Sustainable intensification and diversification options with grain legumes for smallholder farming systems in the Guinea savanna of Ghana

Michael Kermah

Propositions

1. Intercropping is ecologically more beneficial in poorly fertile fields.
(this thesis)

2. Time of sowing is more important than spatial arrangement of crops in relay intercropping.
(this thesis)

3. The proliferation of digital solutions for agriculture make climate change an opportunity rather than a challenge for sub-Saharan Africa to achieve food security.

4. Youth can prosper through individualistic entrepreneurship but are impeded by higher education that leads them to pursue non-existent jobs.

5. Natural resources can be effectively conserved if governed solely by customary laws.

6. The mode of disseminating research results by scientists through academic journals limits the impact of science on society.

7. A vibrant social media presence is more important to get you a job than academic qualification.

8. Deviant childhood behaviour is like a chronic disease more effectively cured by maturity than by parents.

Propositions belonging to the thesis entitled:

Sustainable intensification and diversification options with grain legumes for smallholder farming systems in the Guinea savanna of Ghana

Michael Kermah
Wageningen, 10th February, 2020

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This research was conducted under the auspices of the *C.T. de Wit* Graduate School of Production Ecology and Resource Conservation.

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Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 10 February 2020
at 4 p.m. in the Aula.

Michael Kermah (2020)

Sustainable intensification and diversification options with grain legumes
for smallholder farming systems in the Guinea savanna of Ghana.
157 pages.

PhD Thesis, Wageningen University, Wageningen, NL (2020).
With references and summary in English

ISBN: 978-94-6395-228-6
DOI: https://doi.org/10.18174/507853

*To my late beloved big sister, **Janet Ebah Kermah,** your toil to ensure the family succeeds will never be in vain, you will forever live in my heart, our hearts.*

Food security is a critical issue in the Guinea savanna of Ghana where about 60% of the rural population, mostly smallholder farmers are food insecure. Food insecurity results from poor crop yields due to low soil fertility compounded by erratic unimodal rainfall and the inability of households to purchase required supplemental food. Rapid population growth means that the numbers of food insecure people are likely to increase, necessitating sustainable intensification and diversification to increase crop production per unit area of land. This thesis focused on testing spatial and temporal intensification and diversification options suitable for the variable biophysical and socio-economic conditions of smallholder farming systems in the Guinea savanna to increase productivity, mitigate the risk of crop failure, and thus to increase food self-sufficiency. One site in the southern Guinea savanna and one in the northern Guinea savanna were selected which differed in biophysical and socio-economic resources. In each site, field experiments were conducted on three fields differing in soil fertility (fertile, medium fertile, poorly fertile) to quantify: N_2-fixation and N contribution to soil fertility by grain legumes in sole and intercropping; impact of replacement intercropping on increasing resource use efficiency and crop productivity; and productivity of relay (additive) intercropping and rotation of grain legumes with maize. Scenario analysis was performed with data from the N2Africa Ghana project supplemented with data from the on-farm experiments and literature to test the impacts of intensification and diversification options on household food self-sufficiency. Sole legumes fixed larger amounts of N_2 than under intercropping. The soil N balance was generally positive and similar between intercrops and sole crops suggesting that both systems could be sustainable intensification and diversification options. Poor fields stimulated grain legumes to rely on atmospheric N_2 for growth leading to more positive soil N balances than in fertile fields. Consequently, legumes in poor fields were more competitive with maize and led to greater intercrop yield advantage than in fertile fields. Across all fields and sites, intercropping enhanced the efficiency in resource use resulting in a 26% to 46% yield advantage over sole cropping. Intercrops were more efficient and productive in the drier northern Guinea savanna than in the wetter southern Guinea savanna. Yet the absolute larger grain yields achieved in fertile fields and in the southern Guinea savanna with more favourable soil fertility and rainfall resulted in greater net benefits. This suggests that intercropping is beneficial both in poorly fertile and fertile fields though the benefits take different dimensions. Legume-cereal rotation was superior in increasing the yield of maize without N fertiliser ranging from 0.38 t ha^{-1} in NGS to 1.01 t ha^{-1} in SGS due to residual N and non-N benefits compared with continuous maize cropping. Sowing cowpea first and relaying maize decreased maize grain yield substantially from 0.29 t ha^{-1} (14%) in SGS to 0.82 t ha^{-1} (83%) in NGS, representing 14% and 83% grain yield reductions relative to maize sown at the beginning of the season. These grain yield reductions were due to inadequate rainfall received by the relay maize. When maize was sown from the onset of the season and the cowpea relayed, the cowpea grain yield reduction was relatively smaller compared with that of maize. Such cowpea grain yield decline was similar between the SGS and NGS and ranged from 28% (0.18 t ha^{-1}) to 47% (0.26 t ha^{-1}) relative to the cowpea sown from the onset of the season. The cumulative grain yield of this relay system over two seasons was similar to that of the legume-cereal rotations even with cowpea failing to yield in the first season. The scenario analysis revealed a high incidence of food insufficiency among smallholder farm households in the Guinea savanna of Ghana. This ranged from 56% in the Northern region with relatively favourable rainfall, soil fertility and larger land area cropped per farm to 45% in the Upper East and Upper West regions with comparatively less rainfall, poor soils and smaller land area cropped. In addition, 21% of households in the Northern region and 37% in the Upper East and Upper West regions could only survive on their own food production for six months or less. However, the scenario analysis suggested that through intensification and diversification with grain legumes, the proportion of food self-sufficient households in the Guinea savanna could increase by 25 – 43% and those self-sufficient for a maximum of half a year decreased to 3 – 15%. Households could also generate substantial marketable surpluses to earn income. However, the total size of land cropped by a farm household matters, and improved access to markets and credit are needed to acquire the relevant inputs. Also, multi-year analysis using modelling would be relevant in providing insights on long-term nutrient balances, especially of N and soil organic matter to understand the long-term sustainability of the various options.

Key words: Guinea savanna, soil fertility, intensification, diversification, intercropping, rotation, N_2-fixation, grain legumes, maize, farm households, smallholder farming systems

Table of contents

Chapter 1

General introduction

1.1. Sustainable intensification of farming systems in the Guinea savanna

Agriculture in the Guinea savanna region of West Africa epitomises the struggle for food, nutrition and income security facing smallholder farmers in sub-Saharan Africa (SSA). This situation has largely been the outcome of persistent low crop productivity and weak financial capacity of smallholder farm households to purchase adequate food needs to supplement their own food production. The intrinsically poor soil fertility, particularly poor nitrogen (N) availability, has been identified as the most pressing predicament that has led to the chronic low crop yields on farmers' fields (Dakora et al., 1987; Bationo et al., 1998; Sanginga, 2003). Grain legumes fix atmospheric nitrogen (N_2) and contribute to soil fertility enhancement and maintenance improving the productivity of subsequent crops or crops grown in association with them (Giller, 2001). Besides fixing nitrogen, grain legumes provide edible seeds rich in protein, amino acids and micronutrients and contribute to the nutrition needs of smallholder farm families (Giller, 2001; Kerr et al., 2007; Belane and Dakora, 2011). Intensifying and diversifying crop production with grain legumes is essential in the Guinea savanna region to alleviate the persistent food, nutrition and income insecurity of smallholder farms.

The poor soil fertility coupled with climate stresses, particularly irregular rainfall, bring a risk of crop failure in sole cropping systems. Diversification of crop production is of utmost importance in this agro-ecological zone (AEZ) to improve the resilience of farming systems to climate stresses, increase crop productivity and protect food, nutrition and income for farm households. On top of these, the rapid growing population in the Guinea savanna region of West Africa, and in SSA in general (United Nations, 2017) has resulted in an increased demand for food (Vanlauwe et al., 2014). The situation has increased pressure on agricultural land and necessitated sustainable intensification of crop production systems (Pretty et al., 2011; Vanlauwe et al., 2014).

Intensification of cereal-based low-input production systems in an attempt to ensure household food and income security has led to rapid soil fertility depletion and negative nutrient balances (Stoorvogel and Smaling, 1990; Bationo et al., 1998; Sanginga, 2003). Depletion of nitrogen in smallholder farming systems in the Guinea savanna is estimated to be in the range of 36 – 80 kg N ha^{-1} $year^{-1}$ (Stoorvogel and Smaling, 1990; Manyong et al., 2001). Farm households need to substantially increase fertiliser use to produce enough food to meet the needs of the growing population. It is no surprise that at the Abuja Fertiliser Summit in 2006, the African Heads of States declared to increase fertiliser use by farmers from an average of 8 kg ha^{-1} to 50 kg ha^{-1} by 2015 (African Fertiliser Summit, 2006).

Intensification of crop production only through increased mineral fertiliser use, combined with recycling organic resources is insufficient. This is so because the majority of smallholder farm households are already trapped in poor economic conditions and lack access to financial resources to purchase adequate mineral fertilisers needed for increased crop production (Manyong et al., 2001; Tittonell and Giller, 2013). Low availability of mineral fertilisers and poor rural road networks impede increased mineral fertiliser use. Sustainable intensification is needed to improve crop productivity per unit area of land with efficient use of both ecological resources and the external inputs that can be afforded (Pretty et al., 2011; Tittonell and Giller, 2013; Reddy, 2016). In this context, an integrated soil fertility management (ISFM) approach with the inclusion and intensification of legumes to biologically fix and contribute N to improve soil fertility and household food is crucial (Vanlauwe et al., 2010).

In the Guinea savanna AEZ of West Africa, grain legumes are known to fix between 15 – 210 kg N ha^{-1} per season – a wide range depending on the legume productivity and soil fertility (Dakora et al., 1987; Sanginga, 2003; Yusuf et al., 2009a; Belane and Dakora, 2010). Intensification of grain legume production in smallholder farming systems is thus vital for sustainable intensification of crop production. Therefore, insights on suitable crop diversification and intensification options are required to appropriately integrate and intensify grain legumes production in the dominant cereal-based systems to improve soil fertility and crop productivity.

1.2. Cropping system diversification with grain legumes

Crop or cropping system diversification refers to a shift from often a less productive, less resilient and less sustainable crop or cropping system to a more productive, resilient and sustainable one (Reddy, 2016). The shift is usually in response to specific farm goals. These may include new markets (Reddy, 2016), soil fertility improvement (Teklewold et al., 2013), pests and diseases suppression (Krupinsky et al., 2002; Teklewold et al., 2013), increasing crop productivity and stabilising household food, nutrition and income (Matlon, 1991). Crop diversification is also used as an insurance against a possible crop failure (Vierich and Stoop, 1990; Malton et al., 1991; Rusinamhodzi et al., 2012). Crop diversification is thus a key pathway to sustainable intensification of crop production (Vanlauwe et al., 2014).

Several crop diversification options exist within the framework of sustainable intensification (e.g. agro-forestry, green manure intercropping and rotations with cereals). Cereal-grain legume rotation, spatial and temporal intercropping systems appear readily adaptable to the biophysical and socio-economic context of smallholder farming systems in the Guinea savanna and are being used.

Cereal-legume intercropping improves resource use efficiency and productivity of component crops due to complementary use of environmental resources for growth compared with sole cropping (Ofori and Stern, 1987; Rao and Singh, 1990; Willey, 1990). Complementarity occurs due to differences in acquisition and use of environmental resources (e.g. light, water, nutrients) by the intercrop components (Ofori and Stern, 1987; Willey, 1990). However, the complementary interactions can be affected by the choice and arrangement of intercrops, the timing of planting, as well as the fertility of the soil (Willey, 1990; Midmore, 1993).

Increased productivity of maize after a grain legume relative to maize after maize has been widely reported in the Guinea savanna of West Africa (Sauerborn et al., 2000; Sanginga et al., 2002; Franke et al., 2018). The N contributed to the soil by grain legumes and non-N benefits of rotating grain legumes with maize (pests and diseases suppression, improved soil properties, soil microbial biomass and activity) have been reported to account for the increased productivity of maize after grain legumes (Stevenson and van Kessel, 1996; Giller, 2001; Yusuf et al., 2009b). Nevertheless, the residual N benefits of rotating maize with grain legumes will be affected by soil fertility which has an impact on the amount of N_2-fixed and N contributed to the soil (Giller, 2001), though other biophysical factors relating to soil fertility might also influence the residual benefits.

1.3. Soil fertility enhancement strategies

The use of mineral fertilisers, animal manure, agroforestry, green manures, natural or bush fallows and grain legumes are strategies within the confines of integrated soil fertility management to increase crop yields in smallholder farming systems in SSA (Vanlauwe et al., 2010; 2014). Many of these strategies are not feasible in the context of the prevailing biophysical and socio-economic resources of smallholder farms in the Guinea savanna of West Africa. For instance, natural fallow system is no longer suitable due to a shorter time to regenerate soil fertility as population continues to increase with heightened pressure on agricultural land (Sanginga, 2003). The use of animal manure is hindered by limited availability (Manyong et al., 2001), labour and transport constraints (Bala et al., 2011) and inefficient storage and handling by farmers (Rufino et al., 2006; Franke et al., 2008b). Green manures and agroforestry trees are not preferred by farmers because they do not generally provide immediate edible yield to support household food, nutrition and income (Giller, 2001; Adjei-Nsiah et al., 2007; Giller et al., 2009). Limitations to the increased use of mineral fertilisers are discussed in Section 1.1. Grain legumes are thus a key element for soil fertility enhancement within the smallholder setting in the Guinea savanna where there is a high incidence of food and nutrition insecurity.

1.4. Problem statement and justification of research

Ghana has recorded a steady increase in food security but with a marked regional disparity. Food security still remains a critical concern in northern Ghana (located in the Guinea savanna agro-ecological zone) with roughly 60% of the rural population who are mostly smallholder farmers being food insecure (WFP, 2009; 2013). The population growth rate of 1.2 – 2.9 % (GSS, 2013) indicates that the numbers of food insecure people are expected to increase in northern Ghana. This calls for sustainable intensification and diversification to increase crop production per unit area of land in order to increase food availability to meet the growing demand.

However, crop productivity in smallholder farming systems in the Guinea savanna of Ghana continues to be constrained by poor and declining soil fertility, especially nitrogen availability (Sauerborn et al., 2000). This is against the backdrop that the majority of the available soil fertility enhancement options are generally not feasible within the smallholder setting in the Guinea savanna as discussed in Sections 1.2 and 1.3. The negative impact of poor soil fertility on crop yields are further compounded by the erratic unimodal rainfall regime that characterises the single cropping season in the Guinea savanna (Stoop, 1986; Vierich and Stoop, 1990). These expose smallholder farmers to the risk of crop failure in sole cropping systems. Spatial and temporal sustainable intensification and diversification options are essential to mitigate the risk of crop failure in sole cropping, improve crop productivity and safeguard household food and income (Stoop, 1986; Vierich and Stoop, 1990). Intensification of grain legume production is vital for such diversification and sustainable intensification (Giller, 2001).

Sustainable intensification and diversification options with grain legumes can be influenced by the prevailing biophysical (e.g. climate, length of growing season, soil type and fertility, farm size) and socio-economic (finance, input and output markets) properties of smallholder farms. A large variability exists among AEZs and farms within the different zones in the Guinea savanna in terms of the above-mentioned properties (Vierich and Stoop, 1990; Oikeh et al., 1998). Therefore, evaluation of sustainable intensification and diversification options needs to take account of such differences in resources and their influence on the suitability and productivity of each option, and eventually the impact on food self-sufficiency. Increasing the total food production of smallholder farms in the Guinea savanna of Ghana is crucial to achieving household food self-sufficiency. This is because in sub-Saharan Africa, farm households' own food production constitute roughly 70% of total household food availability Frelat et al. (2016).

Yet, evaluations of spatial and temporal maize-grain legume intensification and diversification options to offer opportunities for smallholder farms in the Guinea savanna have largely been confined to experimental stations instead of farmers' fields. Most of these studies (e.g. Agyare et al., 2006; Konlan et al., 2013) do not take account of the diverse soil fertility status in farmers' fields and the relative differences in the other biophysical properties between farms in contrasting sites. Also, previous studies (e.g. Agyare et al., 2006; Ajeigbe et al., 2010; Konlan et al., 2013) have focused mainly on distinct alternate row arrangement of maize and grain legume intercrops (Agyare et al., 2006; Konlan et al., 2013) and legume-cereal rotations (e.g. Sauerborn et al., 2000; Sanginga et al., 2002; Agyare et al., 2006; Yusuf et l., 2009a; 2009b). Knowledge is needed on how the diverse biophysical and socio-economic properties of the different AEZs, farm households and fields impact on the suitability and productivity of sustainable intensification and diversification options with grain legumes. Additionally, insights are needed on the potential impacts of sustainable intensification and diversification options with grain legumes on household food self-sufficiency. At present, such research knowledge and/or insights are generally lacking. My PhD research is focused on filling these knowledge gaps. This is in line with the goal of N2Africa – Putting nitrogen fixation to work for smallholder farmers in Africa (Giller et al., 2013), within which this PhD work was conducted. N2Africa is a large-scale "research-in-development" project conducted in several sub-Saharan African countries including Ghana. The project is aimed at increasing biological N fixation of grain legumes to contribute to increasing soil fertility, grain legume productivity and productivity of cereal crops grown in association with them towards improving food, nutrition and income of smallholder farm households (Ampadu-Boakye et al., 2016).

1.5. Study objectives and research questions

This study focused on exploring spatial and temporal maize-grain legume intensification and diversification options that offer opportunities to reduce the risk of crop failure in sole cropping systems; maintain soil fertility; enhance resource use efficiency and increase crop productivity under on-farm conditions towards increasing food self-sufficiency of smallholder farm households in the Guinea savanna of Ghana.

Specifically, the study sought:

1) To quantify the influence of cropping system and soil fertility status on grain yield, N_2-fixation and net N contribution to soil fertility improvement in the southern and northern Guinea savanna AEZs of northern Ghana.
2) To determine the impact of soil fertility status and different spatial maize-grain legume intercropping patterns on grain yield, intercrop efficiency and productivity

as well as economic profitability in contrasting sites in the southern and northern Guinea savanna AEZs of northern Ghana.

3) To assess the productivity of short duration maize and cowpea relay intercropping systems relative to continuous cropping of maize, soybean-maize, groundnut-maize and natural fallow-maize rotations under different soil fertility status in the southern and northern Guinea savanna AEZs of Ghana to offer sustainable intensification options for smallholder farms.
4) To provide insights on the diversity of resources availability and allocation in contrasting regions in the Guinea savanna of Ghana, the influence on sustainable intensification and diversification options with grain legumes, and how these in turn impact on food self-sufficiency of smallholder farm households.

Research questions

The study addresses the following research questions arranged according to the thesis chapters.

Chapter 2:

- What are the effects of cropping pattern and soil fertility status on N_2-fixation and net N contribution by grain legumes to soil fertility improvement?
- What is the influence of AEZs on N_2-fixation and net N contribution to soil fertility enhancement by different grain legume species?

Chapter 3:

- What are the impacts of spatial arrangements of maize-grain legume intercrops and sole crops on resource use efficiency, crop productivity and economic profitability?
- Do soil fertility status influence resources use efficiency, intercrop productivity and economic profitability of intercrops and sole crops?

Chapter 4:

- Which maize and cowpea relay patterns are suitable for the contrasting AEZs in the Guinea savanna?
- Are maize and cowpea relay patterns more or less productive compared with the more common continuous maize, grain legume-maize and fallow-maize rotations?

Chapter 5:

- What are the implications of the variable biophysical and socio-economic resources in the different regions, and farm households within regions on food self-sufficiency?
- What are the impacts of sustainable intensification and diversification options with grain legumes on smallholder household food self-sufficiency in the Guinea savanna?

Chapter 6:

In this concluding chapter I bring together the work as a whole and discuss the overall question:

- Do the maize-grain legume diversification and intensification options fit in the diverse biophysical and socio-economic contexts of smallholder farming systems in the Guinea savanna?
- What needs to be considered and what opportunities exist for smallholder farm households to benefit from promising sustainable intensification and diversification options with grain legumes?
- Are crop intensification and diversification options with grain legumes nutrient exhaustive or could they be sustainable?

1.6. Study setting

The study was conducted in the Guinea savanna region of northern Ghana. This region is the main area for grain legumes production in Ghana and the operational area of the N2Africa project (Rusike et al., 2013). The region has a single cropping season per year and inherently poor soil fertility, which along with erratic rainfall presents risks to crop failure. Further, the area is characterised by low crop productivity and high household food and nutrition insecurity compared with other AEZs in Ghana. Farmers' fields were selected with different soil fertility status in contrasting sites in the southern and northern Guinea savanna AEZs (Fig. 1.1). This was to capture the diversity in climate and soil characteristics that can affect the productivity of maize-grain legume intensification and diversification options. Agriculture is the main occupation in the area with about 80% of households engaged in crop production and about 70% keeping livestock. Maize is the main food security crop cultivated by more than 95% of farm households. Main grain legumes are groundnut, cowpea and soybean, and legumes in rotation with maize or continuous maize as sole crops form the dominant cropping systems.

1.7. Thesis outline

Chapter 2 focuses on quantifying the amount of biological N_2 fixed by grain legumes in intercropping and sole cropping, and the relative contribution of residual N to improve soil fertility and crop productivity. The effect of soil fertility status on biological N_2-fixation and net N contribution to soil fertility enhancement by grain legumes is analysed. The reliability of partial soil N balance as an indicator for assessing the sustainability of cropping systems is assessed.

In Chapter 3, we assess the impact of different spatial arrangement of maize-grain legume intercrops and soil fertility status on resource use efficiency and crop productivity under on-farm conditions. The agronomic and economic performances of the different spatial intercrop arrangements relative to the respective sole crops are discussed.

Chapter 4 explores the suitability of short duration maize-cowpea relay systems as ecological intensification and diversification options to contribute to mitigating the risk of crop failure in sole cropping systems and increase household food availability. The agronomic performance of different maize-cowpea relay patterns is compared with grain legume-maize rotations and continuous maize production systems.

Chapter 5 provides an understanding on the diversity of smallholder farming systems in the Guinea savanna of Ghana and the impact on household food self-sufficiency. Using the baseline survey data of the N2Africa Ghana project and supplemented with data from the preceding chapters and literature, we identified patterns of resources allocation to the main crops and developed scenarios for intensification and diversification with grain legumes to improve crop productivity and household food self-sufficiency.

In Chapter 6, I place the different maize-grain legume intensification and diversification options into the broader context of smallholder farming systems in the Guinea savanna of Ghana, and by extension West Africa. The potential of the maize-grain legume intensification and diversification options in contributing to achieving household food self-sufficiency, and the possible challenges and opportunities associated with each is discussed. Finally, the major conclusions drawn from the study are synthesised and recommendations for further research are presented.

