32.

Acheampong, P. P., Owusu Danquah, E., Dissanayake, H. G., Hayford, P., & Weebadde, C. (2019). A Socioeconomic Study of Transition Zone Yam Farmers Addressing Constraints and Exploring Opportunities for Integrating Pigeonpea into Yam Cropping Systems. Sustainability, 11(3), 717.

Adu, S. V. (1992). Soils of the Kumasi region of Ghana. Kwadaso-Kumasi: *Soil Research Institute*.1992.

Akwag, A. A., Berchie, J. N., Echavez, M. L., Dapaah, H. K., Kebede, T., Njue, S. W., & Labrada, H. R. (2000). Sustainable farming practices- towards reducing the expansion of the forest savanna transitional zone of the sekyere-west and Ejura-Sekyeredumase districts of the Ashanti region of Ghana. International Center for Development Oriented Research in Agriculture and Crops Research Institute, Working Document Series 86, Ghana.

Anaadumba, P. (2013). Analysis of incentives and disincentives for yams in Ghana. *Technical note series*, MAFAP, FAO, Rome.

Babaleye, T. (2005). Improving livelihood through yam production systems, an IITA Publication. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Bank of Ghana (BoG), 2020. Monthly Interest Rates Report. 2020. BoG, Accra, Ghana. www.bog.gov.gh/economic-data/interest-rates/

Bantie, Y.B. (2014). Determination of effective spatial arrangement for intercropping of maize and potato using competition indices at south Wollo, Ethiopia. *International Journal of Research*, *2*(8), pp.2311-2476.

Behera, B., Mohanty, S.K., & Mishra, A. (2010). Productivity, profitability and sustainability of integrated nutrient management practices in yam (*Dioscorea esculenta*) + maize (*Zea mays*) intercropping system. *Indian Journal of Soil Conservation*, 38(3), pp.217-222.

Basso, B., Dumont, B., Cammarano, D., Pezzuolo, A., Marinello, F. & Sartori, L. (2016). Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone. *Science of the total environment*, 545, pp.227-235.

Crane, T. A. (2014). Bringing science and technology studies into agricultural anthropology: Technology development as cultural encounter between farmers and researchers. Culture, Agriculture, Food and Environment, 36(1), 45-55.

Darfour, B., & Rosentrater, K.A. (2016). Agriculture and food security in Ghana. American Society of Agricultural and Biological Engineers. 2016 *ASABE Annual International Meeting 162460507*.

Dudhade, D.D., Deshmukh, G.P., Harer, P.N. & Patil, J.V. (2009). Studies on intercropping of pulse crops with pigeonpea under rainfed condition. *Legume Research-An International Journal*, 32(3), pp.215-217.

Egbe, O. M., & Idoko, J. A. (2009). Agronomic assessment of some sweet potato varieties for intercropping with pigeonpea in Southern Guinea Savanna of Nigeria. *Journal of Agricultural and Biological Science*, 4(4), 23-32.

Egbe, M. O., & Idoko, J. A. (2012). Evaluation of pigeonpea genotypes for intercropping with maize and sorghum in southern Guinea Savanna: Economic benefits. *International journal of Agriculture and forestry*, *2*(1), 108-114.

Ekanayake, I. J. and Asiedu, R. (2003). Problems and perspectives of yam-based cropping systems in Africa. *Journal of Crop production*, 9(1-2), pp.531-558.

Ennin S. A., Owusu Danquah E., Frimpong F., Akom M., Osei-Adu J., Lamptey J. N. L., Oteng-Darko P., Osei K., Osuman A. S., Aidoo A. K., Adama I., & Appiah-Danquah P. (2016). Yam Production and Marketing Guide. H. Adu-Dapaah, J. N. L. Lamptey, I. S. Baning, B. N. Frimpong JOA and SAE, editor. *CSIR-Crops Research Institute*; Kumasi, Ghana.

Ennin S. A, Otoo E, Tetteh F. M. (2009). Ridging, A Mechanized Alternative to Mounding for Yam and Cassava Production. *West Afr. J. Appl. Ecol*. P. 15.