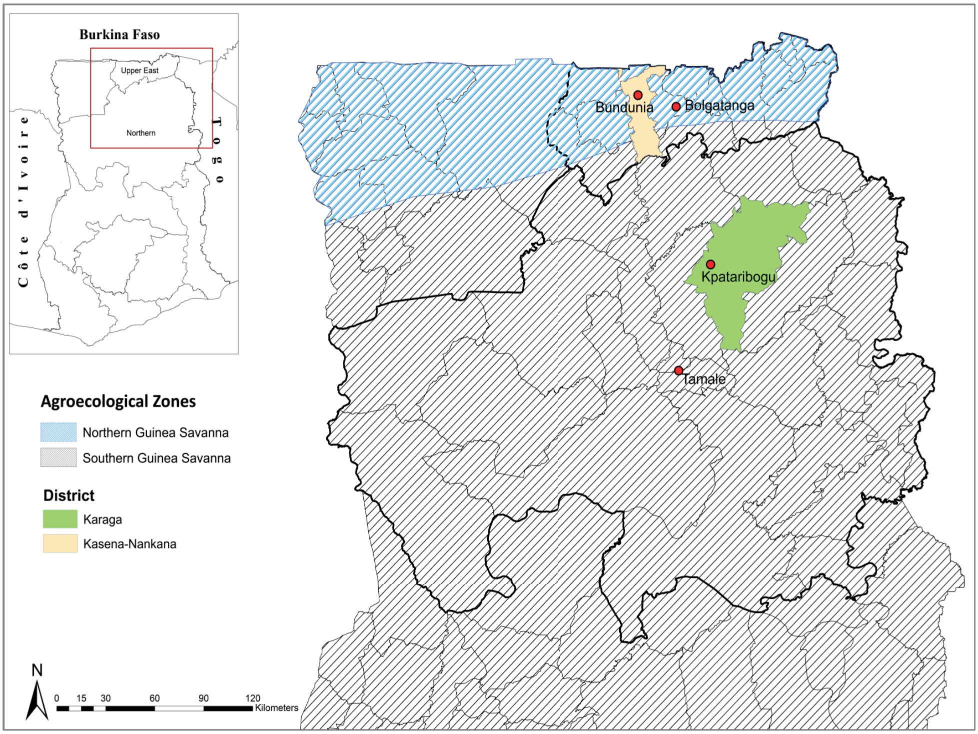

Fig. 1.1. Map of Ghana showing the contrasting sites of the study (Kpataribogu located in the Karaga district of Northern Region in the Southern Guinea Savanna, SGS; and Bundunia located in the Kassena-Nankana East Municipal of the Upper East Region in the Northern Guinea Savanna, NGS).

Chapter 2

N_2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana

This chapter is published as:

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 and Environment 261, 201–210.

Abstract

Continuous cereal-based cropping has led to a rapid decline in soil fertility in the Guinea savanna agro-ecological zone of northern Ghana with corresponding low crop yields. We evaluated the effects of cropping system and soil fertility status on grain yields and N_2-fixation by grain legumes and net N contribution to soil fertility improvement in contrasting sites in this agro-ecological zone. Maize was intercropped with cowpea, soybean and groundnut within a row with a maize stand alternated with two equally spaced cowpea or groundnut stands and, in the maize-soybean system, four equally spaced soybean stands. These intercrops were compared with sole crops of maize, cowpea, soybean and groundnut in fertile and poorly fertile fields at sites in the southern (SGS) and the northern (NGS) Guinea savanna. The proportion of N derived from N_2-fixation (%Ndfa) was comparable between intercrops and sole crops. However, the amount of N_2-fixed was significantly larger in sole crops due to a greater biomass accumulation. Legumes in poorly fertile fields had significantly smaller shoot δ^{15}N enrichment (–2.8 to +0.7‰) and a larger %Ndfa (55–94%) than those in fertile fields (–0.8 to +2.2‰; 23–85%). The N_2-fixed however was larger in fertile fields (16–145 kg N ha^{-1}) than in poorly fertile fields (15–123 kg N ha^{-1}) due to greater shoot dry matter and N yields. The legumes grown in the NGS obtained more of their N requirements from atmospheric N_2-fixation (73–88%) than legumes grown in the SGS (41–69%). The partial soil N balance (in kg ha^{-1}) was comparable between intercrops (–14 to 21) and sole legumes (–8 to 23) but smaller than that of sole maize receiving N fertiliser (+7 to +34). With other N inputs (aerial deposition) and outputs (leaching and gaseous losses) unaccounted for, there is uncertainty surrounding the actual amount of soil N balances of the cropping systems, indicating that partial N balances are not reliable indicators of the sustainability of cropping systems. Nevertheless, the systems with legumes seem more attractive due to several non-N benefits. Our results suggest that soybean could be targeted in the SGS and cowpea in the NGS for greater productivity while groundnut is suited to both environments. Grain legumes grown in poorly fertile fields contributed more net N to the soil but growing legumes in fertile fields seems more lucrative due to greater grain and stover yields and non-N benefits.

Keywords: Cowpea; Soybean; Groundnut; Maize; Partial N balance

2.1. Introduction

The Guinea savanna agro-ecological zone of northern Ghana is characterised by a single cropping season (with 180-200 growing days), a unimodal rainfall pattern and an annual mean precipitation of 1100 mm (SRID, 2016). The soils in many parts of the region are poor in fertility, particularly N (Dakora et al., 1987). Shortened fallow periods have exerted pressure on the already fragile soils (Dakora et al., 1987; Franke et al., 2004). These, issues compounded by continuous cereal-based systems without sufficient nutrient inputs to the soil, have led to wide scale declines in soil fertility and persistently poor crop yields on smallholder farms (Sanginga, 2003).

The incorporation of grain legumes into cereal-based cropping systems can contribute to the replenishment of soil fertility through the fixation of atmospheric nitrogen (N_2), while supplying protein-rich grains for household food and nutrition (Giller, 2001). In the West African Guinea savanna, grain legumes fix between 15 and 201 kg N ha^{-1} per season (Dakora et al., 1987; Sanginga et al., 1997; Belane and Dakora, 2010; Yusuf et al., 2014). A net N contribution of up to 48 kg ha^{-1} by groundnut (Yusuf et al., 2014) and 125 kg N ha^{-1} by cowpea (Dakora et al., 1987) with the grain exported from the field has been documented. Consequently, incorporation of grain legumes into cereal-based cropping systems represents an opportunity to address these soil fertility concerns. Legumes can be incorporated through sole-cropped legume-cereal rotations as predominantly practised by farmers in the region. However, the increased risk of crop failure in sole cropping due to an unpredictable rainfall regime in the single cropping season threatens household food security. Accordingly, intercropping the main cereals (especially maize which is the dominant crop in the area) with grain legumes can alleviate such risks to safeguard household food and income security (Giller, 2001).

The high labour requirements and the general yield reduction of the main crop in cereal-legume intercropping compared with sole cropping are a concern for farmers. Nevertheless, cereal-legume intercropping may improve diversification in nutrient uptake by the component crops, environmental resources use efficiencies and increased yield per unit area relative to sole cropping (Willey, 1990). Cereal-legume intercropping thus presents an alternative to sole cropping. The diverse bio-physical environments and variable crop management strategies lead to a large variability in benefits from N_2-fixation and net N contribution of legumes to the soil (Giller, 2001). Also, grain legume species and varieties differ in their contribution to soil N fertility enhancement (Giller, 2001). This suggests a need for targeting different legume species to different agro-ecological zones or contrasting environments within an agro-ecological zone for increased yields and soil fertility improvement.

Several studies have quantified N_2-fixation and net N contribution to the soil in the Guinea savanna of West Africa (e.g. Eaglesham et al., 1981; Sanginga et al., 1997; Ogoke et al., 2003; Yusuf et al., 2008) and northern Ghana (e.g. Dakora et al., 1987; Naab et al., 2009; Belane and Dakora, 2010; Konlan et al., 2015). Only few studies (e.g. Eaglesham et al., 1981; Konlan et al., 2015) assessed the effect of maize-grain legume intercropping on N_2-fixation. Even so, the net N contributions to the soil from the intercrop systems were not measured. In addition, the wide variability in soil fertility across the different fields in the West African Guinea savanna agro-ecological zone was not considered. The objectives of this study were to determine the effects of: (i) intercropping, (ii) soil fertility status and (iii) grain legume species on grain yield, N_2-fixation and net N contribution to soil fertility improvement in the southern and northern Guinea savanna agro-ecological zones of northern Ghana.

2.2. Materials and methods

2.2.1. On-farm trials and trial management

The field trials were conducted on-farm in the 2013 cropping season at Kpataribogu {9°58' N, 0°40' W; 172 m above sea level (masl)} in the Karaga District (southern Guinea savanna, SGS) and at Bundunia (10°51' N, 1°04' W; 185 masl) in the Kassena-Nankana East Municipal (northern Guinea savanna, NGS) of northern Ghana. Rainfall was recorded with rain gauges at both trial sites. A total of 598 mm in the SGS and 532 mm rainfall in the NGS were received during the growing season. The soils at both sites are classified as Savanna Ochrosol and Groundwater Laterites in the interim Ghana soil classification system (Adjei-Gyapong and Asiamah, 2002) and as Plinthosols in the World Reference Base for soil resources (WRB, 2015). Two field types representing fertile and poorly fertile soil conditions were selected at each site, using farmers' knowledge and the help of agricultural extension officers. Fields selected were under mono-cropped maize, grain legume or cotton in the three preceding seasons. Soils of each field were sampled at 0-15 cm depth prior to land preparation, thoroughly mixed and about 1 kg sub-sample was air-dried, sieved through a 2 mm-mesh sieve and analysed for pH (1:2.5 soil:water suspension), organic C (Walkley and Black), total N (Kjeldahl), available P (Olsen), exchangeable K, Mg, and Ca (in 1 M ammonium acetate extracts) and texture (hydrometer method).

Treatments consisted of cowpea – *Vigna unguiculata* (L.) Walp; soybean – *Glycine max* (L.) Merr. and groundnut – *Arachis hypogaea* L. intercropped with maize (*Zea mays* L.) or grown as sole crops. In the intercrop treatments, maize and legumes were grown within the same row. A maize stand was alternated with two equally spaced cowpea or groundnut stands within a row. In the maize-soybean system, a maize stand was alternated with four soybean stands within a row. Maize and all intercropped legumes were sown at one seed per hill, while sole legumes were sown at two seeds per hill. Inter-row spacing was 75 cm in all treatments. Intercropped maize was spaced at 50 cm within a row while intra-row spacing for sole maize was 25 cm. Sole cowpea and groundnut had an intra-row spacing of 25 cm and that of sole soybean was 12.5 cm. These resulted in plant populations (plants ha^{-1}) of 26,667 and 53,333 for maize, 53,333 and 106,666 for cowpea and groundnut, and 106,666 and 213,334 for soybean, respectively for intercrops and sole crops. The spatial planting arrangements of the different cropping patterns are shown in Fig. 2.1. The experimental design was a randomised complete block design. Blocks of treatments were replicated four times per fertility level at each site and treatments were randomised within blocks. A single plot measured 4.5 × 4.0 m.

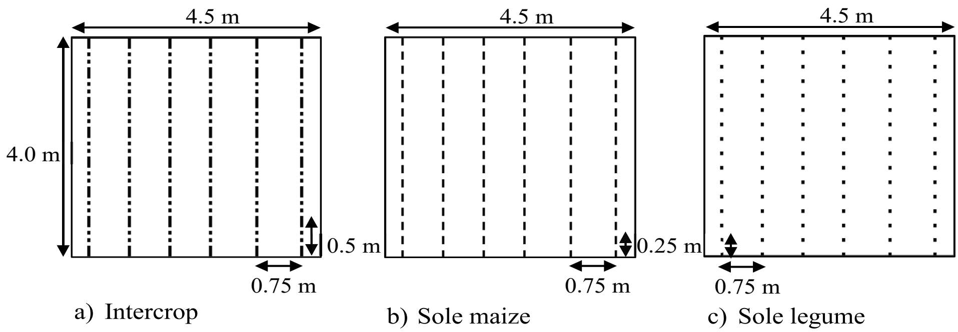

Fig. 2.1. Schematic overview of cropping patterns: a) maize-legume within-row intercrop treatment, b) sole maize treatment and c) sole legume treatment. The intercrop scheme shown is for maize-cowpea and maize-groundnut systems. For the maize-soybean intercrop, a maize stand was alternated with four soybean stands within a row. Sole legume scheme (Fig. 2.1c) is for sole crops of cowpea and groundnut (16 plant stands per row). Sole soybean treatment had 32 plant stands per row (0.125 m intra-row spacing).

The land was tractor-ploughed, ridged and sowing done on the apex of the ridges. The varieties used were Padi-tuya: SARC 3-122-2 (cowpea), Jenguma: Tgx 1448-2E (soybean), Samnut 22 (groundnut) in SGS and Chinese variety (groundnut) in NGS, and Obatanpa: GH83-63SR (maize). All crops were sown on July 1-2 in the SGS and July 16-17 in the NGS. Sowing was relatively late due to a late onset of rains. Soybean seeds were inoculated with the commercial inoculant Legumefix (Legume Technology, UK) containing *Bradyrhizobium japonicum* strain 532c (re-isolated in Brazil from strain USDA 442 Wisconsin, USA) at sowing at the rate of 5 g of inoculant per kg of seed. At sowing, 25 kg P ha^{-1} and 30 kg K ha^{-1} as TSP and MoP were uniformly applied to all treatments. Urea was spot-applied to only maize stands at a rate of 25 kg N ha^{-1} for intercropped maize and 50 kg N ha^{-1} for sole maize. Half of the N was applied at three weeks after sowing (WAS) and the other half at six WAS. All fertilisers were band-applied at 3 cm depth and 5 cm from the plants. No N fertiliser was applied to sole legumes. Plots were weeded twice with hoe at 3 and 6 WAS.

2.2.2. Yields, N_2-fixation and N uptake measurements

Legume shoot biomass was sampled at mid-pod filling stage from a 3.0 m^2 subplot, separated into shoots and pods and both the total and sub-sample fresh weights were taken in the field. Grain and stover yields were assessed from a 4.5 m^2 subplot at crop maturity with both total and sub-sample fresh weights taken in the field. Fresh to dry weight conversion factors were used to convert the sub-sample fresh weights to dry weights: Cowpea (biomass harvest at mid-pod-filling: shoot=0.17, pod=0.18; harvest at crop maturity: haulm=0.19, pod =0.64, grain to pod ratio=0.77, husk to pod ratio=0.23), soybean (biomass harvest at mid-pod-filling: shoot=0.29, pod=0.31; harvest at crop maturity: haulm=0.91, pod=0.69, grain to pod ratio=0.71, husk to pod ratio=0.29), groundnut (biomass harvest at mid-pod-filling: shoot=0.22, pod=0.31; harvest at crop maturity: haulm=0.34, pod=0.66, grain to pod ratio=0.64, husk to pod ratio=0.36) and maize (harvest at crop maturity: haulm=0.38, cob=0.71, grain to cob ratio=0.79, core to cob ratio=0.21). These were derived from experimental data by taking pooled means of several treatments and have previously been reported by Kermah et al. (2017). Legume and maize grain yields are presented at 12% and 14% moisture content, respectively, shoot biomass and stover yields on a dry weight basis. Stover yield includes both the haulms and the husks.

Non-legume broad-leaved weeds growing along the borders of the main plots were sampled from each block and used as reference plants for estimating N_2-fixation using the ^{15}N natural abundance method (Unkovich et al., 2008). Several reference weed species were collected per block and the mean $\delta^{15}N$ enrichment of these reference species was used in estimating the proportion of N derived from atmosphere (%Ndfa). The weighted $\delta^{15}N$ of whole shoots was calculated from the separate $\delta^{15}N$ measurements of shoots and pods harvested at mid-pod filling and used to estimate %Ndfa.

As N concentrations in legume grain and stover at maturity were not measured, legume N uptake was estimated with mean N concentrations taken from Nijhof (1987): cowpea grain: 2.90%, cowpea stover: 1.73%; soybean grain: 6.10%, soybean stover: 1.05%; groundnut grain: 4.50%, groundnut stover: 1.40%. For maize, N concentrations in grain and stover measured from experimental plots in an adjacent trial at each site (with the same maize variety and similar fertiliser treatment as in our trial) were used to calculate N uptake: in the SGS maize grain: 1.46%, maize stover: 0.63% and in the NGS, maize grain: 1.41%, maize stover: 0.55. The C:N ratios were calculated assuming that the carbon concentration in the crop residues was 40% (Partey et al., 2014).

2.2.3. Calculations and statistical analysis

The weighted δ^{15}N for whole shoot was calculated as:

$$\{(\text{shoot N} \times \delta^{15}\text{N shoot}) + (\text{pod N} \times \delta^{15}\text{N pod})\}/(\text{shoot N} + \text{pod N}) \qquad (1)$$

Shoot N = %N shoot/100 × shoot dry matter yield (kg ha^{-1}); Pod N = %N pod/100 × pod dry matter yield (kg ha^{-1}). %N derived from N_2-fixation (%Ndfa) was calculated from the weighted δ^{15}N values using the equation of Unkovich et al. (2008) as:

$$\%\text{Ndfa} = \{(\delta^{15}\text{N}_{\text{ref}} - \delta^{15}\text{N}_{\text{leg}})/(\delta^{15}\text{N}_{\text{ref}} - \text{B})\}100 \qquad (2)$$

where $\delta^{15}N_{ref}$ and $\delta^{15}N_{leg}$ are the δ^{15}N natural abundance of the shoots of the non-N_2-fixing reference plants (fully dependent on N from the soil) and the δ^{15}N natural abundance of the N_2-fixing legumes, respectively; and B is the δ^{15}N of shoots of the test legume fully dependent on N_2-fixation (a measure of isotopic fractionation during N_2-fixation). The smallest weighted δ^{15}N value for each legume shoot was used as the B value (Peoples et al., 2002): i.e. cowpea: –3.52; soybean: –2.04 and groundnut: –0.71. Shoot N_2-fixed (kg ha^{-1}) was calculated as:

$$\text{Shoot } N_2\text{-fixed (kg ha}^{-1}) = \%\text{Ndfa} \times \text{whole shoot N} \qquad (3)$$

The amount of N_2-fixed in the whole plant as reported in this paper was calculated assuming that 30% of N_2 fixed was present in the roots (Unkovich et al., 2008):

$$\text{Total } N_2\text{-fixed (kg ha}^{-1}) = \text{shoot } N_2\text{-fixed} / (0.70) \qquad (4)$$

Eq. (4) was used to estimate the total amount of N_2-fixed for soil N balance determination as the inclusion of the N_2-fixed in below-ground dry matter has a significant impact on the soil N balance (Peoples et al., 2009).

The net N (kg ha^{-1}) contribution to the soil N economy was calculated in two scenarios as:

Scenario 1 (only grain exported): (5)

(i) Intercrop = total N_2-fixed + applied N – legume grain N – maize grain N
(ii) Sole legume = total N_2-fixed – grain N
(iii) Sole maize = applied N – grain N

Scenario 2 (grain + stover exported): (6)

(i) Intercrop = total N_2-fixed + applied N – legume grain N – legume stover N – maize grain N – maize stover N
(ii) Sole legume = total N_2-fixed – grain N – stover N
(iii) Sole maize = applied N – grain N – stover N

Statistical analysis was conducted using GenStat (version 18.1, VSN International Ltd). Data were analysed with a linear mixed model. For each legume species, data for both cropping systems and soil fertility status were analysed together for each site with cropping system and soil fertility as fixed factors and replication as a random factor. To test for the effect of legume species on shoot $\delta^{15}N$ and %Ndfa, data for both cropping systems across fertility status for all three legume species were analysed together per site with cropping system, fertility and legume species as fixed factors and replication as random factor. For cross-site analysis, data for all cropping systems across fertility status for each legume species for both sites were analysed together with all factors including site kept fixed and replication as random factor. Both individual and interaction effects of these factors on N_2-fixation and soil N balance were analysed. The standard error of differences between means (SED) was used to compare treatment means at a significance level of $P<0.05$.

2.3. Results

2.3.1. Soil fertility classification

The soil analysis confirmed the farmers' soil fertility classification at both sites (Table 2.1). The fertile fields had superior soil fertility parameters than the poorly fertile fields at both sites. In the SGS, the fertile field had favourable OC, P, exchangeable Ca and ECEC while in the NGS, pH, OC, N, P, Ca and ECEC were more favourable for crop growth in the fertile field. At both sites however, available P was low and likely to limit crop growth without the application of P fertiliser. The soils in the SGS had better fertility characteristics, particularly a higher OC, N and ECEC, than the soils in the NGS which were more sandy and acidic. Soil available P and exchangeable cations were similar at both sites.

Table 2.1. Physico-chemical properties of the experimental fields differing in soil fertility in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

	SGS		NGS	
Soil fertility parameter	Fertile field	Poorly fertile field	Fertile field	Poorly fertile field
pH	6.2	5.8	5.4	4.7
Organic C (g kg^{-1})	10.9	7.4	6.2	3.9
Total N (g kg^{-1})	0.9	0.8	0.6	0.2
Olsen P (mg kg^{-1})	2.6	1.7	2.8	1.9
K (cmol$_+$ kg^{-1})	0.3	0.2	0.2	0.1
Ca (cmol$_+$ kg^{-1})	1.7	1.3	1.6	0.8
Mg (cmol$_+$ kg^{-1})	0.7	0.7	0.9	0.7
ECEC (cmol$_+$ kg^{-1})	10.2	5.2	6.9	3.0
Sand (g kg^{-1})	563	538	738	798
Silt (g kg^{-1})	321	400	160	160
Clay (g kg^{-1})	116	61	101	41

2.3.2. δ^{15}N enrichment of reference weed species

In the NGS, significant differences (P = 0.019) were observed in the δ^{15}N enrichment of the different weed reference species used to estimate the %Ndfa (Table 2.2). The δ^{15}N values differed between soil fertility status (P < 0.001 in SGS; P = 0.029 in NGS), with larger values in the fertile fields. Averaged over species and soil fertility levels, δ^{15}N values were significantly larger in the SGS than in the NGS (Table 2.2).

Table 2.2. The $\delta^{15}N$ natural abundance (‰) in different species of broad-leaved non-N_2-fixing reference plants and grain legumes (as affected by cropping system) at different soil fertility status at sites in southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

Plant species	SGS		NGS	
	$\delta^{15}N$ (‰)	Range $\delta^{15}N$ (‰)	$\delta^{15}N$ (‰)	Range $\delta^{15}N$ (‰)
Fertile field				
Non-N_2-fixing reference weeds				
Hyptis spicigera			4.0	1.7 – 6.1
Borreria scabra	5.9	5.9	1.5	1.5
Mitracarpus villosus	4.0	2.7 – 6.8		
Aspilia bussei	5.9	4.5 – 6.8	2.9	0.9 – 7.6
Commelina benghalensis	3.9	3.0 – 4.7		
Acanthospermum hispidium			4.0	2.5 – 6.0
Leucas martinicensis			3.9	3.2 – 4.6
Legumes				
Intercrop CP	2.2	1.2 – 3.5	-0.8	-1.1 – -0.5
Sole CP	1.8	0.8 – 3.6	-0.8	-1.4 – -0.2
Intercrop SB	-0.5	-0.9 – 0.3	-0.7	-1.1 – -0.2
Sole SB	-0.3	-0.9 – 0.5	-0.3	-0.6 – 0.03
Intercrop GN	0.9	0.6 – 1.7	0.1	-0.3 – 0.8
Sole GN	1.4	1.0 – 1.9	-0.1	-0.1 – 0.04
Poorly fertile field				
Non-N_2-fixing reference weeds				
Hyptis spicigera	2.9	2.2 – 3.6	3.8	2.5 – 5.5
Borreria scabra	3.3	1.1 – 5.1	1.8	0.9 – 3.0
Mitracarpus villosus	1.9	1.4 – 2.4	2.2	1.0 – 3.9
Aspilia bussei	3.3	1.9 – 5.8		
Commelina benghalensis	4.3	3.7 – 4.7		
Legumes				
Intercrop CP	0.1	-0.3 – 0.6	-2.6	-2.7 – -2.5
Sole CP	0.1	-1.3 – 1.2	-2.8	-3.5 – -2.4
Intercrop SB	-0.5	-1.4 – 0.8	-1.0	-1.6 – -0.2
Sole SB	-0.5	-1.2 – 0.1	-1.7	-2.0 – -1.4
Intercrop GN	0.1	-0.1 – 0.3	-0.5	-0.7 – -0.4
Sole GN	0.7	0.1 – 1.8	-0.4	-0.5 – -0.3
SED (weed species)	*n.s.*		*0.89**	
SED (legume species)	*0.27****		*0.12****	
SED (fertility effect weeds)	*0.41***		*0.48**	
SED (fertility effect legumes)	*0.25***		*0.13****	
SED (cropping system)	*n.s.*		*n.s.*	
SED (all plant species)	*0.40****		*0.41****	

* Significant at P<0.05, ** Significant at P<0.01, *** Significant at P<0.001.