Ennin, S. A., Isaaka, R. N., Acheampong, P. P., Numafo, M., & Owusu Danquah, E. (2014). Mechanization, Fertilization and Staking Options for Environmentally Sound Yam Production. *African Journal Agricultural Research,* 9(29), 2222-2230.

Ennin, S. A., Owusu Danquah, E., and Acheampong, P. P. (2013). “Chemical and integrated nutrient management options for sustainable yam production,” in *Book of Abstracts of the First Global Conference on Yam* (Accra, International Institute of Tropical Agriculture (IITA)), 23.

FAOSTAT, (2016). Agriculture Organization of the United Nations Statistics Division. Rome, Italy

Fischer, K. (2016). Why new crop technology is not scale-neutral—A critique of the expectations for a crop-based African Green Revolution. *Research Policy,* 45(6), 1185-1194.

Fuglie, K., Gautam, M., Goyal, A., & Maloney, W. F. (2019). Harvesting Prosperity: Technology and Productivity Growth in Agriculture. The World Bank.

Ghaffarzadeh, M. (1997). Economic and biological benefits of intercropping berseem clover with oat in corn-soybean-oat rotations. *Journal of Production Agriculture*, *10*(2), pp.314-319.

Ghana Statistical Services (GSS), (2014). National Accounts Statistics. GSS, Accra, Ghana

Ghana Export Promotion Authority (GEPA). 2018. Yams in the United States Competitor Analysis 2018, GEPA, Market Reports, Accra, Ghana.

Gittinger, J. P. (1982). Economic Analysis of Agricultural Projects (No. Edn. 2). *John Hopkins University Press.*

Hawkins, R., Heemskerk, W., Booth, R., Daane, J., Maatman, A. & Adekunle, A.A. (2009). Integrated Agricultural Research for Development (IAR4D). In *A Concept Paper for the Forum for Agricultural Research in Africa (FARA) Sub-Saharan Africa Challenge Programme (SSA CP)*. FARA, Accra, Ghana.

Jain R. Arora A & Raju S. (2009). A Novel Adoption Index of Selected Agricultural Technologies: Linkages with Infrastructure and Productivity. *Agricultural Economics Research Review* 22; pp 109-120

Lal, R. (1976). No-tillage effects on soil properties under different crops in western Nigeria. Soil science society of America journal, 40(5), pp.762-768.

Kiwia, A., Kimani, D., Harawa, R., Jama, B., & Sileshi, G. W. (2019). Sustainable intensification with cereal-legume intercropping in Eastern and Southern Africa. *Sustainability*, *11*(10), 2891.

Le Buanec, B. (1972). Absorption and uptake of major nutrients by yams. GERDAT. Groupement d'Etudes et de Rechèrche pour le Dévelopment de l'Agronomie Tropicale. IRAT. Institut de Rechèrches Agronomiques Tropicales et des Cultures Vivrières. Nogent-sur-Marne (Côte d'Ivoire) Reunion d'Agronomie de l'IRAT: 1974.

Loevinsohn M, Sumberg J, Diagne A (2012) under what circumstances and conditions does adoption of technology result in increased agricultural productivity? Protocol. London: EPPI Centre, Social Science Research Unit, Institute of Education, University of London

Ministry of Food and Agriculture (MoFA), (2010). Meduim Term Agricultural Sector Investment Plan (METASIP), 2011-2015. Ministry of Food and Agriculture, Republic of Ghana.

Ministry of Food and Agriculture (MoFA), (2017). Agriculture in Ghana; facts and figures. *Statistics, Research and Information Directorate (SRID),* Ministry of Food and Agriculture, Republic of Ghana.

Mutegi, J., & Zingore, S. (2014). Pigeon peas could work for smallholder African farmers in multiple ways. *ISFM Policy Highlight*, 2.

National Development Planning Commission, (2010). Ghana Shared Growth and Development Agenda (GSGDA)-Costing Framework, (2010–2013). Volume II.

Ngwira, A. R., Aune, J. B., & Mkwinda, S. (2012). On-farm evaluation of yield and economic benefit of short-term maize legume intercropping systems under conservation agriculture in Malawi. *Field crops research*, 132, 149-157.