SED = combined standard error of differences between means for: weed species across fertility; legume species across fertility; fertility across weed species or legume species; cropping system across fertility; and all plant species (both legumes and weed species combined).

2.3.3. Shoot biomass, grain and stover yields

Legume shoot dry matter and shoot N yields were in most cases significantly larger in sole crops than intercrops (Table 2.3). Legumes in fertile fields provided significantly greater shoot dry matter and N yields of cowpea at both sites, while that of soybean was superior in the fertile field in the NGS only (Table 2.3). Mean soybean shoot dry matter and N yields were 1066 kg ha^{-1} and 28 kg N ha^{-1} significantly greater in SGS, while shoot dry matter of cowpea was 349 kg ha^{-1} significantly larger in NGS but shoot N yield was rather 9 kg ha^{-1} less in the NGS. Groundnut shoot dry matter (< 1 t ha^{-1}) and N yield (max 31 kg ha^{-1}) were low at both sites.

Intercropping significantly reduced grain yields of all three legume species and of maize compared with the sole crops in the SGS, but these differences were often not significant in the NGS (Table 2.4). The influence of soil fertility on grain yield differed among legume species. Only grain yields of cowpea and soybean were larger ($P < 0.001$ generally) in the fertile fields at both sites (Table 2.4). Maize grain yields were in most cases greater ($P < 0.01$ generally) in the fertile fields at both sites, with a mean of 547 kg ha^{-1} and 806 kg ha^{-1} more maize grain produced in the fertile fields than the poorly fertile fields in the SGS and NGS, respectively (Table 2.4). Mean cowpea grain yield was 190 kg ha^{-1} significantly greater in the NGS, compared with the yield in the SGS, while soybean and maize grain yields were 267 and 1417 kg ha^{-1}, respectively greater in the SGS. Stover yields of cowpea, soybean and maize followed similar trends as grain yields (Table 2.4). Consistently greater stover yields were obtained in sole cropping and in fertile fields at both sites. Soybean and maize stover yields were significantly greater in the SGS, while that of cowpea was similar between sites. Groundnut grain and stover yields were generally poor at both sites with no difference in grain yield but significantly larger stover yield in the SGS (Table 2.4).

2.3.4. δ^{15}N of legumes, %Ndfa and N_2-fixed

Shoot δ^{15}N of legumes did not significantly differ between intercrops and sole crops (Table 2.2). An exception was groundnut in the SGS where the intercrop had a significantly smaller δ^{15}N. The shoot δ^{15}N values of legumes were significantly ($P < 0.001$) smaller than that of the non N_2-fixing reference weeds despite the observed variability in δ^{15}N enrichment of the reference weeds (Table 2.2). The δ^{15}N signatures differed ($P < 0.001$) among legume species. For example, in the SGS, shoot δ^{15}N was significantly smaller in soybean than in groundnut and cowpea. Legumes on poorly fertile fields had smaller ($P < 0.01$) shoot δ^{15}N enrichment at. Legumes in the NGS with relatively poorer soils (Table 1) had smaller shoot δ^{15}N enrichment ($P < 0.001$) than in the SGS (Table 2.2).

%Ndfa was not influenced by cropping system but differed ($P < 0.001$) between legume species and sites (Table 2.3). In the SGS for instance, mean %Ndfa of soybean (69%) and groundnut (58%) was larger ($P < 0.001$) than that of cowpea (41%). In the NGS, %Ndfa was significantly larger in groundnut (88%) than in cowpea (74%) and soybean (73%). %Ndfa was larger ($P < 0.05$) in the poorly fertile fields and in the NGS with relatively poorly fertile fields than in the SGS (Table 2.3).

The amount of N_2-fixed by legumes followed a similar trend to shoot dry matter and N yields (Table 2.3). Sole crops fixed significantly more N_2 than intercrops. Exceptions were N_2-fixed by cowpea and groundnut in the SGS which were similar in intercrops and sole crops. The differences in N_2-fixed between the fertility levels were only significant for cowpea ($P < 0.001$) and soybean ($P < 0.006$) in the NGS. However, in the fertile fields, legumes fixed on average 11 and 31 kg ha^{-1} more N_2 than in the poorly fertile fields in the SGS and the NGS, respectively (Table 2.3). N_2-fixed differed significantly between sites but this varied among the legume species. N_2-fixed by cowpea and groundnut averaged across fertility and cropping systems was 13 and 9 kg ha^{-1}, respectively larger in the NGS than in the SGS while 31 kg ha^{-1} more N_2 was fixed by soybean in the SGS.

Table 2.3. The proportion of N derived from N_2-fixation (%Ndfa), shoot dry matter, whole shoot N and total N_2-fixed by cowpea (CP), soybean (SB) and groundnut (GN) measured at mid-pod filling stage at different soil fertility status and cropping systems in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

		SGS				NGS			
Fertility status	Cropping system	Ndfa (%)	Shoot dry matter (kg ha^{-1})	Shoot N (kg ha^{-1})	N_2-fixed (kg ha^{-1})	Ndfa (%)	Shoot dry matter (kg ha^{-1})	Shoot N (kg ha^{-1})	N_2-fixed (kg ha^{-1})
Fertile	Intercrop CP	23	1741	56	16	64	2147	47	43
	Sole CP	29	2449	75	31	64	2806	60	54
Poorly	Intercrop CP	55	743	23	18	83	878	15	17
fertile	Sole CP	56	640	21	17	87	1135	19	23
	[a]SED (system)	*n.s.*	*61***	*3**	*n.s.*	*n.s.*	*196**	*n.s.*	*n.s.*
	[b]SED (fertility)	*11**	*161****	*5****	*n.s.*	*4***	*191****	*3****	*4****
Fertile	Intercrop SB	77	3344	89	97	67	3563	96	92
	Sole SB	74	4909	136	145	57	5413	156	127
Poorly	Intercrop SB	63	2643	72	67	75	1272	30	33
fertile	Sole SB	62	5448	142	123	92	1833	45	57
	[a]SED (system)	*n.s.*	*469****	*12***	*14***	*n.s.*	*380**	*13**	*13**
	[b]SED (fertility)	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*4***	*559***	*15****	*15***
Fertile	Intercrop GN	58	776	23	19	81	579	17	19
	Sole GN	48	963	28	21	85	953	31	38
Poorly	Intercrop GN	73	518	14	15	94	570	16	22
fertile	Sole GN	54	957	28	21	92	839	25	33
	[a]SED (system)	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*110**	*3***	*4***
	[b]SED (fertility)	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*4**	*n.s.*	*n.s.*	*n.s*

[a] Combined SED for cropping system across soil fertility; [b] Combined SED for soil fertility; * Significant at $P<0.05$, ** Significant at $P<0.01$, *** Significant at $P<0.001$

Prob. F. for site comparisons (cowpea): %Ndfa ($P<0.001$), Shoot dry matter ($P=0.016$), Shoot N ($P=0.0014$), N_2-fixed ($P=0.021$)

Prob. F. for site comparisons (soybean): %Ndfa (n.s.), Shoot dry matter ($P=0.013$), Shoot N ($P=0.009$), N_2-fixed ($P=0.010$)

Prob. F. for site comparisons (groundnut): %Ndfa ($P<0.001$), Shoot dry matter (n.s.), Shoot N (n.s.), N_2-fixed ($P=0.010$)

Table 2.4. Grain, stover yields and harvest index (HI) of cowpea (CP), soybean (SB), groundnut (GN) and maize (MZ) under different soil fertility status and cropping systems at sites in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

		SGS					NGS				
Fertility status	Cropping system	Legume grain yield (kg ha^{-1})	Legume stover yield (kg ha^{-1})	Maize grain yield (kg ha^{-1})	Maize stover yield (kg ha^{-1})	HI (%)	Legume grain yield (kg ha^{-1})	Legume stover yield (kg ha^{-1})	Maize grain yield (kg ha^{-1})	Maize stover yield (kg ha^{-1})	HI (%)
Fertile	Intercrop CP	1080	1938			36	1570	2465			39
	Sole CP	1456	2519			37	1896	3035			38
	Intercrop MZ			2413	2971	45			1144	1517	43
	Sole MZ			3237	3764	46			1516	1953	44
Poorly fertile	Intercrop CP	596	1200			33	532	1345			28
	Sole CP	683	1646			29	578	1228			32
	Intercrop MZ			1824	2577	41			632	970	39
	Sole MZ			2380	3138	43			711	1253	36
	ᵃSED (system)	95*	124**	100***	171**		72*	87*	n.s.	n.s.	
	ᵇSED (fertility)	83***	114***	148**	118**		133***	241***	183**	184**	
Fertile	Intercrop SB	1329	1913			41	1666	1669			50
	Sole SB	2206	2994			42	2189	2210			50
	Intercrop MZ			2250	2833	44			1599	1945	45
	Sole MZ			3352	3981	46			2026	2434	45
Poorly fertile	Intercrop SB	849	1084			44	577	662			47
	Sole SB	1882	2796			40	767	922			45
	Intercrop MZ			2116	2685	44			746	1001	43
	Sole MZ			2551	2849	47			787	1266	38
	ᵃSED (system)	132***	192***	162**	222*		n.s.	56***	n.s.	160*	
	ᵇSED (fertility)	104**	n.s	n.s.	243*		150***	137***	68***	66***	

[a] Combined SED for cropping system across soil fertility; [b] Combined SED for soil fertility; * Significant at P<0.05, ** Significant at P<0.01, *** Significant at P<0.001
Prob. F. for site comparisons (MZ-CP): Cowpea grain yield (P=0.032), Cowpea stover yield (n.s.), Maize grain yield (P<0.001), Maize stover yield (P<0.001)
Prob. F. for site comparisons (MZ-SB): Soybean grain yield (P=0.013), Soybean stover yield (P<0.001), Maize grain yield (P<0.001), Maize stover yield (P<0.001)

Table 2.4 continued.

Fertility status	Cropping system	SGS Legume grain yield (kg ha^{-1})	SGS Legume stover yield (kg ha^{-1})	SGS Maize grain yield (kg ha^{-1})	SGS Maize stover yield (kg ha^{-1})	SGS HI (%)	NGS Legume grain yield (kg ha^{-1})	NGS Legume stover yield (kg ha^{-1})	NGS Maize grain yield (kg ha^{-1})	NGS Maize stover yield (kg ha^{-1})	NGS HI (%)
Fertile	Intercrop GN	198	698			22	266	602			31
	Sole GN	359	1371			21	310	664			32
	Intercrop MZ			2532	3220	44			1185	1542	43
	Sole MZ			3056	3572	46			1652	2020	45
Poorly fertile	Intercrop GN	175	686			20	242	496			33
	Sole GN	353	1153			23	237	649			27
	Intercrop MZ			2262	2879	44			696	1229	36
	Sole MZ			2428	3162	43			712	1418	33
	[a]*SED (system)*	67*	151*	n.s.	n.s.		n.s.	39*	79*	133*	
	[b]*SED (fertility)*	n.s.	n.s.	n.s.	n.s.		n.s.	n.s.	124**	176*	

[a] Combined SED for cropping system across soil fertility; [b] Combined SED for soil fertility; * Significant at $P<0.05$, ** Significant at $P<0.01$, *** Significant at $P<0.001$
Prob. F. for site comparisons (MZ-GN): Groundnut grain yield (n.s.), Groundnut stover yield ($P<0.001$), Maize grain yield ($P<0.001$), Maize stover yield ($P<0.001$)

2.3.5. N uptake and soil N balance

N uptake by sole maize was remarkably consistent for each field type in the different experimental combinations (Table 2.5). The combined N uptake by maize and legume in intercropping systems was larger ($P < 0.001$) than that by sole crops of maize and legumes (Table 2.5). An exception was sole soybean that had larger N uptake in the SGS but similar N uptake as the intercrop in the NGS. In general, total N uptakes (kg ha^{-1}) by sole crops of cowpea (mean of 67 in SGS, 73 in NGS) and soybean (mean of 155 in SGS, 107 in NGS) were significantly larger than that of sole maize (63 in SGS, 27 in NGS). N uptake of groundnut (34 in SGS, 22 in NGS) was smaller than that of sole maize due to the poor yields of groundnut. Soybean grain N uptake was larger ($P < 0.001$) than that of cowpea, maize and groundnut, while stover N uptake was significantly larger in cowpea than in the other crops. Cowpea, soybean and maize in fertile fields had a significantly increased N uptake, with a mean of 32, 30 and 11 kg ha^{-1} more total N uptake, respectively in the SGS and 60, 89 and 15 kg ha^{-1}, respectively in the NGS.

Sole maize had a significantly better soil N balance than intercrops and sole legumes at both sites (Fig. 2.2). Thus, there was no evidence of an N sparing effect from intercropping or sole cropping of legumes. Soil N balance was comparable between intercrops and sole crops. Only the sole crop of groundnut had a significantly larger soil N balance than the intercrops in the NGS when both grain and stover were exported. Intercrops in the SGS had a mean soil N balance of –2 kg N ha^{-1}, while sole legumes contributed 2 kg N ha^{-1} when only grain was exported (Fig. 2.2a and b). In the NGS however, the soil N balance of intercrop systems (+ 12 kg ha^{-1}) was slightly larger than that of sole legumes (+ 9 kg ha^{-1}) (Fig. 2.2c and d). Intercrops and sole legumes consistently provided negative N returns to the soil when both grain and stover were exported, except for groundnut in the NGS. A negative soil N balance of sole maize, with removal of both grain and stover, was observed only in the SGS which had significantly greater maize grain and stover yields with corresponding greater N uptakes (Tables 3.4 and 3.5). Legume residues had a relatively lower C:N ratio (cowpea: 23:1, groundnut: 29:1, soybean: 38:1) compared with the maize (63:1 in SGS, 73:1 in NGS) which will aid N mineralisation. Residues of cowpea and groundnut are likely to be mineralised faster and release N than that of soybean due to the relatively lower C:N ratio than soybean. Crops in fertile fields had consistently significantly smaller soil N balance (Fig. 3.2). Legume species performed differently across sites in their contribution of net N to the soil. In the SGS, soybean contributed on average +9 kg ha^{-1} net N to the soil, +2 kg N ha^{-1} by groundnut and -11 kg N ha^{-1} by cowpea when only grain was exported. Groundnut gave a +22 kg ha^{-1} net N, +8 kg ha^{-1} by cowpea and +2 kg ha^{-1} by soybean in the NGS. However, when both grain and stover were exported, only the site in the NGS recorded a +10 kg ha^{-1} net N contributed to the soil N pool by groundnut.

Table 2.5. Estimated grain and stover N uptakes and N harvest index (NHI) of cowpea (CP), soybean (SB), groundnut (GN) and maize (MZ) under different soil fertility status and cropping systems at sites in southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana. N uptakes of intercrops represents the combined uptake by the legume and maize intercrop components while the intercrop NHI is for the legume component only.

		SGS				NGS			
Fertility Status	Cropping system	Grain N (kg ha^{-1})	Stover N (kg ha^{-1})	Total N (kg ha^{-1})	NHI (%)	Grain N (kg ha^{-1})	Stover N (kg ha^{-1})	Total N (kg ha^{-1})	NHI (%)
Fertile	Intercrop CP+MZ	66	53	119	48	62	51	113	52
	Sole CP	42	44	86	49	55	53	108	51
	Sole MZ	47	24	71	66	21	11	32	66
Poorly fertile	Intercrop CP+MZ	44	37	81	45	24	28	52	38
	Sole CP	20	28	48	42	17	21	38	45
	Sole MZ	35	20	55	64	10	7	17	59
	[a]SED (system)	3***	2***	5***		3***	2***	4***	
	[b]SED (fertility)	2***	1***	3***		4***	3***	7***	
Fertile	Intercrop SB+MZ	114	38	152	80	125	29	154	86
	Sole SB	135	31	166	81	134	23	157	85
	Sole MZ	49	25	74	66	29	13	42	69
Poorly fertile	Intercrop SB+MZ	83	28	111	83	46	13	59	83
	Sole SB	115	29	144	80	47	10	57	82
	Sole MZ	37	18	55	67	11	7	18	61
	[a]SED (system)	7***	2***	9***		9***	1***	10***	
	[b]SED (fertility)	5**	2*	7**		6***	1***	6***	
Fertile	Intercrop GN+MZ	46	30	76	47	29	16	45	60
	Sole GN	16	19	35	46	14	9	23	61
	Sole MZ	45	23	68	66	23	11	34	68
Poorly fertile	Intercrop GN+MZ	41	28	69	47	21	14	35	61
	Sole GN	16	16	32	50	11	9	20	55
	Sole MZ	35	20	55	64	10	8	18	56
	[a] SED (system)	3***	2**	5***		2***	1***	3***	
	[b] SED (fertility)	n.s.	n.s.	n.s.		1***	0.4**	1***	

[a] Combined SED for cropping system across soil fertility. [b] Combined SED for soil fertility.
* Significant at P<0.05, ** Significant at P<0.01, *** Significant at P<0.001
Prob. F. for site comparisons (MZ-CP): Grain N (P<0.001), Stover N (P=0.008), Total N (P<0.001)
Prob. F. for site comparisons (MZ-SB): Grain N (P<0.001), Stover N (P<0.001), Total N (P<0.001)
Prob. F. for site comparisons (MZ-GN): Grain N (P<0.001), Stover N (P<0.001), Total N (P<0.001)

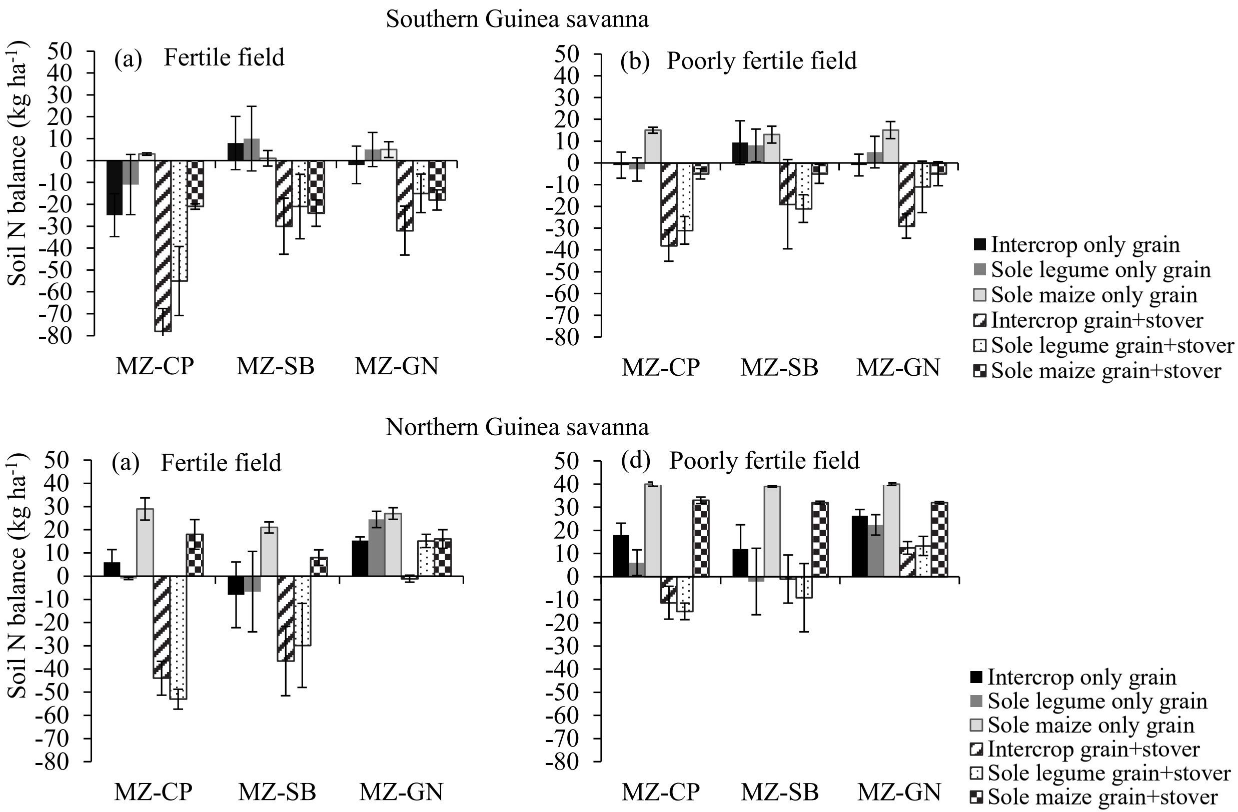

Fig. 2.2. Soil N balance as influenced by different cropping systems in (a) a fertile field in SGS, (b) a poorly fertile field in SGS, (c) a fertile field in NGS and (d) a poorly fertile field in NGS of northern Ghana with grain only or both grain and stover exported. The soil N balance of intercrops combines both maize and legumes. The error bars represent the standard errors of means.

2.4. Discussion

2.4.1. Soil fertility, δ^{15}N of weed reference species and ^{15}N natural abundance method

The δ^{15}N signatures of the reference weeds varied among species, soil fertility status and site (Table 2.2). The reference plant is used to represent the δ^{15}N of the soil N available to the legume test crops (Unkovich et al., 2008) – i.e. if the δ^{15}N of the available soil N is uniform with depth and time, all reference plants should give the same value. Therefore, the different δ^{15}N signatures of the weed species may reflect different isotopic discrimination among the species or extraction from different rooting depths. The variation could also be due to changes in the δ^{15}N of the plant-available soil N pool in the course of the growing season and the relative differences in N uptake by the different reference weed species resulting from temporal differences in the volumes of soil explored by their roots (Cadisch et al., 2000; Chalk et al., 2016). By contrast, the differences in δ^{15}N signatures between fertility status and sites presumably relate to different histories of fertiliser and crop residues use (the latter resulting in differences in turnover of N) or different isotopic discrimination during soil formation. Differences in N losses between fertility and sites, particularly through leaching due to the differences in clay content between fertile and poorly fertile fields, and sand content between both sites (Table 2.1) could contribute to the observed heterogeneity in δ^{15}N enrichment of the reference weeds between fertility and sites. It is notable that the fertile soils at both sites and the soils in the SGS site which had greater soil organic carbon and nitrogen contents (Table 2.1) had consistently higher δ^{15}N signatures.

The variability in δ^{15}N signatures of the reference weeds (and of the different legumes, particularly in the SGS) observed within a field (Table 2.2) could be associated with spatial heterogeneity resulting from non-uniform application of mineral N fertilisers by farmers and uneven deposition of manure and urine by livestock which graze freely in the fields (Peoples et al., 2002; Unkovich et al., 2008). The variation could also be the outcome of differences in soil water content (Unkovich et al., 2008) and associated differences in N losses (particularly leaching and denitrification) across a field due to the mostly undulating topography of the fields created by ploughing by farmers without harrowing to level the fields.

The values observed in this study are within the range of 2.1–5.2‰ reported for reference weed species sampled from 63 farms in the Guinea savanna of northern Ghana (Naab et al., 2009). The variability in δ^{15}N enrichment of the same reference species within a field suggests a within field variability in plant available soil N status, possibly due to non-uniform application of N fertilisers (Peoples et al., 2002). The variability and lack of consistency in δ^{15}N enrichment within reference species is problematic for the accurate estimation of %Ndfa in farmers' fields with the natural abundance method. However, using the mean δ^{15}N enrichment of several reference weed species in each location is likely to give a more reliable estimate of the δ^{15}N enrichment by the legumes and hence of N_2-fixation (cf. Belane and Dakora, 2010).

2.4.2. Cropping system, soil fertility and shoot dry matter yield and N_2-fixation

Legume shoot δ^{15}N enrichment and %Ndfa were generally comparable between legumes in intercrops and in sole crops, as also observed by Ofori et al. (1987) and van Kessel and Roskoski (1988) for cowpea. Shoot δ^{15}N values observed in this study are close to the range of –1.5 to + 1.5 in 30 field-grown cowpea genotypes measured using ^{15}N natural abundance in the Guinea savanna of northern Ghana (Table 2.3; Belane and Dakora, 2010). The variability in legume shoot δ^{15}N enrichment and %Ndfa values reflects the influence of environmental conditions (e.g. soil fertility and soil type) (Table 2.1) and suggests that poor soil fertility leads to a smaller shoot δ^{15}N and a greater %Ndfa (Giller, 2001).

Sole legumes consistently fixed more N_2 than intercropped legumes (Table 2.3). This was a result of the larger shoot dry matter yields and the corresponding greater shoot N accumulated by sole crops (Table 2.3), as the amount of N_2-fixed greatly depends on shoot dry matter yield (Giller, 2001) and the accumulated shoot N (Peoples et al., 2009). Also, Konlan et al. (2015) reported a greater N_2-fixation in sole groundnut than in groundnut intercropped with maize in the Guinea savanna of northern Ghana. Yet when the shoot dry matter yields were poor, such as in the SGS where cowpea yields were relatively smaller and groundnut which had poorer yields at both sites, the amount of N_2-fixed was similar between sole crops and intercrops. Good soil fertility enhanced the production of shoot dry matter (Table 2.3), which also led to more N_2 fixed. Our results corroborate other studies in the Guinea savanna (e.g. Yusuf et al., 2014), Western Kenya (e.g. Ojiem et al., 2007) and elsewhere (e.g. Giller and Cadisch, 1995) reporting that although low soil fertility enhances the %Ndfa, legumes on more fertile fields fix larger amounts of N_2. The late sowing of groundnut due to the late onset of rainfall resulted in a poor shoot dry matter yield, low accumulated shoot N and a relatively small amount of N_2 fixed, in comparison with results from other studies (cf. Dakora et al., 1987; Yusuf et al., 2014). This indicates that early sowing of groundnut is essential in this environment for good yield and N_2 fixation. The N_2-fixed by sole cowpea was in line with that observed in farmers' field in the Guinea savanna of northern Ghana (Naab et al., 2009) and Nigeria (e.g. Sanginga et al., 2000; Yusuf et al., 2008). For soybean, comparable amounts of fixed N_2 were reported by Sanginga et al. (1997) and Ogoke et al. (2003).

2.4.3. Crop yields, N uptake and net N contribution to soil fertility improvement

The more favourable soil fertility characteristics and rainfall in the SGS favoured a greater production of grain and stover of maize, soybean and groundnut but cowpea gave larger grain yields in the NGS with poor rainfall and soil fertility (Tables 2.1 and 2.4). Intercropping resulted in greater combined grain N removal (Table 2.5) as also observed by Hauggard-Nielsen et al. (2008). The soil N balance calculations suggest that sole maize (with a modest rate of applied N) has a positive N balance relative to the systems with legumes (Fig. 2.2). At first glance this is difficult to explain: legumes fix N_2 from the atmosphere and are expected to contribute more N to the cropping systems than cereals. Yet a number of factors come into play that need consideration. The N balance as calculated is a partial balance representing the difference only between the N removed in products of grain (and stover where included) and the N added through fertiliser or N_2-fixation. As such other inputs such as aerial deposition and losses of N through leaching, volatilization of ammonia or denitrification are not accounted for.

The N fertiliser was applied to the maize crop in equal split doses at three and six weeks after sowing when the maize was growing actively to ensure efficient uptake. Nevertheless, N recovery efficiencies from fertiliser rarely reach 50% (Ladha et al., 2005; Chikowo et al., 2009). We cannot rule out the possibility that perhaps, the N applied as urea was lost through leaching due to the sandy nature of the soils, particularly in the NGS (Table 2.1). Poss and Saragoni (1992) found that more than 30% of the urea applied to maize grown in Togo was lost through leaching and that accounted for more than 29% of the N outputs. Full N balance calculations for Ghana by Stoorvogel and Smaling (1990) indicated that about 30% of the N outputs were losses through leaching and gases. Elsewhere, Karlen et al. (1996) suggested that 46% of N applied in split doses to maize was lost through leaching, volatilisation or denitrification. Though the urea was applied in furrows at 3 cm depth below the soil surface and covered after application we cannot also rule out possible losses through ammonia volatilisation. Cai et al. (2002) estimated up to 12% loss of urea-N applied to maize through ammonia volatilisation with a similar placement method. Thus, there is an uncertainty around the fate of the actual amount of N left in the soil to benefit a succeeding crop through partial N balance calculations. This suggests that partial N balances are an unreliable indicator of the sustainability of crop production systems (Janssen, 1999; Roy et al., 2003), as suggested by Bassanino et al. (2011) in determining sustainability of agro-environments in Italy.

It is worth noting that soil N mining with the removal of stover was more severe for systems with legumes due to greater N uptake than maize (Fig. 2.2). This is more pronounced for cowpea than soybean and groundnut due to greater stover yield (Table 2.5) as the variety used produced a large biomass with little shedding of leaves at maturity. Soybean sheds most of its leaves at maturity and groundnut gave poor residue yield. To offset soil N mining, the stover has to be retained in the fields but this is rarely done with groundnut where whole plants are harvested and shelled at home. Other issues associated with retaining of residues in the fields are discussed below.

Intercropping is known to reduce soil borne diseases (Hiddink et al., 2010). By contrast, continuous cropping of sole maize due to the more positive partial soil N balance can lead to diseases and pests build-up which can be averted or suppressed by rotating it with grain legumes (Stevenson and van Kessel, 1996). The large C:N ratio of sole maize residues (63:1 in SGS, 73:1 in NGS) can lead to N immobilization, decreasing the N available to a succeeding cereal crop. Interactions between mixed legume-maize (low-high C:N ratio) residues resulting from intercropping may increase the rate of mineralisation of maize residues, improving the amount of mineralised N relative to sole maize to benefit subsequent crop, while improving soil microbial biomass and activity (Frimpong et al., 2011; Partey et al., 2014). The relatively smaller C:N ratio of sole legume residues (cowpea: 23:1, groundnut: 29:1, soybean: 38:1) can result in a relatively rapid N mineralization releasing N for the subsequent cereal crop (Palm et al. 2001).

The generally higher N concentration of legume residues than that of maize (Palm et al., 2001) suggests that the systems with legumes may produce better quality residues as feed for livestock and a possible better manure quality. These non-N benefits of the systems with legumes could make them more appealing to farmers than continuous sole cropping of maize, despite the more positive partial soil N balance. Nevertheless, the rapid mineralisation of sole legume residues, particularly cowpea and groundnut might increase the risk of N leaching losses compared with that of sole maize or mixed legume-maize residues from intercropping. On-field grazing by free-roaming animals during the off-season could lead to removal of large amounts of the residues retained in the fields, reducing potential benefits of retaining residues. It may be worthwhile to export the residues to feed livestock and the manure applied to the fields in the subsequent season to directly benefit the succeeding crop (Franke et al., 2008b). This seems an attractive option to reduce those losses by conserving the residues and associated benefits (Franke et al., 2008b). Efficient handling, storage and transport of manure would be essential in this case to avoid possible nutrient losses and reduced benefits (Rufino et al., 2006).

The legumes gave a different net N benefits in both agro-ecological zones, which reflected the relative %Ndfa or dependence on soil N for growth and the harvest index (HI) of the different legumes at each agro-ecological zone (Table 2.4). With exception of soybean, each legume species contributed a positive net N to the soil in each cropping system where the N harvest index (NHI) was smaller than the corresponding %Ndfa (Fig. 2.2; Table 2.4; data for grain N of intercropped legume only not shown). For instance, the positive net N returns to the soil by groundnut in both the SGS and NGS were due to its high %Ndfa (Table 2.3) and relatively low HI (compared with cowpea and soybean) which led to smaller grain N removal and NHI being smaller than the %Ndfa (Tables 2.3 and 2.5). However, groundnut gave less benefits for food and fodder than soybean and cowpea (Table 2.4) due to the late sowing. Therefore, in seasons with delayed onset of rainfall, it may be useful to grow relatively early maturing groundnut varieties (e.g. Edorkpo-Munikpa, 90 maturity days) in the Guinea savanna environment**.**

In the SGS, soybean had a higher HI than cowpea and groundnut (Table 2.4). Soybean also had higher %Ndfa compared with cowpea and groundnut in the SGS and soybean grown in the NGS (Table 2.3). However, %Ndfa of soybean was smaller than its NHI and will require 6% (intercrop) and 18% (sole crop) more Ndfa to return a net positive N to the soil. Nevertheless, with a relatively higher %Ndfa of soybean in the SGS than the NGS, combined with a high biomass production resulting in the total amount of N_2-fixed being greater than its NHI, it contributed N to the soil in the SGS. This indicates that a positive net N input into the soil can be expected when the total amount of N_2-fixed (kg ha^{-1}) by a grain legume is greater than its NHI even if the %Ndfa is smaller than the NHI. Cowpea relied more on soil N for growth in the SGS, had a higher HI compared with groundnut with corresponding larger grain N exported (NHI > %Ndfa and total N_2-fixed), hence a net deficit N returns to the soil (Fig. 2.2). Though cowpea HI and grain N removal were comparable between both sites, a relatively larger reliance on atmospheric N_2-fixation for growth by cowpea grown in the NGS than the SGS and its NHI being smaller than the %Ndfa (Tables 2.3, 2.4 and 2.5) led to a positive net N returns to the soil in the NGS (Fig. 2.2). The different performance of cowpea and soybean (N_2-fixation, grain and stover yields) across the contrasting environments in the Guinea savanna confirms the need to target the legume species to specific environments within the Guinea savanna.

The differences in rainfall and soil fertility characteristics between the two trial sites are in line with the differences in rainfall pattern (SRID, 2016) and soil fertility features (Jayne et al., 2015) between the SGS and the NGS. This suggests that the selected sites and the results are fairly representative of each agro-ecological zone in the Guinea savanna of northern Ghana. Nevertheless, trials in multiple sites within each agro-ecological zone are needed to validate the differential performance and benefits of cowpea and soybean in the contrasting environments. The net N contributed by sole legumes in this study fall within ranges reported by previous studies in the West African Guinea savanna where only grain is exported (cf. Sanginga et al., 2000 for cowpea; Ogoke et al., 2003 for soybean; Yusuf et al., 2014 for groundnut).

The amount of N_2-fixed was larger in fertile fields (Table 2.3), but greater yields and a larger amount of N exported in grain (Tables 2.4 and 2.5) led to a smaller soil N balance compared with poorly fertile fields (Fig. 2.2). This indicates a trade-off between grain production for food and soil fertility improvement by grain legumes as demonstrated by Ojiem et al. (2007), which also depend on the legume variety (e.g. dual-purpose or grain variety). Such competing objectives need to be considered in choosing fields and legume varieties for production in the Guinea savanna. The results show a better potential for net N benefit by growing grain legumes in poorly fertile fields (Fig. 2.2). Yet, greater input of residues by legumes grown in fertile fields (Table 2.4) may enhance soil fertility by improving soil structure, microbial biomass and quantity of mineralized N to benefit subsequent cereal crops than in poorly fertile fields. The potential benefits of growing legumes may thus be limited in poorly fertile fields as also observed by Ojiem et al. (2007).

2.5. Conclusions

Intercropping or sole cropping of grain legumes have little effect on the %Ndfa but the higher density and larger area cultivated to sole legumes lead to greater shoot dry matter and amount of N_2-fixed in sole crops. Even though %Ndfa is enhanced by growing legumes in poorly fertile fields, the overall benefits of growing grain legumes in those fields are limited as compared with the fertile fields. The results suggest that soybean can be targeted in the SGS and cowpea in the NGS for both household food and soil fertility maintenance. Groundnut is suited to both environments but growing of early maturing varieties may be essential for improved yields and soil fertility enhancement when the start of the rainy season delays. The uncertainty that surrounds calculated partial N balances of cropping systems raises issues about the extent of their usefulness and shows that partial N balances are unrealistic indicators of the sustainability of cropping systems.

Acknowledgements

Funding support provided by the Bill and Melinda Gates Foundation through the N2Africa project through a grant to Wageningen University is gratefully acknowledged. Michael Kermah gratefully acknowledges financial support from the Netherlands Organization for International Co-operation in Higher Education (NUFFIC) through the Netherlands Fellowship Programme (NFP), and thanks the CSIR-Savanna Agriculture Research Institute, Tamale for the use of its facilities to conduct this work.

Chapter 3

Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana

This chapter is published as:

Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. Field Crops Research 213, 38–50.

Abstract

Smallholder farmers in the Guinea savanna practise cereal-legume intercropping to mitigate risks of crop failure in mono-cropping. The productivity of cereal-legume intercrops could be influenced by the spatial arrangement of the intercrops and the soil fertility status. Knowledge on the effect of soil fertility status on intercrop productivity is generally lacking in the Guinea savanna despite the wide variability in soil fertility status in farmers' fields, and the productivity of within-row spatial arrangement of intercrops relative to the distinct-row systems under on-farm conditions has not been studied in the region. We studied effects of maize-legume spatial intercropping patterns and soil fertility status on resource use efficiency, crop productivity and economic profitability under on-farm conditions in the Guinea savanna. Treatments consisted of maize-legume intercropped within-row, 1 row of maize alternated with one row of legume, 2 rows of maize alternated with 2 rows of legume, a sole maize crop and a sole legume crop. These were assessed in the southern Guinea savanna (SGS) and the northern Guinea savanna (NGS) of northern Ghana for two seasons using three fields differing in soil fertility in each agro-ecological zone. Each treatment received 25 kg P and 30 kg K ha^{-1} at sowing, while maize received 25 kg (intercrop) or 50 kg (sole) N ha^{-1} at 3 and 6 weeks after sowing. The experiment was conducted in a randomised complete block design with each block of treatments replicated four times per fertility level at each site. Better soil conditions and rainfall in the SGS resulted in 48, 38 and 9% more maize, soybean and groundnut grain yield, respectively produced than in the NGS, while 11% more cowpea grain yield was produced in the NGS. Sole crops of maize and legumes produced significantly more grain yield per unit area than the respective intercrops of maize and legumes. Land equivalent ratios (LERs) of all intercrop patterns were greater than unity indicating more efficient and productive use of environmental resources by intercrops. Sole legumes intercepted more radiation than sole maize, while the interception by intercrops was in between that of sole legumes and sole maize. The intercrop however converted the intercepted radiation more efficiently into grain yield than the sole crops. Economic returns were greater for intercrops than for either sole crop. The within-row intercrop pattern was the most productive and lucrative system. Larger grain yields in the SGS and in fertile fields led to greater economic returns. However, intercropping systems in poorly fertile fields and in the NGS recorded greater LERs (1.16 to 1.81) compared with fertile fields (1.07 to 1.54) and with the SGS. This suggests that intercropping is more beneficial in less fertile fields and in more marginal environments such as the NGS. Cowpea and groundnut performed better than soybean when intercropped with maize, though the larger absolute grain yields of soybean resulted in larger net benefits.

Key words: Soil fertility, Spatial arrangement, Radiation interception, LER, Net benefit.

3.1. Introduction

The Guinea savanna of West Africa is characterised by poor and declining soil fertility due to continuous cereal-based cropping systems without adequate soil nutrient replenishment (Dakora et al., 1987; Sanginga et al., 2003). The declining soil fertility coupled with an erratic unimodal rainfall regime has increased the risk of crop failure in sole cropping systems. Intercropping, the simultaneous or sequential growing of two or more crop species on the same piece of land (Willey, 1990), could mitigate risk of crop failure. For instance, in case the main crop (typically maize, *Zea mays* L.) fails to produce yield due to erratic distribution of rainfall within a season, the added grain legume provides food for the farm household (Rusinamhodzi et al., 2012). Consequently, farmers in the Guinea savanna commonly practise cereal-legume intercropping to safeguard household food and income. The inclusion of grain legumes is essential for soil fertility sustenance as they contribute to soil fertility enhancement through biological fixation of atmospheric nitrogen (N_2) and N mineralised from legume residues (Giller, 2001). Legumes also provide grain rich in protein and minerals for household nutrition and income (Giller, 2001).

The greater crop yields and productivity of intercrops relative to sole crops result from complementary use of resources for growth by the intercrop components (Willey, 1979; Ofori and Stern, 1987; Rao and Singh, 1990; Willey, 1990). Differences in acquisition and use of light, water and nutrients by the different intercrop components (Ofori and Stern, 1987; Willey, 1990) results in inter-species competition being smaller than intra-species competition (Vandermeer, 1989). The complementary effect can be temporal where peak demands for resources by component crops occur at different times or spatial where complementary resource use occurs due to differences in canopy and root structures (Willey, 1990). Complementarity is also likely as intercropped maize uses N from the soil for growth whilst the legume can rely more on atmospheric N_2-fixation for growth. These can be influenced by soil fertility status, spatial planting arrangements and choice of intercrop components (Midmore, 1993). Weeds and diseases may be better suppressed in intercropping than in sole cropping although this may be influenced by the intercropping pattern and the resulting canopy structure (Liebman and Dyck, 1993; Trenbath, 1993).

Spatial intercropping patterns have been studied in the Guinea savanna of northern Ghana (e.g. Agyare et al., 2006; Konlan et al., 2013) and Nigeria (e.g. Ajeigbe et al., 2010) mainly under controlled conditions. All these studies assessed the performance of different distinct alternate row intercropping patterns of maize and legumes. Rusinamhodzi et al. (2012) reported greater LER when the intercrops were planted in the same row rather than in distinct rows in Central Mozambique. Other studies (Agyare et al., 2006; Konlan et al., 2013) generally showed intercrop advantages over sole crops that declined as the width of adjacent strips of each crop was increased. For instance, Konlan et al. (2013) reported a larger LER for 1 to 1 alternate rows of maize and groundnut than for 2 to 2 alternate row intercrops. In some cases, sole crops were more productive than intercrops when two or more rows of intercropped maize were alternated with the same number of groundnut (*Arachis hypogaea* L.) rows (Konlan et al., 2013).

Knowledge on the ecological and economic performance of within-row maize-legume intercrop pattern in relation to the distinct row intercrop patterns and sole crops is limited to controlled trials in the Guinea savanna region. Studies conducted in Turrialba, Costa Rica (Chang and Shibles, 1985) and Western Australia (Ofori and Stern, 1986) reported greater maize-cowpea (*Vigna unguiculata* (L.) Walp) intercrop advantages under low soil N and P conditions. Searle et al. (1981) and Ahmed and Rao (1982) also observed larger maize-soybean (*Glycine max* (L.) Merr.) intercrop advantages when soil N fertility was poor. As smallholder farms in the Guinea savanna vary widely in soil fertility status, a better understanding of the relative performance of intercrop in relation to soil fertility is required. We studied the effects of soil fertility status and different spatial maize-legume intercropping patterns and monocultures on grain yields, intercrop efficiency and productivity and economic profitability in contrasting sites in the southern and northern Guinea savanna agro-ecological zones of northern Ghana.

3.2. Materials and methods

3.2.1. Study sites and on-farm experiments

The trials were conducted on farmers' fields in the cropping seasons of 2013 and 2014. The sites were Kpataribogu (9°58' N, 0°40' W) in Karaga District (southern Guinea savanna, SGS; 1076 mm mean annual rainfall) and Bundunia (10°51' N, 1°04' W) in Kassena-Nankana East Municipal (northern Guinea savanna, NGS; 990 mm mean annual rainfall) in northern Ghana. Both sites have a single rainy season which extends from May to October in SGS and from June to October in NGS. The soils at both sites are predominantly sandy soils classified as Savanna Ochrosol and Groundwater Laterites in the Interim Ghana Soil Classification System (Adjei-Gyapong and Asiamah, 2000) and as Plinthosols in the World Reference Base for soil resources (WRB, 2015).

At each site, three field types representing a highly fertile field (HF), a medium fertile field (MF) and a field low in fertility (LF) were selected and used for both seasons. Fields were selected using farmers' knowledge with the assistance of Agricultural Extension Officers, followed by soil physico-chemical analysis. The selected fields were under mono-cropping in the three preceding seasons, *i.e.* in the SGS site HF: soybean-groundnut-maize, MF: maize-soybean-maize, LF: groundnut-soybean-cotton; in the NGS site HF: maize-maize-maize, MF: maize-groundnut-fallow, LF: maize-maize-groundnut. Previously mono-cropped fields were selected to reduce within-field variability. Soils were sampled at 0-15 cm depth at each trial field prior to land preparation in 2013. All soil cores were thoroughly mixed and about 1 kg sub-samples per field were air-dried and passed through a 2 mm-mesh sieve. These were analysed for pH (1:2.5 soil:water suspension), organic C (Walkley and Black), total N (Kjeldahl), available P (Olsen), exchangeable K, Mg, and Ca (in 1 M ammonium acetate extracts) and texture (hydrometer method). Some of these soil physico-chemical analysis data presented in Table 3.2 are reported in Kermah et al. (submitted).