Obiazi, C. C. (1995). Sustainable supply of stakes for yam production. *Journal of sustainable agriculture*, 5(3), pp.133-138.

Otoo, E., Anchirina, V. M., Ennin, S. A., & Asiedu, R. (2008). Sustainable yam production in Ghana the non-staking option. *Journal of Food, Agriculture & Environment*, 6(3&4), 391-396.

Otu, O. I. & Agboola, A. A. (1991). The suitability of *Gliricidia sepium* in-situ live stake on the yield and performance of white yam (*Dioscorea rotundata*). In *Symposium on Tropical Root Crops in a Developing Economy* 380 (pp. 360-366).

Owusu Danquah, E., Ennin, S. A., Lamptey, J. N. L., & Acheampong, P. P. (2014). Staking Options for Sustainable Yam Production in Ghana. *Sustainable Agricultural Research*. vol. 4 (1):106-113.

Pinstrup-Anderson, P. (1982). Agricultural Research and Technology in Economic Development (London: *Longmans*, 1982).

Senkondo, E. M. M., Msangi, A. S. K., Xavery, P., Lazaro, E. A. & Hatibu, N. (2004). Profitability of rainwater harvesting for agricultural production in selected semi-arid areas of Tanzania. *Journal of Applied Irrigation Science*, 39(1), pp.65-81.

Seran, T. H., & Brintha, I. (2010). Review on maize based intercropping. *Journal of agronomy*, 9(3), 135-145.

Tetteh, N. E. (2019). Rubber/plantain agroforestry: potentials for household food security in the rubber growing areas of Ghana. *PhD thesis*. College of Agriculture and Natural Resources, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi – Ghana.

Vawda, Y. A., Moock, P., Gittinger, P. J & Patrinos, A. H. (2001). Economic analysis of World Bank education projects and project outcomes. *The World Bank*.

Yang, C., Fan, Z & Chai, Q. (2018). Agronomic and economic benefits of pea/maize intercropping systems in relation to N fertilizer and maize density. *Agronomy*, 8(4), p.52.

Yusuf, I.A., Aiyelari, E. A., Lawal, F. A. (2016). Economic analysis of sorghum/soyabean intercrop systems by partial budget in the guinea savannah of Nigeria. *Continental Journal of Agricultural Economics*, 2016, 8 (1), pp.9-12.

Zhang, L., Yan, C., Guo, Q., Zhang, J. & Ruiz-Menjivar, J. (2018). The impact of agricultural chemical inputs on environment: global evidence from informetrics analysis and visualization. *International Journal of low-Carbon technologies*, 13(4), pp.338-352.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH DIRECTION

Conclusions

This present research was conducted to provide some answers towards addressing dwindling yam productivity, land degradation, and deforestation resulting from shifting cultivation and search for stakes that characterized smallholder yam production in West Africa. The general objective was to evaluate the effect of pigeonpea-yam cropping system on yam productivity on continuously cropped fields.

The study was built on an earlier socio-economic survey that identified yam farmers' perception and knowledge of pigeonpea in the major yam growing areas of Ghana. A farmer participatory on-station study was implemented on continuously cropped fields at Fumesua (Forest Zone) and Ejura (Forest-Savannah transition zone) in Ghana during the 2017, 2018, and 2019 cropping season for the field evaluation. An integrated soil fertility management of pigeonpea biomass and fertilizer were laid out for the study with yam planted in alleys of pigeonpea (PA), yam planted with pigeonpea as a border (PB) and sole yam as cropping systems and further divided into three where no, half (23-23-30 N-P_2O_5-K_2O kg/ha) and full (45-45-60 N-P_2O_5-K_2O kg/ha) recommended fertilizer rate for yam production were applied. Planting yam in PA with half fertilizer rate resulted in similar tuber yield as planting yam in PA with a full fertilizer rate. Also, planting yam with pigeonpea (Yam in PA and PB) without fertilizer presents a better yam tuber yield than cultivating sole yam with fertilizer on a continuously cropped field.