Table 3.1a. Unit input and labour costs and grain prices used in estimating total variable cost (TC) and total revenue (TR) in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana

	SGS		NGS	
	2013	2014	2013	2014
Input costs (US$ ha^{-1})				
Maize seeds	9.0	6.6	7.6	7.6
Soybean seeds	40.0	27.0	39.5	28.6
Groundnut seeds	56.2	37.7	59.6	47.4
Cowpea seeds	37.5	20.1	30.4	25.2
Urea	54.3	50.4	54.3	50.4
TSP	99.5	66.0	99.5	66.0
MoP	51.1	33.9	51.1	33.9
Insecticide	6.5	4.0	6.5	4.0
Inoculant	15.0	15.0	15.0	15.0
Labour input (US$ ha^{-1})				
Ploughing	43.2	32.7	74.0	57.3
Ridging	74.0	49.1	61.7	49.1
Sowing	6.8	4.9	8.6	4.9
Fertiliser application	6.2	4.9	6.2	4.9
Spraying	6.2	4.9	8.6	4.9
Weeding	8.6	6.6	8.6	6.6
Harvesting	8.6	6.6	8.6	6.6
Threshing	4.9	4.1	4.9	4.1
Grain prices (US$ kg^{-1})				
Maize	0.51	0.38	0.37	0.36
Soybean	0.88	0.76	0.95	0.67
Groundnut (shelled)	1.86	1.43	2.52	1.79
Cowpea	1.12	0.76	1.17	0.95

Exchange rate for costs: GH¢2.00=US$1.00 in 2013; GH¢3.02=US$1.00 in 2014 (average rate for each year, i.e. inputs acquisition to harvest). Exchange rate for grain prices: GH¢2.08=US$1.00 in 2013; GH¢3.20=US$1.00 in 2014 (average rate for 3rd and 4th quarters of each year, i.e. harvest and selling period). Exchange rates were obtained from Bank of Ghana quarterly bulletin.

Table 3.1b. Estimated labour requirements (days ha^{-1}) of field operations of maize and legumes under sole crop systems used in estimating TC.

Activity	Cowpea	Soybean	Groundnut	Maize	Source
Sowing	12	17	11	10	Franke et al. (2010)
P&K application	2	4	2	2	Ojiem et al. (2014)
N application	-	-	-	7	Franke et al. (2006)
Spraying	2	-	-	-	Own observation
First weeding	36	36	36	25	Franke et al. (2006)
Second weeding	30	30	30	21	83% of first weeding[a]
Harvesting	14	14	34	12	Franke et al. (2010)
Threshing	17[b]	29	46[c]	23	Franke et al. (2006)

[a] Heemst et al. (1981); [b, c] Ojiem et al. (2014); [b] Includes the shelling of groundnut

Table 3.2. Physical and chemical properties of the three types of fields differing in soil fertility in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) agro-ecologies of northern Ghana. The SED represents the standard error of difference between means.

Soil fertility parameter	SGS				NGS			
	HF	MF	LF	SED[a]	HF	MF	LF	SED[a]
pH	6.2	5.4	5.8	0.3	5.4	4.3	4.7	0.5
Organic C (g kg^{-1})	10.9	9.0	7.4	1.4	6.2	3.1	3.9	1.3
Total N (g kg^{-1})	0.9	0.8	0.8	0.05	0.6	0.3	0.2	0.2
Olsen P (mg kg^{-1})	2.6	2.6	1.7	0.4	2.8	2.6	1.9	0.4
K ($cmol_+$ kg^{-1})	0.3	0.2	0.2	0.05	0.2	0.1	0.1	0.05
Ca ($cmol_+$ kg^{-1})	1.7	1.6	1.3	0.2	1.6	0.5	0.8	0.5
Mg ($cmol_+$ kg^{-1})	0.7	0.6	0.7	0.05	0.9	0.1	0.7	0.3
ECEC ($cmol_+$ kg^{-1})	10.2	6.6	5.2	2.1	6.9	1.8	3	2.2
Sand (g kg^{-1})	563	738	538	89	738	883	798	59
Silt (g kg^{-1})	321	180	400	91	160	101	160	28
Clay (g kg^{-1})	116	81	61	23	101	16	41	36

[a] SED represents the standard error of differences between means and was calculated following the procedure described by Saville (2003).

3.2.2. Experimental design, treatments and crop management

Three grain legumes, cowpea (CP), soybean (SB) and groundnut (GN) were intercropped with maize (MZ) in different spatial arrangements: (i) maize-legume intercropped within-row, (ii) one row of maize alternated with one row of legume, (iii) two rows of maize alternated with two rows of legume, (iv) a sole crop of maize and (v) a sole crop of legume. For the within-row treatments, a maize planting hill alternated two equally spaced cowpea or groundnut hills, or four soybean hills within the same row. An inter-row spacing of 75 cm was maintained for all treatments and crops. Intra-row spacing was 50 cm for intercropped maize within-row, 25 cm for sole maize and all distinct rows intercropped maize and for sole cowpea and sole groundnut. Soybean had an intra-row spacing of 12.5 cm in both the distinct row intercrops and the sole crop. Maize (intercropped and sole) and all legumes within-row treatments were sown at one seed per hill, while all distinct row and sole legume treatments were sown at two seeds per hill. The resultant plant sowing densities (plants ha^{-1}), respectively for intercrops and sole crops were: maize (26,667 and 53,333), cowpea and groundnut (53,333 and 106,666) and soybean (106,666 and 213,332). The experiment was conducted in a randomised complete block design with blocks of treatments replicated four times per fertility level at each site. Treatments were randomised within blocks and a plot measured 4.5 m × 4.0 m.

The land was ploughed with a tractor and ridged manually in the SGS and with a tractor in the NGS, reflecting the common practices at both sites. Sowing was done on the top of the ridges using locally preferred crop varieties: cowpea–Padi-tuya (SARC 3–122-2); soybean–Jenguma (Tgx 1448-2E); groundnut–Chinese and maize–Obatanpa (GH83–63SR). Groundnut variety, Samnut 22 was used in 2013 in the SGS. In 2013, all crops were sown simultaneously (July 1–2 in the SGS; July 16–17 in the NGS) due to the late onset of rains. Sowing in 2014 followed the recommended sowing times: maize-groundnut on June 13, maize-soybean on July 4 and maize-cowpea on July 17 in the SGS. All crops in the NGS were sown on July 15 due to the late onset of rains in 2014. Cowpea was sprayed twice at flowering and podding stages with lambda-cyhalothrin (in the SGS) and cypadem 43.6 EC (36 g cypamethrin and 400 g dimethoate per litre) (in the NGS) in the form of an emulsifiable concentrate at a rate of 0.75–1.00 litre ha^{-1} for sole cowpea and 50% of that dosage for intercropped cowpea for each insecticide depending on the presence and population of pests (flower thrips: e.g. *Megalurothrips sjostedti* Tryb. and pod borers: e.g. *Maruca vitrata* Fab.). Soybean seeds were inoculated with Legumefix (LegumeTechnology, UK) *Bradyrhizobium japonicum* strain 532c (re-isolated in Brazil from strain USDA 442 Wisconsin, USA) at a rate of 5 g inoculant per kg seed. All treatments received uniform applications of 25 kg P ha^{-1} as TSP and 30 kg K ha^{-1} as muriate of potash at sowing. Nitrogen in the form of urea was spot-applied to maize at 25 kg N ha^{-1} for intercrops and 50 kg N ha^{-1} for sole crops in two equal split doses at three and six weeks after sowing (WAS). All fertilisers were placed 5 cm from the plants at 3 cm depth. All fields were weeded twice with a hoe at 3 and 6 WAS.

3.2.3. Field measurements

Daily rainfall during the season was measured with rain gauges installed at each site. Photosynthetically active radiation (PAR) interception was measured with AccuPAR LP-80 Ceptometer (Decagon Devices Inc., Pullman, Washington). Measurements were made above and below the crop canopies in each plot at four randomly selected locations. Five successive PAR readings each above and below the canopy were taken and averaged per location with the Ceptometer placed across the crop rows. PAR measurements were made generally under clear skies between 10.00 and 14.00 hours, at 10-15 days' intervals (depending on weather conditions). In the within-row intercrop plots, PAR was measured by considering the whole canopy of the legume and maize components. In the 1 to 1 and 2 to 2 distinct row intercrop plots, PAR readings were taken separately across legume and maize rows and averaged.

Legume biomass was sampled at the mid-pod filling stage from an area of 3.0 m × 1.0 m by cutting plants at the soil surface, separated into shoots and pods, and both total and sub-sample fresh weights taken in the field. Legume and maize grain yields were measured just after physiological maturity by harvesting a 3.0 m × 1.5 m area excluding the border rows. Maize ears and stalks were harvested, and the sheaths were removed by hand. Fresh weights of all cobs and of sub-samples of ten randomly picked cobs were determined in the field. Total and sub-sample fresh weights of legume pods were taken in the field. Conversion factors for the different plant parts were derived from experimental data from trials conducted in the Guinea savanna of northern Ghana and Nigeria. Pooled means of the various treatments were taken and used to calculate the dry weights of the sub-samples (values given are dry matter fractions): Cowpea (mid-pod stage: shoot = 0.17, pod = 0.18; crop maturity: pod = 0.64, grain to pod ratio = 0.77), soybean (mid-pod stage: shoot = 0.29, pod = 0.31; crop maturity: pod = 0.69, grain to pod ratio = 0.71), groundnut (mid-pod stage: shoot = 0.22, pod = 0.31; crop maturity: pod = 0.66, grain to pod ratio = 0.64) and maize (crop maturity only: cob = 0.71, grain to cob ratio = 0.79). These conversion factors are reported in Kermah et al. (submitted). Grain yields are presented at 14% moisture for maize and 12% moisture for legumes; above-ground dry matter yields on dry weight basis.

3.2.4. Assessment of intercrop productivity and profitability

The Land Equivalent Ratio (LER) was used to evaluate resource use efficiency and the productivity of intercrops. LER values above one indicate that intercropping is more productive and efficient in using environmental resources than sole cropping, and values less than one that sole crops were more productive. Individual within-block values of maize or legume grain yields were used as the denominator values to calculate LER.

$$LER = Y_{il}/Y_{sl} + Y_{im}/Y_{sm} \quad (1)$$

where Y_{il} and Y_{im} are intercrop yields of legume and maize respectively while Y_{sl} and Y_{sm} are the sole yields of legume and maize (Mead and Willey, 1980).

A partial budget analysis, accounting of the total variable costs and gross returns of a production system to determine a change (increase or decrease) in profit (Alimi and Manyong, 2000) was done. Net benefit used to determine the relative economic profitability of the cropping systems.

$$\text{Net benefit} = \text{Total revenue (TR)} - \text{Total cost (TC)} \quad (2)$$

Total revenue was estimated as the product of grain yield (t ha^{-1}) and grain price (US\$ t^{-1}). Grain prices were obtained from local market surveys at harvest time when most farmers sell their produce. TC was the sum of the costs of input (seeds, fertilizers and agro-chemical) and labour for the different field activities. Labour cost for each activity was based on the local daily wage per person to perform the activity ha^{-1} and multiplied by the total man-days required to complete the activity under sole maize and legume conditions. TC of the intercrop pattern was the sum of 50% of the TC of each sole crop. For the within row intercrops, the costs of sowing, urea application to maize and weeding were calculated as 68% that of the respective sole crops. This was based on the assumption that those activities require 18% more labour in an intercrop (Rusinamhodzi et al., 2012). Details of unit costs, grain prices and estimated labour requirements are presented in Table 3.1. Net benefits were estimated for each season and averaged.

3.2.5. Data handling and analysis

The percentage intercepted PAR (% IPAR) was calculated following Gallo and Daughtry (1986) as:

$$\%IPAR = [1 - (It/Io)] \times 100 \quad (3)$$

where *It* is the PAR measured just below the lowest green leaves (lowest layer of photosynthetically active leaves) while *Io* is the incident PAR.

The expected intercepted PAR (IPAR) by intercrops based on plant densities was calculated as: (0.5 × sole maize IPAR) + (0.5 × sole legume IPAR). The expected IPAR needed by intercrops to produce the observed combined intercrop grain yields if RUE is similar to that of sole crops was calculated as: {(Sole maize IPAR × (intercrop maize grain yield/Sole maize grain yield)} + {(Sole legume IPAR × (intercrop legume grain yield/Sole legume grain yield)}.

Statistical analysis was conducted using GenStat (version 18.1, VSN International Ltd). The different maize-legume systems and sites were analysed separately initially, and then combined. Data were analysed with a linear mixed model with planting arrangement, soil fertility status and site (for cross site analysis) as fixed factors and replication as random factor to test for effect of planting arrangement, soil fertility and site on crop yields and intercrop productivity (assessed with LER). Analysis of covariance (ANCOVA) to explain the sources of variation in above-ground dry matter and grain yield as well as land equivalent ratios were conducted using the general ANOVA structure with planting arrangement as a fixed factor, replication as random factor and measured total soil N and available P as covariates. For PAR interception, repeated measurements analysis was done with plots as subjects and measurement dates (presented as days after sowing, DAS) as time points. Measurement date × cropping system × soil fertility were kept as fixed factors with the models fitted for correlation within subjects across time using antedependence model order 1 since the intervals between different measurement dates were not equally spaced. The standard error of differences between means (SED) was used to compare treatment means at $P < 0.05$ significance level.

3.3. Results

3.3.1. Soil fertility and rainfall distribution

The site in the SGS received more rainfall than the NGS in both seasons (Fig. 3.1). Total rainfall during the growing season was 598 mm in 2013 and 609 mm in 2014 in the SGS, and 532 mm in 2013 and 423 mm in 2014 in the NGS. The rainfall at both sites was below the long term mean seasonal rainfall values: 861 mm for the SGS and 807 mm for the NGS (Ghana Meteorological Agency, Legon, Accra).

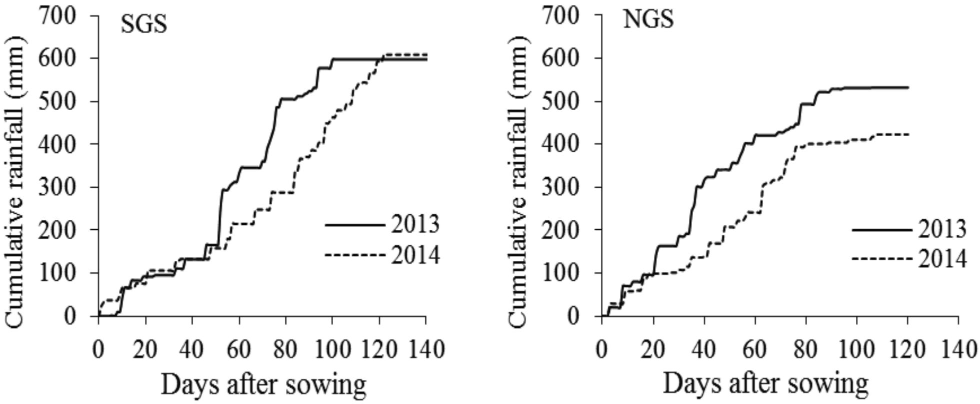

Fig. 3.1. Cumulative rainfall during the 2013 and 2014 growing seasons. In 2014, 0 DAS in the southern Guinea savanna (SGS) refers to the sowing date of the maize-groundnut system (June 13). Maize-soybean and maize-cowpea systems were sown 21 and 34 days later, respectively.

The SGS had relatively more fertile soils with values for pH, OC, N, exchangeable cations and clay content more favourable for crop growth than the NGS (Table 3.2). Available P and exchangeable K were low at both sites. The relatively sandy soils in the NGS were likely to have a low moisture holding ability, while the low soil pH could reduce the availability of micronutrients. Soil OC was sub-optimal for good soil nutrient retention and soil N supply, and likely to limit crop growth at both sites. Exchangeable Ca and Mg were unlikely to limit crop growth at both sites.

Soil chemical analysis largely confirmed the soil fertility classification by the farmers. In the SGS, pH, OC, ECEC and clay content were more favourable for crop growth in the HF field than in the MF field, while both fields had generally larger values of OC, P, exchangeable Ca and ECEC than the LF field (Table 3.2). In the NGS, the HF field had soil fertility characteristics more favourable for crop growth compared with the MF and LF fields, while the latter two were comparable in most cases (Table 3.2).

3.3.2 Radiation interception, above ground biomass and grain yields

Sole legumes intercepted more PAR than intercrops ($P < 0.001$; Fig. 3.2) whilst intercrops intercepted more PAR than sole maize. This was more evident after silking when maize leaves started senescing. Differences in intercepted PAR between intercrop patterns were not significant at the initial growth stages until flowering of legumes and maize. Thereafter, the 1 to 1 and 2 to 2 intercrops intercepted significantly less PAR than the within-row intercrop in most cases. These differences were clearest at early pod-set to late pod-fill stages of the legumes, particularly of cowpea.

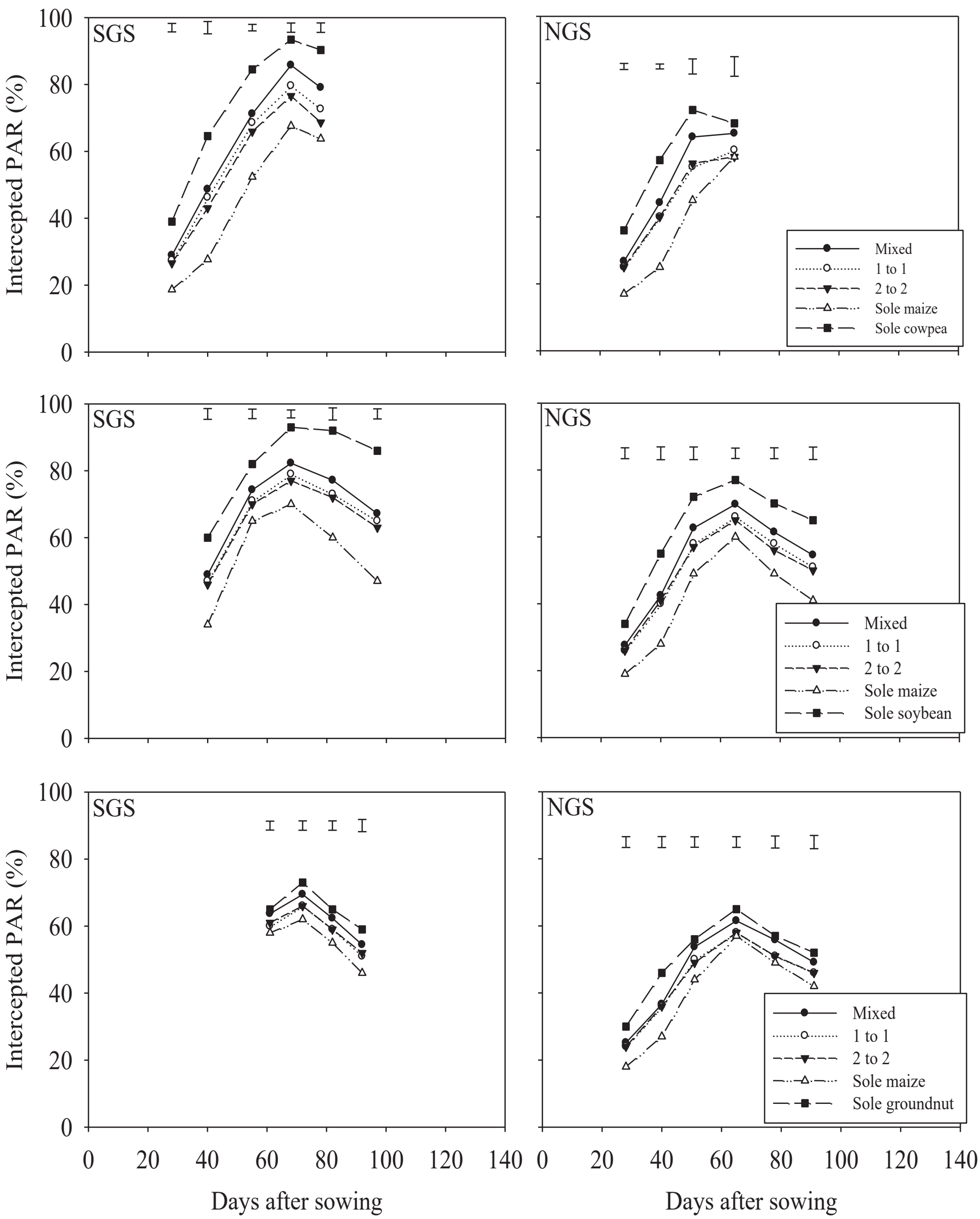

Fig. 3.2. Percentage intercepted PAR as affected by cropping pattern in 2014, averaged over soil fertility levels in the SGS and the NGS of northern Ghana. The error bars indicate the combined standard error of differences between means (SED) for cropping patterns.

The actual PAR intercepted by the intercrops was comparable to the expected PAR interception, if calculated as the sum of 50% of PAR intercepted by each sole crop (Table 3.3). However, the actual PAR intercepted by the intercrops was 10-31% smaller in the SGS and 17–33% smaller in the NGS compared with the expected PAR interception by the intercrops based on grain yields and radiation use efficiency (RUE) in the sole crops (Table 3.3). The crops grown in the HF fields intercepted more PAR than the MF and LF fields *(P* < 0.001; Fig. 3.3). Soil fertility did not affect PAR interception at the initial growth stages but did so from flowering to late pod-fill stages.

Table 3.3. Actual and expected percentage intercepted PAR (%IPAR) by intercrops based on plant densities and radiation use efficiencies (RUE) in sole crops in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

	SGS			NGS		
Cropping pattern	Actual IPAR (%)	Expected IPAR based on plant densities (%)	Expected IPAR based on RUE in sole crops (%)	Actual IPAR (%)	Expected IPAR based on plant densities (%)	Expected IPAR based on RUE in sole crops (%)
MZ-CP						
Mixed	63	60	94	50	47	80
1 to1	59	60	75	45	47	65
2 to 2	56	60	70	45	47	65
Sole MZ	46			36		
Sole CP	74			58		
MZ-SB						
Mixed	70	69	97	53	52	86
1 to1	67	69	81	50	52	71
2 to 2	66	69	76	49	52	69
Sole MZ	55			41		
Sole SB	83			62		
MZ-GN						
Mixed	62	60	88	47	45	75
1 to1	59	60	76	44	45	61
2 to 2	59	60	76	44	45	64
Sole MZ	55			40		
Sole GN	66			51		

CP – cowpea; SB – soybean; GN – groundnut; MZ – maize

F pr for actual vs expected IPAR based on plant densities:
SGS: MZ-CP: *P*=0.676; MZ-SB: *P*=0.235; MZ-GN: *P*=0.720
NGS: MZ-CP: *P*=0.720; MZ-SB: *P*=0.506; MZ-GN: *P*=0.886

F pr for actual vs expected IPAR based on RUE in sole crops:
SGS: MZ-CP (*P*<0.001, SED = 2); MZ-SB (*P*<0.001, SED = 2); MZ-GN (*P*<0.001, SED = 2)
NGS: MZ-CP (*P*<0.001, SED = 2); MZ-SB (*P*<0.001, SED = 2); MZ-GN (*P*<0.001, SED =1)

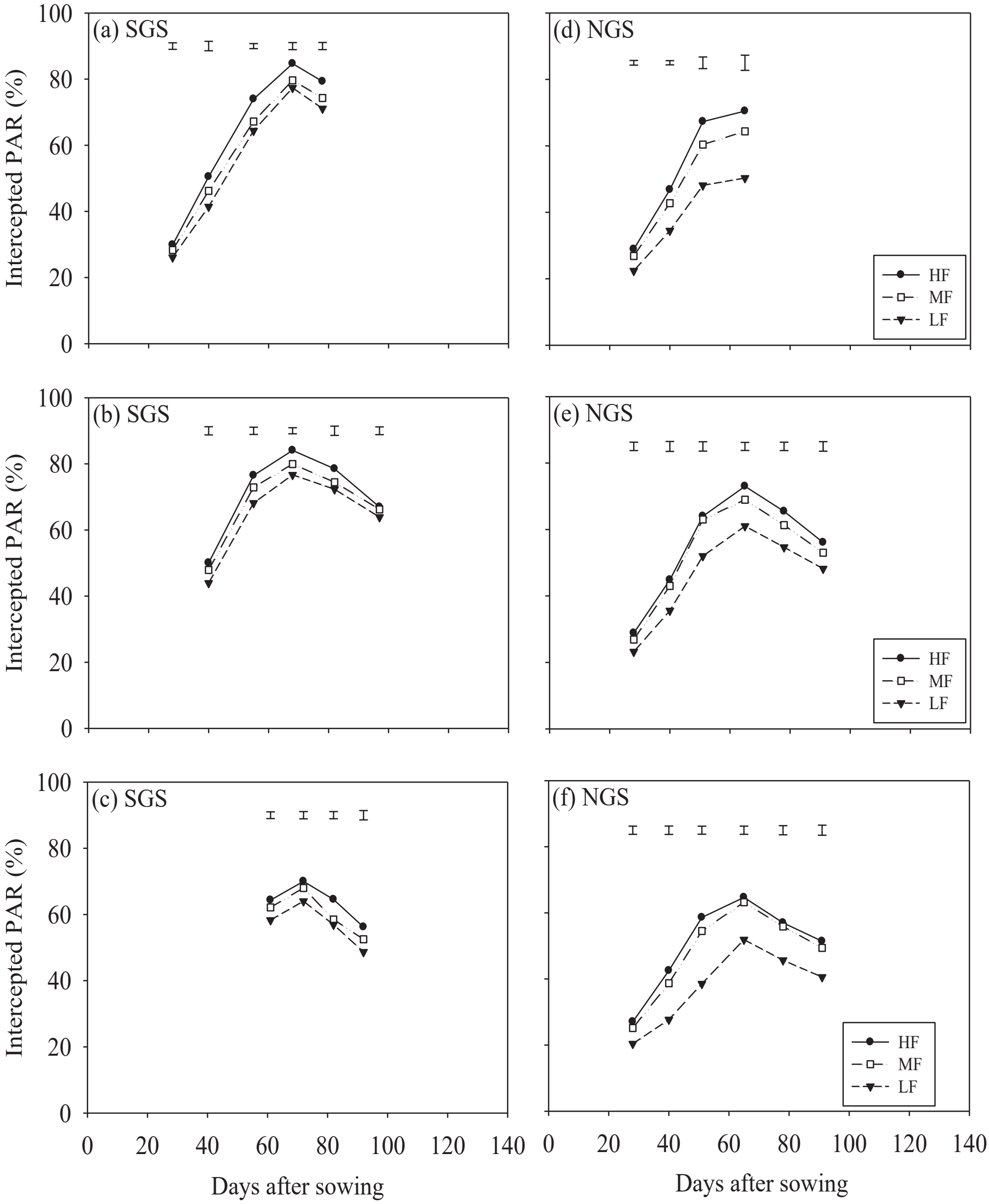

Fig. 3.3. Percentage intercepted PAR as affected by soil fertility status in 2014 in (a) maize-cowpea, (c) maize-soybean and (e) maize-groundnut systems in the SGS and in (b) maize-cowpea, (d) maize-soybean and (f) maize-groundnut systems in the NGS of northern Ghana. Data are averaged over cropping systems. Error bars indicate the combined standard error of differences between means (SED).

Legume biomass yields at mid-pod fill were greater in the SGS than in the NGS ($P < 0.01$) that received less rainfall during the growing season and had soils poorer in fertility (Table 3.4). Sole legumes had greater above-ground biomass yields than the associated intercrops at both sites ($P < 0.001$; Table 3.4). However, intercrop biomass yields were larger compared with 50% of the sole legume yields (which corresponds to yields from the same size of land and density as that of the intercrops) with the differences generally being significant only for the within-row intercrops. Cowpea and soybean biomass yields were significantly greater in within-row systems than in distinct rows intercrops, while those of groundnut were comparable.

Table 3.4. Above-ground dry matter yield (t ha^{-1}) of legumes at mid-pod-fill stage as affected by cropping pattern and fertility status averaged for 2013 and 2014 seasons in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana. The SED shows the standard error of difference between means.

Cropping pattern	SGS				NGS			
	HF	MF	LF	Mean	HF	MF	LF	Mean
MZ-CP within row	1.92	1.71	1.30	1.65	1.92	1.73	1.01	1.56
MZ-CP 1 to 1 rows	1.51	1.32	1.01	1.28	1.45	1.23	0.85	1.17
MZ-CP 2 to 2 rows	1.27	1.13	0.97	1.12	1.41	1.20	0.73	1.11
Sole cowpea	2.84	2.52	1.37	2.24	2.73	1.82	1.15	1.90
Mean	1.89	1.67	1.16	1.57	1.88	1.49	0.94	1.44
SED (arrangement)				0.09				0.09
SED (fertility)				0.07				0.11
SED (interaction)				0.15				0.17
MZ-SB within row	3.45	3.42	2.96	3.27	3.51	2.09	1.26	2.28
MZ-SB 1 to 1 rows	3.17	2.77	2.76	2.90	2.37	1.51	0.88	1.59
MZ-SB 2 to 2 rows	2.97	2.77	2.65	2.80	2.35	1.39	0.92	1.55
Sole soybean	5.84	6.10	5.60	5.85	4.90	2.67	1.69	3.09
Mean	3.86	3.76	3.49	3.70	3.28	1.92	1.19	2.13
SED (arrangement)				0.19				0.14
SED (fertility)				n.s.				0.21
SED (interaction)				n.s.				0.29
MZ-GN within row	1.17	0.86	0.89	0.97	0.87	0.81	0.66	0.78
MZ-GN 1 to 1 rows	0.86	0.88	0.79	0.84	0.76	0.68	0.56	0.66
MZ-GN 2 to 2 rows	0.94	0.87	0.87	0.90	0.76	0.69	0.60	0.69
Sole groundnut	1.79	1.74	1.52	1.68	1.40	1.17	0.87	1.14
Mean	1.19	1.09	1.02	1.10	0.94	0.84	0.67	0.82
SED (arrangement)				0.11				0.05
SED (fertility)				n.s				0.05
SED (interaction)				n.s.				0.08

CP – cowpea; SB – soybean; GN – groundnut; MZ

Biomass yields declined with decreasing soil fertility status, but this decline varied among legume species and sites (Table 3.4). In the SGS, only cowpea and soybean gave larger biomass in the HF field than in the LF field (cowpea: $P < 0.001$; soybean: $P = 0.016$) due to smaller differences soil N and P between the fields, which accounted for smaller variation in the biomass yield compared with variation attributable to planting arrangement (Tables 3.2 and 3.5). On the contrary, all the three legume species produced greater biomass in the HF field than in the LF field in the NGS ($P < 0.001$) as the larger differences in soil N and P status between the fields (Table 3.2) accounted for larger variation in biomass yields relative to variation due to planting arrangement (Table 3.5). Except for cowpea in the NGS, the legumes produced more biomass ($P < 0.001$) in the second season than in the first season at both sites.

Cowpea grain yield was greater in the NGS than in the SGS ($P = 0.008$), while maize, soybean and groundnut yields were greater in the SGS ($P < 0.01$). Sole crops produced greater grain yields than intercrops at both sites ($P < 0.001$; Fig. 3.4). Intercropped maize and legume grain yields were larger compared with 50% of the associated sole yields in most cases ($P<0.001$; Fig. 3.4). The within-row intercrop pattern in general provided larger maize and legume grain yields than the 1 to 1 and 2 to 2 distinct row patterns whereas the latter two had comparable yields. Grain yields differed with cropping season (data not shown). For instance, groundnut produced more grain yield in the second season at both sites ($P < 0.001$). Cowpea grain yield was not significantly affected by season (though the yields declined at both sites in the second season) while soybean grain yield declined in the second season at both sites but significant ($P < 0.001$) only in the NGS. The impact of season on maize grain yield was significant in all maize-legume systems in the NGS while in the SGS, the seasonal effect was significant only for the maize-groundnut system with more maize grain produced in the second season in each case.

Table 3.5. Sum of squares, mean squares and F statistics from Analysis of Covariance indicating the sources of variation in above-ground dry matter yield of grain legumes under different spatial arrangement and selected measured soil properties in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

	SGS					NGS				
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	***Cowpea***									
Covariates	2	4.44	2.22	65.00	<.001	2	7.18	3.59	39.75	<.001
Total N	1	0.22	0.22	6.55	0.031	1	6.16	6.16	68.20	<.001
Avail. P	1	4.22	4.22	123.44	<.001	1	1.02	1.02	11.30	0.008
Residual	9	0.31	0.03	0.36		9	0.81	0.09	1.06	
Block.*Units* stratum										
Arrangement	3	8.95	2.98	31.02	<.001	3	4.86	1.62	19.00	<.001
Residual	33	3.17	0.10			33	2.81	0.09		
Total	47	16.87				47	15.67			
Block stratum	***Soybean***									
Covariates	2	1.15	0.57	1.72	0.233	2	36.02	18.01	53.05	<.001
Total N	1	0.08	0.08	0.25	0.628	1	35.61	35.61	104.88	<.001
Avail. P	1	1.06	1.06	3.19	0.108	1	0.41	0.41	1.21	0.299
Residual	9	2.99	0.33	1.68		9	3.06	0.34	1.46	
Block.*Units* stratum										
Arrangement	3	75.00	25.00	126.07	<.001	3	18.81	6.27	27.03	<.001
Residual	33	6.54	0.20			33	7.65	0.23		
Total	47	85.69				47	65.54			
Block stratum	***Groundnut***									
Covariates	2	0.24	0.12	3.34	0.082	2	0.59	0.30	18.22	<.001
Total N	1	0.00	0.00	0.05	0.821	1	0.50	0.50	30.86	<.001
Avail. P	1	0.24	0.24	6.62	0.03	1	0.09	0.09	5.58	0.042
Residual	9	0.32	0.04	0.56		9	0.15	0.02	1.03	
Block.*Units* stratum										
Arrangement	3	5.57	1.86	29.45	<.001	3	1.79	0.60	37.78	<.001
Residual	33	2.08	0.06			33	0.52	0.02		
Total	47	8.21				47	3.05			

Combined intercrop grain yields (legume + maize yield) differed between the intercrop patterns only in the HF and MF fields. Grain yields declined with decreasing soil fertility at both sites ($P < 0.001$). This was more evident in the NGS where the differences in soil fertility between fields, (e.g. soil N and P) were larger between the fertile and poorly fertile fields and accounted for much of the observed variation in grain yields compared with that of SGS (Tables 3.2 and 3.6). Consequently, the clearer differences in soil fertility status between the fields in NGS were well reflected by grain yields, whereas the decrease in yields with poorer soil fertility was not as clear in the SGS (Fig. 3.4). The grain yields of sole maize were generally comparable or larger than the combined intercrop grain yields in the HF or MF fields.

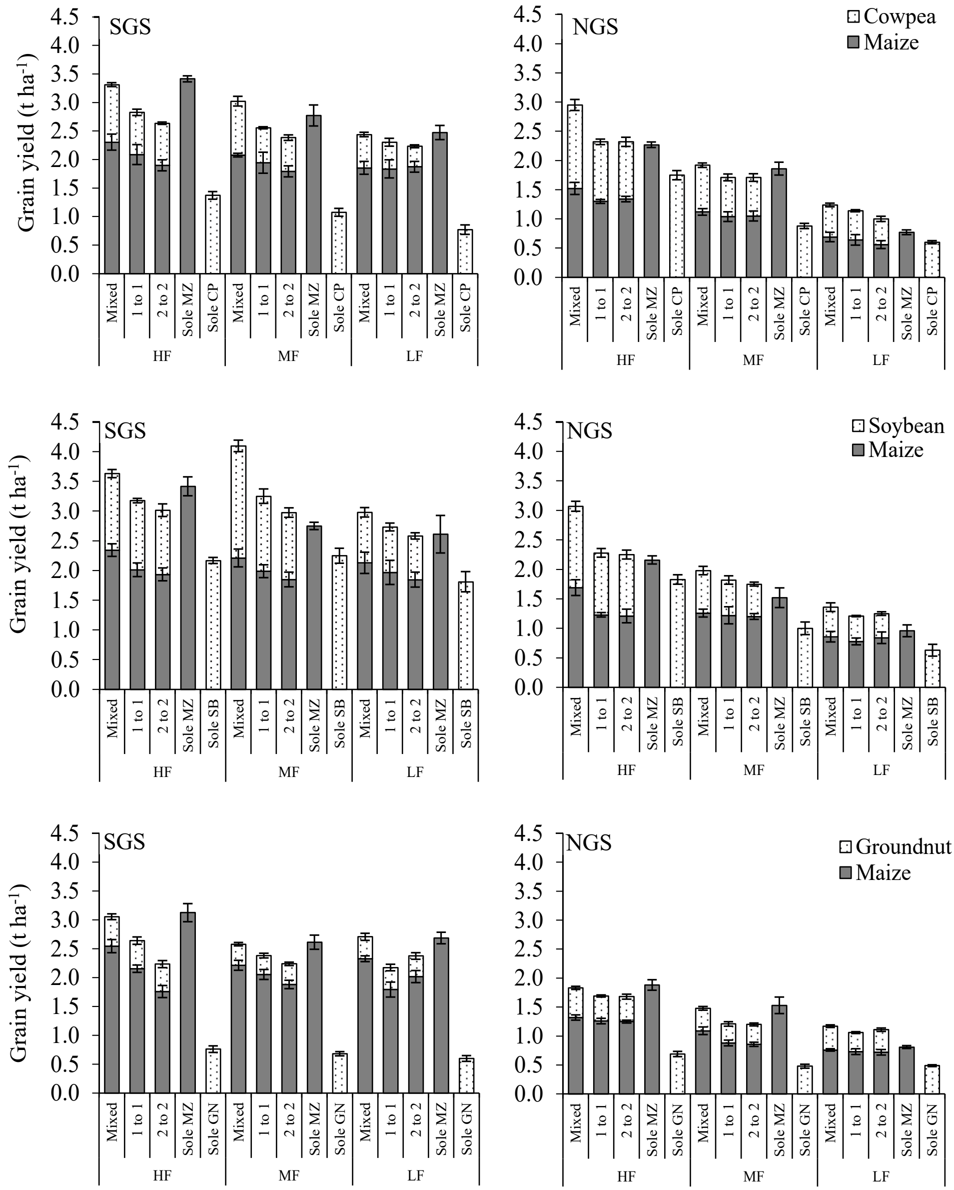

Fig. 3.4. Combined maize and legume intercrop and sole crop grain yields as affected by spatial plant arrangement and soil fertility level, average of 2013 and 2014 seasons in the SGS and NGS of northern Ghana. Error bars represent the standard error of means.

Table 3.6. Sum of squares, mean squares and F statistics from Analysis of Covariance indicating the sources of variation in grain yields of legumes and maize under different spatial arrangement and selected measured soil properties in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

	SGS					NGS				
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	***Cowpea***									
Covariates	2	1.43	0.71	40.5	<.001	2	5.03	2.51	178.08	<.001
Total N	1	0.03	0.03	1.58	0.24	1	5.02	5.02	355.36	<.001
Avail. P	1	1.40	1.40	79.41	<.001	1	0.01	0.01	0.81	0.393
Residual	9	0.16	0.02	1.3		9	0.13	0.01	0.48	
Block.*Units* stratum										
Arrangement	3	2.01	0.67	49.33	<.001	3	1.15	0.38	13.1	<.001
Residual	33	0.45	0.01			33	0.97	0.03		
Total	47	4.04				47	7.28			
Block stratum	***Soybean***									
Covariates	2	2.88	1.44	25.19	<.001	2	5.92	2.96	97.57	<.001
Total N	1	1.69	1.69	29.58	<.001	1	5.92	5.92	195.06	<.001
Avail. P	1	1.19	1.19	20.81	0.001	1	0.00	0.00	0.09	0.773
Residual	9	0.51	0.06	1.31		9	0.27	0.03	1.05	
Block.*Units* stratum										
Arrangement	3	8.92	2.97	68.07	<.001	3	1.79	0.60	20.67	<.001
Residual	33	1.44	0.04			33	0.95	0.03		
Total	47	13.75				47	8.94			
Block stratum	***Groundnut***									
Covariates	2	0.17	0.09	12.07	0.003	2	0.16	0.08	19.95	<.001
Total N	1	0.04	0.034	5.52	0.043	1	0.14	0.14	34.72	<.001
Avail. P	1	0.13	0.13	18.63	0.002	1	0.02	0.02	5.17	0.049
Residual	9	0.06	0.01	1.93		9	0.04	0.00	1.05	
Block.*Units* stratum										
Arrangement	3	0.69	0.23	63.15	<.001	3	0.26	0.09	22.82	<.001
Residual	33	0.12	0.00			33	0.13	0.00		
Total	47	1.05				47	0.58			
Block stratum	***Maize***									
Covariates	2	0.79	0.39	7.33	0.013	2	4.86	2.43	92.64	<.001
Total N	1	0.08	0.08	1.55	0.245	1	4.17	4.17	158.82	<.001
Avail. P	1	0.71	0.71	13.11	0.006	1	0.69	0.69	26.46	<.001
Residual	9	0.48	0.05	0.99		9	0.24	0.03	1.12	
Block.*Units* stratum										
Arrangement	3	7.26	2.42	44.45	<.001	3	2.20	0.73	31.31	<.001
Residual	33	1.80	0.05			33	0.77	0.02		
Total	47	10.33				47	8.07			

3

3.3.3. Land Equivalent Ratios (LER) of intercrops

Mean LER for the different intercrop patterns were all greater than unity which suggested that intercropping led to a more productive use of land than sole cropping (Table 3.7). Partial LER values of maize were mostly above 0.5 at both sites (Fig. 3.5). Intercropped maize was more competitive than the legumes, particularly soybean and groundnut in the SGS (Fig. 3.6). The intercropped legumes performed relatively better in the NGS indicated by more partial LER values above 0.5 (Fig. 3.5a and b) and reduced competitiveness of maize (Fig. 3.6a and b) compared with the SGS, especially in intercropping systems with soybean. This led to a 14% greater mean total LER in the NGS than in the SGS ($P < 0.001$; Table 3.7), with season having no significant effect on the total LER (a mean increase of 2% in SGS and a decline of 5% in the NGS in the second season compared with the first season).

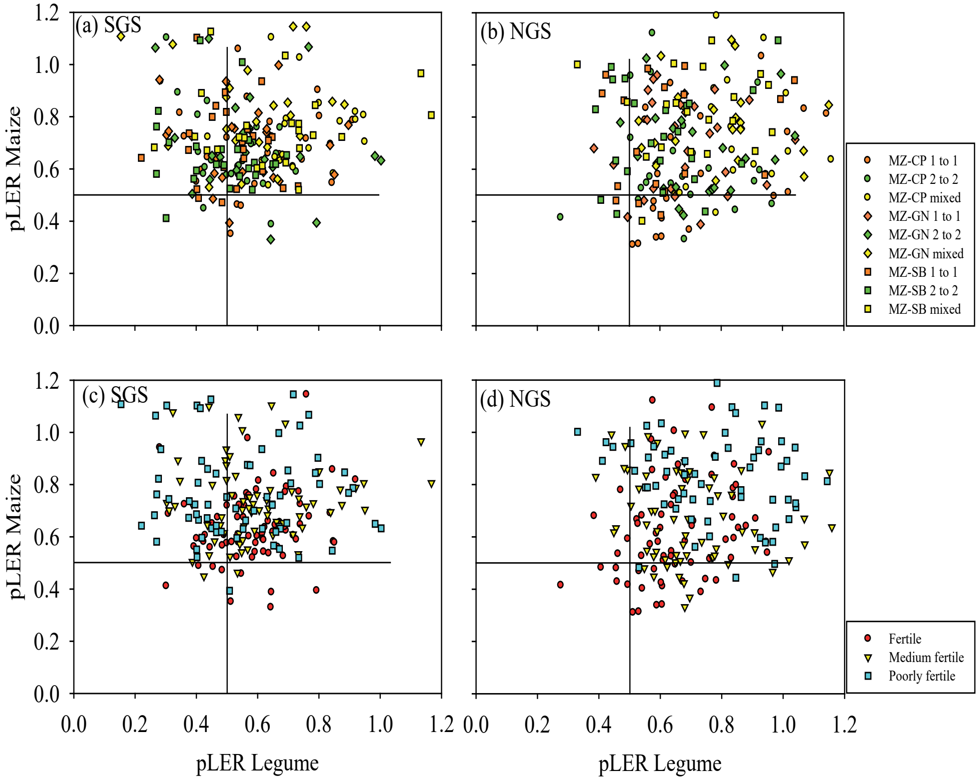

Fig. 3.5. Partial Land Equivalent Ratios (LER) of groundnut, cowpea and soybean intercropped with maize in different spatial planting patterns in (a) the SGS and (b) the NGS, and at different soil fertility levels in (c) the SGS and (d) the NGS for both seasons. MZ-GN refers to maize-groundnut, MZ-CP to maize-cowpea and MZ-SB to maize-soybean intercropping systems. The mixed intercrop refers to the within row intercropping of maize and legume. Data points are from each replicate plot.

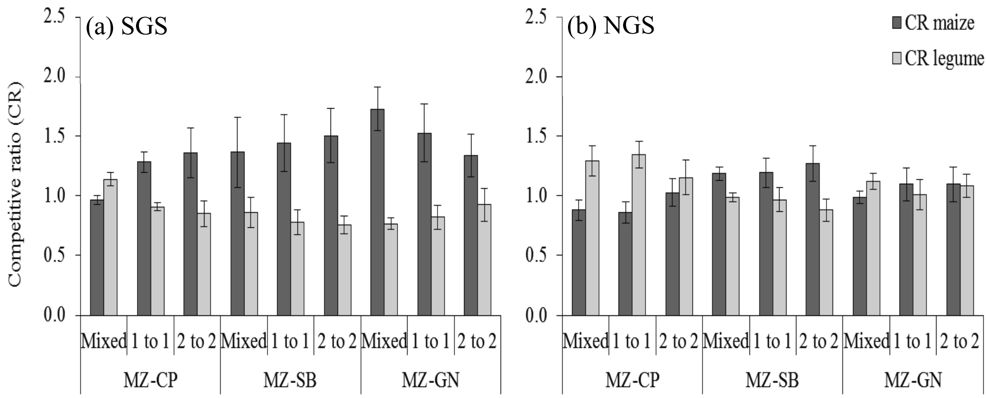

Fig. 3.6. Mean Competitive Ratios (CR) of cowpea, soybean and groundnut intercropped with maize in different spatial arrangements in (a) the southern Guinea savanna (SGS) and (b) the northern Guinea savanna (NGS) of northern Ghana. MZ-GN refers to maize-groundnut, MZ-CP to maize-cowpea and MZ-SB to maize-soybean intercropping systems. The mixed intercrop refers to the within-row intercropping of maize and legume. The error bars indicate the standard error of means.