To evaluate the long-term yam yield sustainability, the field study data were used in the calibration and validation of the SALUS crop model for simulation studies. The results indicated long (10 years) term yields of yam could be sustained with integrated soil fertility management (ISFM) of pigeonpea biomass with recommended inorganic fertilizer rate than with just the use of inorganic fertilizer for yam production on continuously cropped fields.

To ascertain the pigeonpea-yam cropping system's profitability, an economic analysis with three scenarios of a farmer having no access to inorganic fertilizer, a farmer with access to half inorganic fertilizer rate, and a farmer with access to full inorganic fertilizer rate was conducted. The results indicated, planting yam in PA with half and full inorganic fertilizer rates resulted in a similar Income Equivalent Ratio (IER) for all three scenarios in both locations and seasons. Planting yam with pigeonpea (PA and PB) without inorganic fertilizer had better IER than planting sole yam with full inorganic fertilizer rate in both locations. Also, planting yam with pigeonpea (PA and PB) with half inorganic fertilizer rate presented a slightly lower Net Profit Value (NPV) and Internal Rate of Return (IRR) than planting yam with pigeonpea (PA and PB) with full inorganic fertilizer rate, the difference in values were very close, resulting in marginal income gain.

Given the above results, the use of pigeonpea with half inorganic fertilizer rate would sustain yam production and income on continuously cropped fields for smallholder farmers. This is in line with the global call for reducing environmental and ecosystem pollution due to increasing agricultural input use. Also, deforestation and land degradation resulting from shifting cultivation in search of fertile land and stakes can be addressed with the pigeonpea-yam cropping system.

Future research directions

Figure 5.1 gives the future direction of this study. For the present study to benefit yam farmers, there would be the need to scale up the pigeonpea-yam technology to other yam growing areas of Ghana and the rest of the countries along the West Africa yam belt (Nigeria, Togo, Ivory Coast, and Benin). As a Scientist with the CISR – Crops Research Institute (CRI), a national research institution, my collaborations with the International Institute of Tropical Agriculture (IITA), a CGIAR institution gives me the opportunity to scale up this technology to other countries. The CSIR – CRI has collaborated with IITA on major yam projects such as Yam Improvement for Incomes and Food Security in West Africa (YIIFSWA) and Community Action in Improving Farmer-Saved See Yam (CAYSEED). This study would contribute by offering smallholder farmers options that would sustain yam productivity on continuously cropped fields to achieve improved yam productivity, income, and food security.

To ensure cost-effective and rapid scale-up of the pigeonpea-yam cropping system to other yam producing countries, I would continue my collaboration with Bruno Basso's lab at MSU. This is to explore using SALUS and other crop models to simulate and link the long – term improvement in soil fertility and yam productivity resulting from ISFM of pigeonpea biomass and fertilizer along the West Africa yam belt.

To encourage adoption, there is the need to make farmers productive during the 8-12-month lag phase for the maturity of the pigeonpea. The "*doubled-up legumes"* approach where legumes such as cowpea, groundnut, and soybean are cultivated with the pigeonpea may be a way forward. This has been pioneered in East Africa (Malawi and Tanzania) by the Global Change Learning Lab in

Sub-Saharan Africa under the leadership of Dr. Sieglinde Snapp of MSU. I will collaborate with this lab and explore how this approach could be used to make farmers productive during the 8-12 months maturity period of the pigeonpea.

To be able to present to smallholder farmers, a pigeonpea genotype with improved biomass and grain yield, erect stems, and tolerant to pruning, suitable for the pigeonpea-yam cropping system. I will continue my collaboration with Dr. Cholani Weebadde of MSU, my major advisor, and other breeders of CSIR – CRI on pigeonpea breeding and improvement research to meet this objective.

Quantification of environmental benefits such as carbon sink, N, and other nutrients added to the soil associated with the pigeonpea would be needed to enable a comprehensive economic analysis of the pigeonpea-yam cropping system. This would be achieved through collaborations with agriculture and environmental economists. These future research directions would give researchers, farmers, and all stakeholders more insights to guide and support decisions on the pigeonpea-yam cropping system for sustainable and profitable yam production.

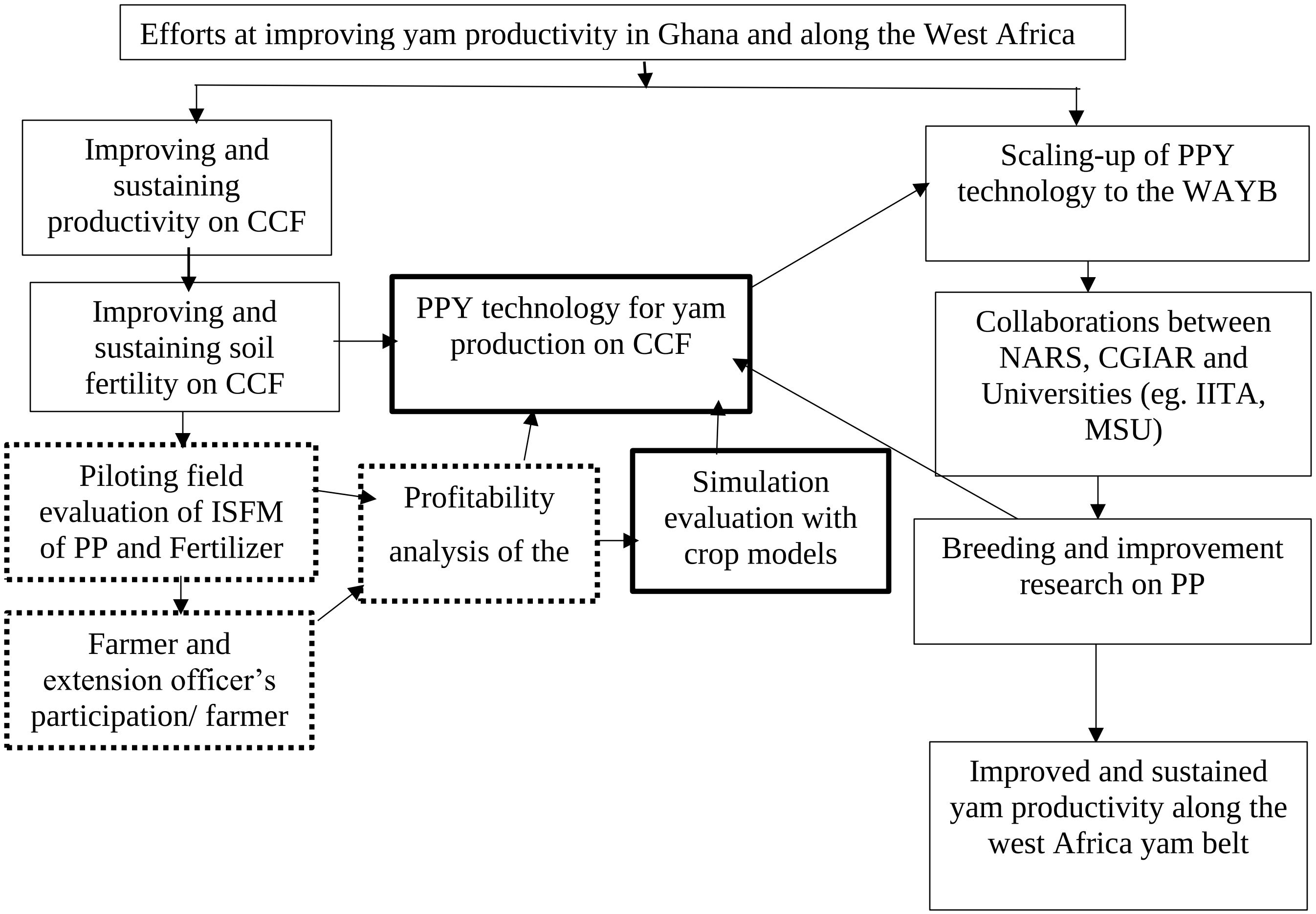

Figure 5.1: The future directions of the study.

The accomplishment of the current study relevant in achieving the overall goal indicated by dotted boxes. Achieved to some extent by the current study are indicated in thick line boxes. Future directions of the current study are indicated by thin line boxes. PP – Pigeonpea, PPY – Pigeonpea-Yam, CCF – continuously cropped field, WAYB – West Africa Yam Belt.