The impact of legume species on LER was significant ($P < 0.046$) in the SGS with cowpea-maize and groundnut-maize systems giving larger total LER values than soybean-maize systems (Table 3.7). This suggests that soybean is less suitable for intercropping than groundnut and cowpea. LER values were greater ($P < 0.05$, generally) in the within-row pattern than in the 1 to 1 and 2 to 2 distinct row patterns at both sites.

Low soil fertility enhanced the performance of the intercropped legumes indicated by larger partial LER values of the legumes in the LF fields compared with partial LER values of legumes in the HF fields (Fig. 3.5c, d). This effect was more visible in the NGS (Fig. 3.5d) where the differences in soil fertility parameters (especially N and P) between the HF and the LF fields were stronger than in the SGS (Table 3.2) and seen in soil N and P being responsible for much of the observed variability in total LER in the NGS than in the SGS (Table 3.8). This led to greater total LER in the LF fields and the LER values declined with increasing soil fertility status with the values in most cases being smaller ($P < 0.05$) in HF fields (Table 3.7).

Table 3.7. Total Land Equivalent Ratios (LER) of maize intercropped with cowpea, soybean and groundnut in different spatial arrangements and at different soil fertility status, averaged over both seasons in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana. SED indicates the combined standard error of difference between means.

Cropping pattern	SGS				NGS			
	HF	MF	LF	Mean	HF	MF	LF	Mean
MZ-CP mixed	1.41	1.65	1.54	1.53	1.52	1.51	1.81	1.61
MZ-CP 1 to 1	1.15	1.28	1.37	1.27	1.18	1.33	1.68	1.40
MZ-CP 2 to 2	1.10	1.21	1.24	1.18	1.18	1.33	1.47	1.33
Mean	1.22	1.38	1.38	1.33	1.29	1.39	1.65	1.44
MZ-SB mixed	1.28	1.65	1.35	1.43	1.54	1.60	1.80	1.65
MZ-SB 1 to 1	1.13	1.29	1.21	1.21	1.15	1.43	1.58	1.39
MZ-SB 2 to 2	1.07	1.18	1.16	1.14	1.13	1.37	1.57	1.36
Mean	1.16	1.37	1.24	1.26	1.27	1.46	1.65	1.46
MZ-GN mixed	1.49	1.40	1.53	1.47	1.45	1.55	1.78	1.59
MZ-GN 1 to 1	1.34	1.28	1.30	1.31	1.30	1.26	1.58	1.38
MZ-GN 2 to 2	1.20	1.26	1.40	1.29	1.29	1.28	1.69	1.42
Mean	1.34	1.31	1.41	1.35	1.35	1.36	1.68	1.46
SED (arrangement)				0.03				0.04
SED (fertility)				n.s.				0.05

CP – cowpea; SB – soybean; GN – groundnut; MZ – maize

Table 3.8. Sum of squares, mean squares and F statistics from Analysis of Covariance indicating the sources of variation in total Land Equivalent Ratios (LER) of maize-grain legume intercrops under different spatial arrangement and selected measured soil properties in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana.

	SGS					NGS				
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum										
Legume species	2	0.20	0.10	1.61	0.216	2	0.01	0.00	0.08	0.924
Covariates	2	0.28	0.14	2.26	0.121	2	2.44	1.22	21.53	<.001
Total N	1	0.28	0.28	4.50	0.042	1	1.82	1.82	32.08	<.001
Avail. P	1	0.00	0.00	0.03	0.874	1	0.62	0.62	10.97	0.002
Residual	31	1.90	0.06	3.74		31	1.76	0.06	2.43	
Block.*Units* stratum										
Arrangement	2	1.52	0.76	46.36	<.001	2	1.40	0.70	29.98	<.001
Arrangement.Legume species	4	0.08	0.02	1.27	0.291	4	0.07	0.02	0.70	0.596
Residual	66	1.08	0.02			66	1.54	0.02		
Total	107	5.05				107	7.23			

3.3.4. Economic profitability of cropping patterns

The crops in the SGS provided greater economic returns than in the NGS (Fig. 3.7). The lower net benefits in the NGS resulted from generally poor grain yields and slightly larger costs of production due to higher cost associated with the use of tractor for ploughing. In general, sole legumes were more profitable than sole maize except sole cowpea and groundnut in the SGS due to relatively low grain yields. High labour requirements to produce legumes (Table 3.1b) contributed to the smaller returns of sole legumes.

The extra time needed for sowing, urea application to maize and weeding in the within-row intercrop system led to consistently greater TC than in the other cropping patterns (data not shown). The distinct row intercrops had larger TC than sole maize due to higher labour costs of legume cultivation. The TC of the distinct row intercrops was smaller than sole legumes which also had larger TC than sole maize (data not shown) due to higher labour requirements for legumes production (Table 3.1b). However, the greater grain yield in intercropping resulted in larger net benefits than in sole cropping of maize and legumes (P<0.001), with the benefits generally larger with the within-row intercrops (Fig. 3.7a, b). The larger grain yields obtained by growing crops in the HF fields led to significantly (P<0.001) greater net benefits, which declined with decreasing soil fertility (Fig. 3.7c, d).

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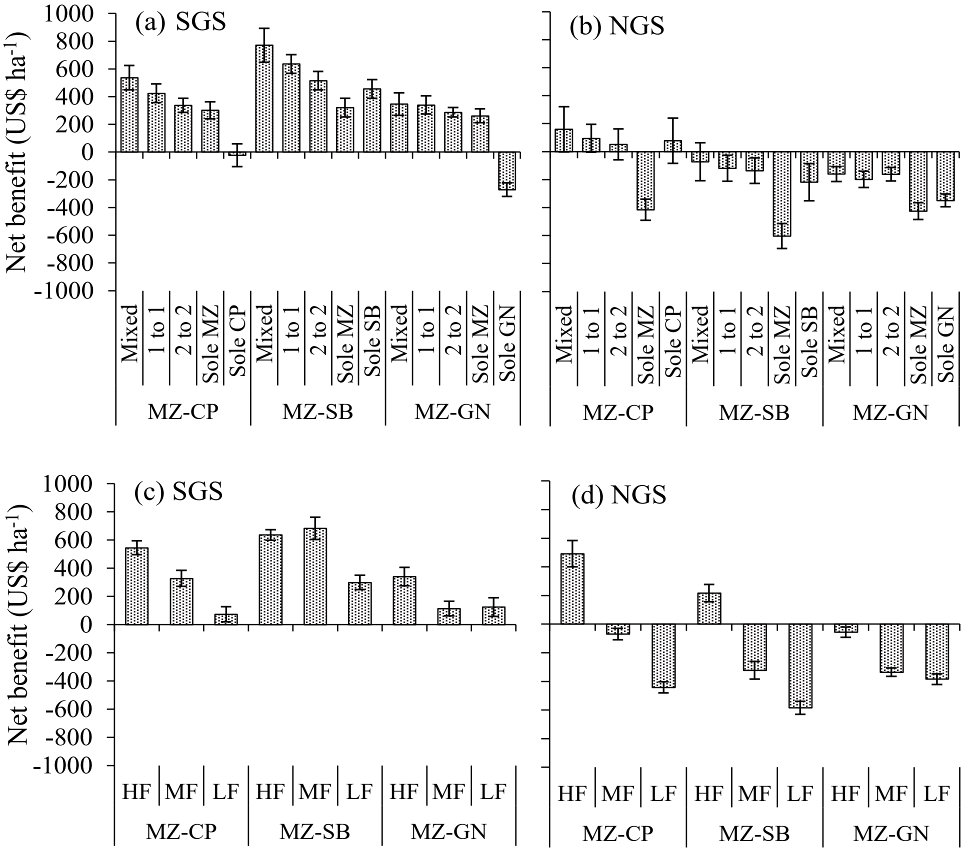

Fig. 3.7. Net benefits from a partial budgeting analysis as influenced by different cropping patterns, in (a) the SGS and (b) the NGS, and as affected by soil fertility status in (c) the SGS and (d) the NGS of northern Ghana. Data presented are averages for two seasons. The error bars indicate the standard error of mean.

3.4. Discussion

3.4.1. Biophysical characteristics and crop production

Soil nutrient concentrations were generally low at both sites (Table 3.2) in relation to critical values for sub-Saharan Africa (Fairhurst, 2012), and are representative for farmers' conditions in northern Ghana (Buri et al., 2010). The differences in soil fertility characteristics between the two sites may be attributable to differences in soil types, as well as past farmers' management. For example, crop residues were commonly retained in the field in the SGS, while they were often exported in the NGS to feed livestock or to be composted. The greater biomass and grain yields produced in the SGS compared with the NGS (Table 3.4; Fig. 3.4) were consistent with the differences in rainfall and soil fertility characteristics that were more favourable for crop growth in the SGS. The lower amount of rainfall received in the NGS (Fig. 3.1) and the predominantly sandy soils (Table 3.2) probably led to less water availability in the NGS, also contributing to smaller yields.

3.4.2. Cropping pattern and soil fertility effects on grain yields

The comparable maize grain yields in intercrops and sole maize in the LF field in NGS that had low soil N status corroborates the finding of Ahmed and Rao (1982) who also observed comparable yields for intercropped and sole maize grain under low soil N conditions. This might be because under low N conditions, there will be less competition for radiation between the intercrop components. Also, there could be a more marked impact of N_2 fixation of the intercropped legume on the maize component under low soil N conditions than under high soil N status. The greater grain yield of maize and legumes (both intercrops and sole crops) in the fertile fields compared with the poorly fertile fields mirrored the soil fertility gradient between the fields at both sites (Table 3.2; Fig. 3.4). In particular, the grain yield differences induced by the soil fertility gradient was remarkably consistent in the NGS where stronger differences in soil fertility between the fields were observed (Table 3.2; Fig. 3.4). Our results agree with the findings of other authors such as Oikeh et al. (1998) in the Guinea savanna of Nigeria and Ojiem et al. (2014) in Western Kenya who observed a consistent decrease in maize and legume grain yields in response to decreases in soil fertility among fields.

3.4.3. Resource use and intercrop productivity

LER values greater than one for the intercrop patterns (Table 3.7) indicate a more efficient and productive land utilization by intercrops compared with the sole crops (Willey, 1985). However, except for maize and soybean intercrops, the combined intercrop grain yields (maize + cowpea or groundnut) were smaller than that of sole maize, particularly in the HF and MF fields. This may be a disincentive for farmers in terms of meeting household food needs if maize is prioritised above the legumes. Given that our trial had a replacement intercrop design, testing of additive intercrops would be worth testing. While the amount of PAR intercepted by the intercrops was comparable with that of 50% of each sole crop (Table 3.3), the combined intercrop grain yields were 26 to 43% larger than the sum of 50% of each sole crop yield. This suggests that RUE in intercrops was greater than in sole crops, as also observed in earlier studies (Reddy and Willey, 1981; Marshall and Willey, 1983; Willey, 1990; Keating and Carberry, 1993). Other authors (Awal et al., 2006; Gao et al., 2010) reported that intercropped maize and sole maize had comparable radiation extinction coefficients and radiation use efficiencies. By contrast, intercropped legumes, for example groundnut, had smaller extinction coefficients and greater radiation use efficiencies than sole groundnut (Harris et al., 1987; Keating and Carberry, 1993; Awal et al., 2006; Gao et al., 2010). The legumes in intercrops fixed 15-97 kg ha^{-1} of N_2 representing 67-71% of N_2 fixed by respective sole crop legumes (Kermah et al., 2018), and this may have improved soil N availability to maize in intercrops in the second season, relative to sole maize. Improved leaf N content and photosynthetic activity of maize in intercrops may have led to enhanced RUE (Sinclair and Horie, 1989; Gimenez et al., 1994) of the intercropped maize in the second season.

We did not rotate the sole legume and sole maize treatments in the second season. With crop rotation, the maize would have benefitted from residual N of the legume from the first season. Rotating sole legume and sole maize could lead to avoidance of pests and diseases build-up relative to continuous intercropping of maize and legumes (Stevenson and van Kessel, 1996). Intercropping, however, can result in better suppression of pests and diseases than continuous cropping of either crop alone (Trenbath, 1993). The different cropping sequences of the different fields could have led to differences in build-up of soil borne pathogens and insect pests that would confound the effect of soil fertility status on crop performance. However, we did not observe differences in pest and disease attack among the crops grown in the different fields which suggests that such effects were not important during the study.

The within row intercrop was more productive than the other intercrop planting patterns, as previously reported in Central Mozambique (Rusinamhodzi et al., 2012). This suggests that the current recommendations of a distinct row intercrop pattern involving two rows of maize alternated with four rows of cowpea that is promoted in the NGS of Nigeria (Ajeigbe et al., 2010) needs to be revisited. However, the distinct row intercrop design is more amenable to mechanisation of some activities, such as sowing, weeding, fertiliser application, though these activities are currently performed manually by smallholders in the region. The larger productivity of the within row system may have been the outcome of a slightly better radiation capture (Fig. 3.2) coupled with an efficient use of the intercepted PAR resulting from the differing canopy architecture compared to distinct row systems (Reddy and Willey, 1981).

Our results show that in maize-legume intercropping, the maize is more competitive than the legume under high soil N conditions as in the SGS leading to a relatively small contribution of legume (Table 3.2; Fig. 3.6a) to the total LER (Table 3.7). Under low soil N conditions such as in the NGS, the competitiveness of the maize is reduced and the intercropped legume gains in relative competitiveness (Table 3.2; Fig. 3.6b; Chang and Shibles, 1985; Midmore, 1993). This is largely due to the ability of legumes to fix N_2 (Kermah et al., submitted) and the apparent reduced competition for radiation between the intercrop components in poorly fertile fields leading to reduced shading of the legume by the intercropped maize crop. This resulted in a competitive balance (similar competitiveness and contributions of the intercrop components to the total LER (Yu et al., 2016)) between the maize and legume intercrop components in the NGS (Fig. 3.5d; Fig. 3.6b) resulting in a greater total LER, particularly in the LF field (Table 3.7; Ofori and Stern, 1986; Yu et al., 2016). Soils in the NGS had a poorer N status (Table 3.2) suggesting that LERs increase with decreasing levels of soil N, as reported by other studies (Searle et al., 1981; Ahmed and Rao, 1982; Ofori and Stern, 1986). Greater LERs in the poorly fertile fields, and in general in the NGS with more marginal growing conditions than in SGS (Fig. 3.1; Tables 3.2 and 3.4) indicate that intercropping is more advantageous under low soil fertility conditions.

3.4.4. Economic profitability as affected by cropping pattern and soil fertility

Greater grain yields in the within-row intercrop systems led to larger net benefits than distinct row intercropping systems, despite the higher labour input in within-row systems. The lower net benefits of sole maize in the NGS (Fig. 3.7b) were the outcome of relatively poor grain yields, making sole cropping of maize economically less attractive in the NGS and farmers may be better off intercropping maize with grain legumes, especially cowpea. Crop production in HF fields was more profitable than in MF and LF fields due to larger grain yields (Fig. 3.4; Fig. 3.7). This indicates that poor soil fertility leads to smaller net benefits, as reported for maize-legume intercrops in Western Kenya by Ojiem et al. (2014). This is a common feature in the Guinea savanna agro-ecology where smallholder farmers are trapped in a vicious cycle of poor soils leading to poor grain yields and consequently poor economic benefits.

3.5. Conclusions

The observed advantage of intercrops over sole crops was associated with an enhanced radiation use efficiency (RUE) by intercrops. While legumes may have achieved a higher RUE in intercropping systems due to their ability to perform relatively well under low-radiation conditions, maize in intercropping may have had a higher RUE due to improved soil N availability in the second season. Intercropping of maize and grain legumes within the same row appears the most productive and lucrative pattern that can be exploited by farmers in the Guinea savanna, though distinct row intercrop patterns are also generally more profitable than sole crops. Benefits of maize-legume intercropping are greater under low soil fertility conditions, presumably due to reduced competition for light and possibly enhanced benefits from legumes' ability to fix N_2. Nevertheless, overall cropping is more profitable in fertile fields due to larger absolute grain yields. Our results show a good potential for maize-legume intercropping for farmers in the Guinea savanna, particularly under more marginal conditions.

Acknowledgements

Funding support provided by the Bill and Melinda Gates Foundation through the N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa project to Wageningen University is gratefully acknowledged. The first author was funded through the Netherlands Fellowship Programme (NFP) of the Netherlands Organization for International Co-operation in Higher Education (NUFFIC). We thank the CSIR-Savanna Agricultural Research Institute, Tamale for the use of its facilities to conduct this work.

Chapter 4

Legume-maize rotation or relay? Options for ecological intensification of smallholder farms in the Guinea savanna of northern Ghana

This chapter is published as:

Kermah, M., Franke, A.C., Ahiabor, B.D.K., Adjei-Nsiah, S., Abaidoo, R.C., Giller, K.E., 2019. Legume-maize rotation or relay? Options for ecological intensification of smallholder farms in the Guinea savanna of northern Ghana. Experimental Agriculture 55, 673–691.

Abstract

Soil nutrient constraints coupled with erratic rainfall have led to poor crop yields and occasionally to crop failure in sole cropping in the Guinea savanna of West Africa. We explored different maize-grain legume diversification and intensification options that can contribute to mitigating risks of crop failure, increase crop productivity under different soil fertility levels, while improving soil fertility due to biological N_2-fixation by the legume. There were four relay patterns with cowpea sown first and maize sown at least 2 weeks after sowing (WAS) cowpea; two relay patterns with maize sown first and cowpea sown at least 3 WAS maize in different spatial arrangements. These were compared with groundnut-maize, soybean-maize, fallow-maize and continuous maize rotations in fields high, medium and poor in fertility at a site each in the southern (SGS) and northern (NGS) Guinea savanna of northern Ghana. Legumes grown in the poorly fertile fields relied more on N_2-fixation for growth leading to generally larger net N inputs to the soil. Crop yields declined with decreasing soil fertility and were larger in the SGS than in the NGS due to more favourable rainfall and soil fertility. Spatial arrangements of relay intercrops did not have any significant impact on maize and legume grain yields. Sowing maize first followed by a cowpea relay resulted in 0.18–0.26 t ha^{-1} reduction in cowpea grain yield relative to cowpea sown from the onset. Relaying maize into cowpea led to a 0.29–0.64 t ha^{-1} reduction in maize grain yield relative to maize sown from the onset in the SGS. In the NGS, a decline of 0.66 and 0.82 t ha^{-1} in maize grain yield relative to maize sown from the onset was observed due to less rainfall received by the relay maize. Groundnut and soybean induced 0.38–1.01 t ha^{-1} more grain yield of a subsequent maize relative to continuous maize, and 1.17–1.71 t ha^{-1} more yield relative to relay maize across both sites. Accumulated crop yields over both years suggest that sowing maize first followed by cowpea relay is a promising ecological intensification option besides the more common legume-maize rotation in the Guinea savanna, as it was comparable with soybean-maize rotation and more productive than the other treatments.

Key words: Cropping sequence, N_2-fixation, Soil N balance, Soil fertility, Rainfall.

4.1. Introduction

The increasing population in sub-Saharan Africa and its associated growing demand for food require the intensification of crop production (Vanlauwe et al., 2014). In the Guinea savanna agro-ecological zone of West Africa, continuous cereal-based cropping without adequate soil nutrient replacement has resulted in a decline in soil fertility with corresponding poor crop yields (Bationo et al., 1998). The duration of fallow period to regenerate soil fertility has become increasingly shorter as a result of population pressure and the competing demands for arable land (Sauerborn et al., 2000; Agyare et al., 2006). Crop or cropping system diversification with the integration of grain legumes is needed, as grain legumes can biologically fix atmospheric N_2 to improve soil fertility and increase (and/or sustain) crop yields. Grain legumes also provide protein-rich edible seeds that contribute substantially to household food, nutrition and income security (Giller, 2001).

Legume-cereal rotations have gained prominence in the Guinea savanna region of West Africa, and increased yields of maize (*Zea mays* L.) succeeding legumes relative to continuous sole maize cropping are well documented (e.g. Oikeh et al., 1998; Sauerborn et al., 2000; Sanginga et al., 2002; Agyare et al., 2006; Franke et al., 2004, 2008a; Yusuf et al., 2009a, b). The increased yields of maize following legumes are partly due to N contributed by the legumes through biological N_2 fixation to improve soil fertility (Giller, 2001; Yusuf et al., 2009a). Non-N benefits, such as reduced pests and diseases incidence, increased soil microbial biomass and activity, and improved soil properties may also contribute to the increased yield of maize in rotation with legumes (Giller, 2001; Yusuf et al., 2009b; Franke et al., 2018).

Soil fertility differs markedly across farmers' fields in the Guinea savanna zone of West Africa and may strongly influence the benefits of legume-maize rotations (Oikeh et al., 1998). For instance, residual biomass production as well as the proportion of N derived from N_2-fixation (%Ndfa) by grain legumes, N_2 fixed, N uptake and net N contribution to the soil differ depending on the fertility of the soil (Kermah et al., 2018). Further, erratic rainfall pattern presents a risk for farmers considering that the Guinea savanna has only one cropping season a year and a bad harvest can seriously threaten food, nutrition and income security (Sauerborn et al., 2000). Legume-maize diversification and intensification systems that maintain the planting density of sole maize (the main crop in northern Ghana) with a grain legume added may provide yield in the event of poor rainfall and failure of the maize (Rusinamhodi et al., 2012). To date, the focus of many studies has been on sole crop legume-maize rotations and distinct alternate arrangement of intercrops. These trials have been conducted mainly on experimental stations (e.g. Sauerborn et al., 2000; Sanginga et al., 2002; Agyare et al., 2006; Yusuf et al., 2009a). In addition, soil fertility status was rarely taken into account in evaluating legume-maize rotations and intercrop systems in the Guinea savanna region of West Africa. Greater productivity of maize and grain legume intercrops when sown within the same row compared with sole crops, or distinct 1 to 1 and 2 to 2 alternate row arrangement of intercrops has been reported in the Guinea savanna of northern Ghana (Kermah et al., 2017), southern Mali (Falconnier et al., 2016) and central Mozambique (Rusinamhodzi et al., 2012).

We therefore studied the agronomic performance of short duration maize and cowpea (*Vigna unguiculata* (L.) Walp) relay cropping patterns sown within the same row. These were compared with continuous maize, soybean (*Glycine max* (L.) Merr.)-maize, groundnut (*Arachis hypogaea* L.)-maize and natural fallow-maize rotations under different soil fertility levels in farmers' fields in the southern and northern Guinea savanna agro-ecological zones of northern Ghana. Our aim was to assess and explore a variety of legume-maize diversification and intensification options that could be offered to smallholder farmers to increase crop productivity.

4.2. Materials and Methods

4.2.1. Study sites

On-farm trials were carried out in the 2013 (Year 1) and 2014 (Year 2) cropping seasons at Kpataribogu (9°58' N, 0°40' W) in the Karaga District (southern Guinea savanna, SGS) and at Bundunia (10°51' N, 1°04' W) in the Kassena-Nankana East Municipal (northern Guinea savanna, NGS). The unimodal rainfall regime at both sites gives rise to a single cropping season that starts with the onset of rainfall from May/June – October in the SGS and June/July – October in the NGS with an erratic distribution pattern. A delay in the onset of rainfall has been observed in recent seasons at both sites. Soils at both sites are generally sandy and poor in fertility. In the Interim Ghana Soil Classification System (Adjei-Gyapong and Asiamah, 2000), the soils are classified as Savanna Ochrosols and Groundwater Laterites.

4.2.2. Experimental design and trial management

Prior to the start of the trials in year 1, three fields each representing highly fertile (HF), medium fertile (MF) and poorly fertile (LF) fields were selected at each site based on farmers' knowledge and support from Agricultural Extension Officers. Past crop performance and/or yield were the main criteria used by the farmers to classify the fields. The fields initially classified as HF and MF fields in the SGS were swopped after soil characteristics became available. Each field was previously under mono-cropped maize, legume or cotton in the three years preceding the start of the trials. Before land preparation in year 1, twelve cores of soil samples were taken at 0-15 cm depth per field, bulked and mixed thoroughly to obtain a composite soil per field. Sub-samples of about 1 kg soil per field were analysed for pH (1:2.5 soil:water suspension), organic C by Walkley and Black wet oxidation method (Nelson and Sommers, 1982), total N by Kjeldahl digestion method (Tel and Hagatey, 1984), available P by Olsen method (Olsen et al., 1954), exchangeable K, Mg, and Ca in 1.0 M ammonium acetate extracts (Nelson and Sommers, 1980) and texture (hydrometer method).

The trial consisted of 10 treatments: four cowpea-maize relay treatments (treatments R1–R4) and two maize–cowpea relay treatments (treatments R5 & R6), a groundnut-maize (GN-MZ), a soybean-maize (SB-MZ) and a natural fallow-maize (FL-MZ) rotations and a continuous sole maize system (MZ-MZ). Details of the treatments are presented in Table 4.1.

Table 4.1. Description of treatments evaluated in the experiment.

Treatment	Year 1 Crop	Variety[a]	Sowing time[c]	Plants /stand	Year 2 Crop	Variety	Sowing time[c]	Plants /stand
CP-MZ relay, 2:1 stands (R1)	Cowpea	Songotra	0	1	Cowpea	Songotra	0	1
	Maize	Dorke SR	3	2	Maize	Dorke SR	2	2
CP-MZ relay, 2:1 stands (R2)	Cowpea	Songotra	0	1	Cowpea	Songotra	0	1
	Maize	Dorke SR	6	2	Maize	Dorke SR	4	2
CP-MZ relay, 1:1 stands (R3)	Cowpea	Songotra	0	1	Cowpea	Songotra	0	1
	Maize	Dorke SR	3	1	Maize	Dorke SR	2	1
CP-MZ relay, 1:1 stands (R4)	Cowpea	Songotra	0	1	Cowpea	Songotra	0	1
	Maize	Dorke SR	6	1	Maize	Dorke SR	4	1
MZ-CP relay, 1:2 stands (R5)	Maize	Dorke SR	0	2	Maize	Dorke SR	0	2
	Cowpea	Bawutawuta	6	1	Cowpea	Songotra	3	1
MZ-CP relay, 1:2 stands (R6)	Maize	Dorke SR	0	2	Maize	Dorke SR	0	2
	Cowpea	Bawutawuta	9	1	Cowpea	Songotra	5	1
GN-MZ rotation	Groundnut	Samnut 22 / Chinese[b]	0	1	Maize	Obatanpa	0	1
SB-MZ rotation	Soybean	Jenguma	0	3	Maize	Obatanpa	0	1
MZ-MZ rotation	Maize	Obatanpa	0	1	Maize	Obatanpa	0	1
FL-MZ rotation	-	-	-	-	Maize	Obatanpa	0	1

CP = cowpea; SB = soybean; GN = groundnut; MZ = maize; FL = fallow.
[a] In relay treatments R1–R4, maize variety Dodzi was used in the NGS.
[b] Samnut 22 used in the SGS and Chinese variety used in the NGS.
[c] Weeks after sowing the first crop.

In relay treatments R1, R2, R5 and R6, maize was spaced at 50 cm within a row with two maize plants per stand and alternated with two equally spaced cowpea stands. In relay treatments R3 and R4, maize was spaced at 25 cm (1 maize plant per stand) and alternated with one cowpea stand within a row. Figure 1 provides a graphical representation of the relay planting arrangements. Intra-row spacing for sole maize was

25 cm. Inter-row spacing was 75 cm for all treatments. Cowpea and maize were sown at a density of 53,333 plants ha^{-1} in all applicable treatments; groundnut and soybean (spaced 10 cm intra-row) had a density of 133,333 and 400,000 plants ha^{-1}, respectively. The trial was set-up in a randomised complete block design replicated four times per fertility level at each site.

Land preparation followed common practices of farmers at each site: ploughing by tractor followed by manual ridging in the SGS and ploughing and ridging by tractor in the NGS. Seeds of all crops were sown on the top of the ridges at both sites. The first crop in each treatment was sown simultaneously on June 30–July 1 in the SGS and July 16–17 in the NGS in year 1 (the onset of rain in the NGS was late), and on July 17 in the SGS and July 15 in the NGS in year 2. In year 1, cowpea harvest coincided with the peak of rainfall which is in August and September, resulting in poor drying of pods and discoloured grains that were largely rejected by farmers. To avoid this, cowpea sowing was done relatively late in the SGS in year 2. The relay crops in R1 to R6 were sown into the first crops at different times specified in Table 4.1. The sowing times of the relay crops were altered in year 2 due to the failure of some relay crops in year 1 partly due to the late sowing of those crops.

In year 1, urea at a rate of 50 kg N ha^{-1} was applied uniformly to each maize treatment in two equal doses at 3 and 6 weeks after sowing (WAS) of maize. In relay plots, urea was applied only to maize plants. In year 2, no N fertiliser was applied to maize in any treatment in order to measure the residual N and non-N effects of the grain legumes on the succeeding maize. TSP at a rate of 25 kg P ha^{-1} (57 kg P_2O_5 ha^{-1}) and muriate of potash at 30 kg K ha^{-1} (36 kg K_2O ha^{-1}) were applied uniformly to all treatments at sowing in both years. All fertilisers were placed at 3 cm depth, 5 cm away from the plants and covered. Weeding was done with a hoe in each treatment at 3 and 6 WAS. A third weeding was done in R1–R6 at 9 WAS the first crop. Seeds of soybean were inoculated with a commercial inoculant, Legumefix (LegumeTechnology, UK) containing *Bradyrhizobium japonicum* strain 532c (re-isolated in Brazil from strain USDA 442 Wisconsin, USA) at a rate of 5 g of inoculant per kg of seeds at sowing. Cowpea in all treatments was sprayed twice with lambda-cyhalothrin (SGS) and cypadem 43.6 EC (36 g cypamethrin and 400 g dimethoate per litre) (NGS) in the form of an emulsifiable concentrate at 0.75-1.00 litre ha^{-1} per insecticide at flowering and podding stages, contingent on pests incidence and pressure {i.e. flower thrips (e.g. *Megalurothrips sjostedti* Tryb.) and pod borers (e.g. *Maruca vitrata* Fab.)} in accordance with farmers' practice.

4.2.3 Rainfall, crop yield, N_2-fixation and N balance measurements

Daily rainfall during the growing season at each site was measured using rain gauges. Above-ground legume biomass was sampled in a 1.0 m x 2.25 m area at mid-pod filling stage and separated into shoots and pods. Total and sub-sample fresh weights of shoots and pods were taken in the field. At maturity, a 2.0 x 2.25 m area was harvested for legume and maize yield determination. Total and sub-sample fresh weights of legume pods, maize cobs and stover of all crops were recorded in the field. Fresh weight to dry weight conversion factors for the different plant parts were used to calculate the dry weights of the sub-samples. These conversion factors were derived from experimental data of trials conducted in the Guinea savanna of northern Ghana and Nigeria and previously reported by Kermah et al. (2017; 2018). Above-ground legume biomass and stover yield of all crops are presented on a dry weight basis, maize grain at 14% and legume grain at 12% moisture contents. N uptake by legumes in year 1 was estimated with N concentration values taken from Nijhof (1987). These were cowpea grain: 2.90%, stover: 1.73%; soybean grain: 6.10%, stover: 1.05% and groundnut grain: 4.50%, stover: 1.40%. Maize N uptake in both years was calculated with maize grain and stover N concentrations measured in year 2.

A selection of non-legume broad-leaved reference weeds were sampled from the fallow plots in each block at the biomass sampling stage of the legumes. The mean $\delta^{15}N$ enrichment of these reference weeds was used for estimating the proportion of N derived from the atmosphere (%Ndfa) by the legumes using the ^{15}N natural abundance method (Unkovich et al., 2008). N_2-fixation was measured for the HF and LF fields only. The separately measured $\delta^{15}N$ of the legume shoots and pods harvested at mid-pod filling were used to calculate the weighted $\delta^{15}N$ for the whole shoots.

$$\text{Weighted } \delta^{15}N \text{ of whole shoot} = \{(\text{shoot N} \times \delta^{15}N \text{ shoot}) + (\text{pod N} \times \delta^{15}N \text{ pod})\}/(\text{shoot N} + \text{pod N}). \quad (1)$$

Shoot N was calculated as: %N shoot/100 × shoot dry matter yield (kg ha^{-1}), while pod N was determined as: %N pod/100 × pod dry matter yield (kg ha^{-1}). %Ndfa was estimated using the weighted $\delta^{15}N$ of the whole shoot following Unkovich et al. (2008) as:

$$\%Ndfa = \{(\delta^{15}N_{ref} - \delta^{15}N_{leg})/(\delta^{15}N_{ref} - B)\}\ 100 \quad (2)$$

where $\delta^{15}N_{ref}$ is the $\delta^{15}N$ natural abundance of shoots of the non-N_2-fixing reference plants (fully dependent on soil N) and $\delta^{15}N_{leg}$ is the $\delta^{15}N$ natural abundance of the N_2-fixing legume. B is the $\delta^{15}N$ of shoots of the test legume fully dependent on N_2-fixation and a measure of isotopic fractionation during N_2-fixation. The smallest weighted $\delta^{15}N$ value for the whole shoot of each legume was used as the B value: – 0.80 (cowpea), – 1.46 (soybean) and – 0.56 (groundnut). The amount of N_2 fixed in the whole plant was estimated using Equation 3 assuming that 30% of the N_2 fixed was present in the roots (Unkovich et al., 2008). The inclusion of N_2-fixed in below-ground dry matter is vital as it has a strong impact on soil N balance estimation (Peoples et al., 2009).

Total N_2-fixed (kg ha^{-1}) = (%Ndfa × whole shoot N)/0.70. (3)

Net N contributed to the soil N economy (kg ha^{-1}) was calculated as: (4)

(i) Cowpea-maize relay = total N_2-fixed + applied N – cowpea grain N – maize grain N
(ii) Sole legume = total N_2-fixed – grain N
(iii) Sole maize = applied N – grain N

4.2.4 Data analysis

GenStat (version 18.1, VSN International Ltd) was used for statistical analysis. Data for relay and crop rotation systems were initially analysed separately and then combined (for maize data) within a site and across sites for comparisons. Data were analysed with a linear mixed model with cropping sequence, soil fertility and site kept fixed (for cross site analysis) and replication as a random factor. When significant differences between means were observed, the standard error of differences between means (SED) was used to compare treatment means at a significant level of $P < 0.05$.

4.3. Results

4.3.1. Soil characteristics and rainfall

Soil organic C, total N, exchangeable K, ECEC and clay content were more favourable for crop growth ($P < 0.05$) in the SGS than in the NGS (Table 4.2). Soil organic C and total N were slightly favourable for crop growth in the HF field than in the LF field while available P and ECEC were slightly better in the LF field in the SGS. In the NGS, soil C, total N, ECEC and clay content were slightly favourable for crop growth in the HF field relative to the LF field.

A total of 598 mm rain in Year 1 and 503 mm in Year 2 were recorded during the growing period in the SGS (4.1a, c); 532 mm in Year 1 and 423 mm in Year 2 were recorded in the NGS (Fig. 4.1b, d). Rainfall was generally well distributed during the growing periods. Relay crops received less rainfall compared with the first crops, with maize in relay R2 & R4 and cowpea in relay R6 (in a descending order) receiving the smallest amount of rainfall in both Years.

Table 4.2. Physical and chemical characteristics of the three different field types used for the trials in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) (from Marinus, 2014). SED represents the standard error of differences between soil fertility levels.

	SGS				NGS			
Soil fertility characteristic	HF	MF	LF	SED*	HF	MF	LF	SED*
pH (H_2O)	5.6	5.7	5.8	0.1	5.2	4.1	5.0	0.5
Organic C (g kg^{-1})	8.2	9.4	6.2	1.3	4.3	3.5	3.9	0.3
Total N (g kg^{-1})	0.8	0.7	0.6	0.1	0.4	0.5	0.3	0.1
Olsen P (mg kg^{-1})	2.2	2.5	3.6	0.6	2.6	4.1	2.7	0.7
Exch. K^+ ($cmol_+$ kg^{-1})	0.2	0.2	0.2	0.01	0.2	0.1	0.2	0.02
Exch. Ca^{2+} ($cmol_+$ kg^{-1})	1.4	1.2	1.5	0.1	1.5	0.7	1.0	0.4
Exch Mg^{2+} ($cmol_+$ kg^{-1})	0.6	0.6	0.8	0.1	0.6	0.2	0.6	0.2
ECEC ($cmol_+$ kg^{-1})	7.3	6.0	7.9	0.8	4.0	4.0	3.1	0.4
Sand (g kg^{-1})	623	603	503	52	823	863	843	16
Silt (g kg^{-1})	281	301	401	52	121	81	121	19
Clay (g kg^{-1})	96	96	96	0.01	56	56	36	9

* Calculated following Saville (2003).

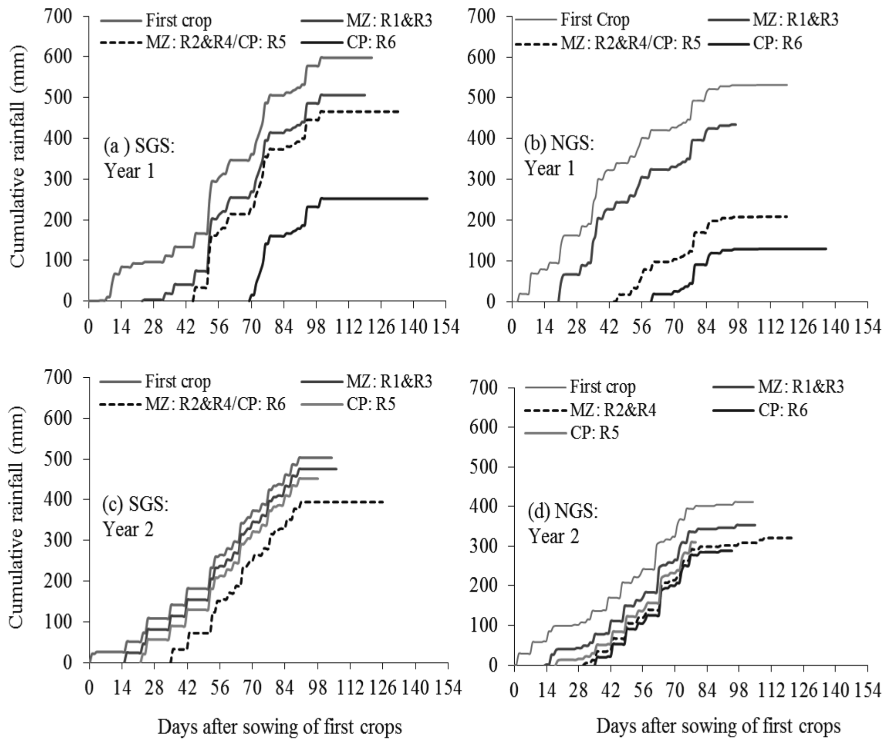

Fig. 4.1. Accumulated rainfall from sowing to harvest time of crops in different cropping sequences in Year 1 and Year 2 in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS). In Year 1, cowpea in R5 and maize in R2 & R4 were sown on the same day. In Year 2, maize in R2 & R4 and cowpea in R6 were sown on the same day in the SGS due to drought at 4 WAS the first crop.

4.3.2. δ^{15}N of reference weeds and legumes, shoot N, %Ndfa and N_2-fixation

The δ^{15}N signatures of the different reference weeds and the legumes did not significantly differ between sites, although the mean values were slightly smaller in the NGS (Fig. 4.2). The reference weeds species had larger δ^{15}N values ($P < 0.001$) than the legumes (Fig. 4.2a, b). Soybean (– 0.9‰) had smaller ($P < 0.001$) δ^{15}N than cowpea (2.3‰) and groundnut (0.7‰) in the SGS (Fig. 4.2a). In the NGS, the δ^{15}N was comparable between soybean (– 0.3‰) and groundnut (0.4‰) but both had smaller ($P < 0.01$) values than cowpea (1.4‰) (Fig. 4.2b). The δ^{15}N signatures of the reference weeds and legumes were strongly influenced by soil fertility with smaller values ($P < 0.001$) observed in the LF fields (Fig. 4.2c, d).

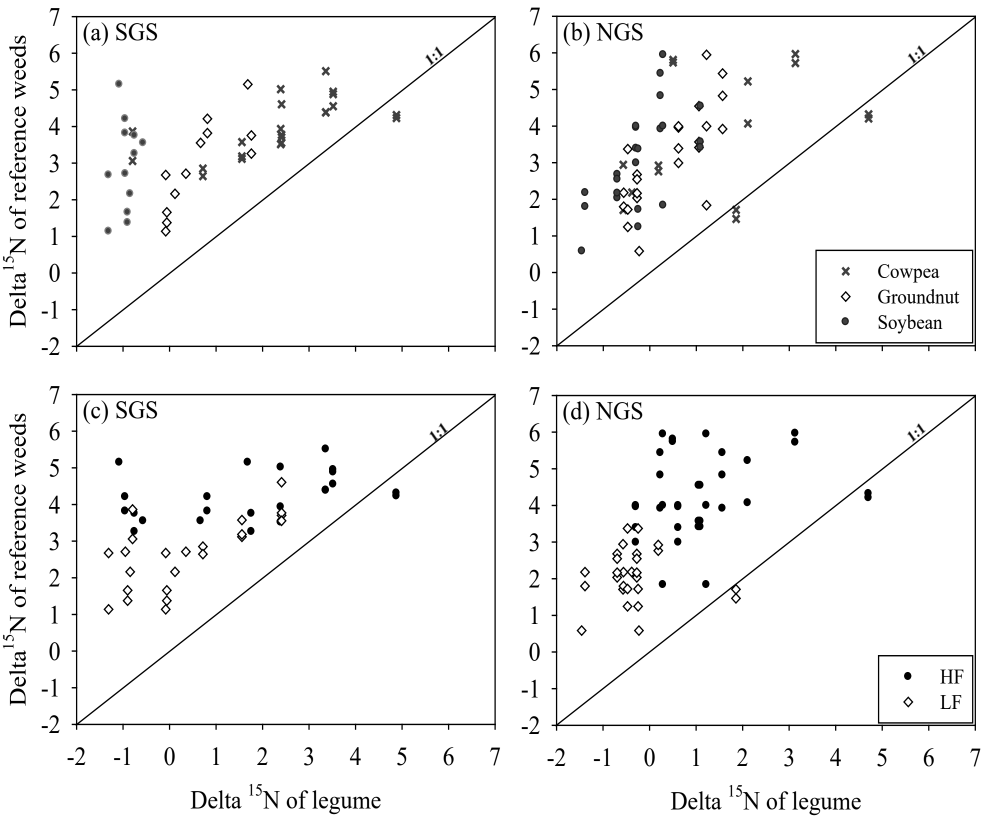

Fig. 4.2. Comparison of δ^{15}N natural abundance (‰) enrichment in grain legumes and in broad-leaved non-N_2-fixing reference plants as affected by grain legume type (a) and (b) and soil fertility status (c) and (d) in the southern Guinea savanna (SGS) and the northern Guinea savanna (NGS).

Above-ground shoot dry matter yields of cowpea and soybean were similar between sites, but groundnut accumulated more shoot dry matter ($P < 0.001$) in the SGS than in the NGS (Table 4.3). Shoot N content followed a similar trend as shoot dry matter yield with only groundnut producing a 17% larger ($P = 0.048$) N yield in the SGS. Shoot dry matter yield of soybean was comparable between the HF and LF fields at both sites whereas cowpea and groundnut produced more shoot dry matter in the HF fields (Table 4.3).

Shoot N content, %Ndfa and the total amount of N_2-fixed by the legumes did not differ between sites (Table 4.3). Soybean consistently had the largest shoot N content, followed by groundnut and cowpea in a descending order. Shoot N content generally declined with decreasing soil fertility status, but the differences were only significant in the SGS (Table 4.3). The %Ndfa was comparable in soybean and groundnut, while the %Ndfa of cowpea was considerably smaller (*P* < 0.001) than that of soybean and groundnut at both sites (Table 4.3). The %Ndfa of legumes grown in the LF fields was greater than in the HF fields (Table 4.3). The amount of N_2 fixed was however comparable between LF and HF fields due to a higher biomass production of legumes in the HF fields.

4.3.3. Legume and maize N uptake and soil N balance in Year 1

Averaged across treatments and soil fertility levels, legume and maize N uptakes in the SGS were 21 kg ha^{-1} and 29 kg ha^{-1} larger than in the NGS (Table 4.3). The N harvest index (NHI) of the different crops did not differ between sites. Grain N uptake and NHI of groundnut were smaller than those of the other crops (Table 4.3). Soil fertility affected grain N uptake (*P* < 0.05, SGS; *P* < 0.01, NGS) with less N exported through grain in the LF than in the HF fields. As a result, NHI was generally smaller in the LF fields, though the difference was significant only in the SGS (*P* < 0.01) (Table 4.3).

Table 4.3. Shoot dry matter yield (DM) at mid-pod filling stage, shoot N, N_2-fixation, N uptake, N harvest index (NHI) and soil N balance of cowpea (CP), soybean (SB), groundnut (GN) and maize (MZ) at different soil fertility levels in Year 1 in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS). SED shows standard error of differences between means.

Site / Fertility level / Treatment	Shoot DM (kg ha^{-1})	Shoot N (kg ha^{-1})	Ndfa %	N_2-fixed/ (kg ha^{-1})	N applied (kg ha^{-1})	Grain N (kg ha^{-1})	Stover N (kg ha^{-1})	NHI (%)	N balance (kg ha^{-1})[a]
SGS									
HF field									
CP + MZ (R2)	1541	47	18	12	50	32+12	15+7	68/63	18
SB - MZ	5305	144	88	183	0	142	35	80	41
GN - MZ	2361	60	61	53	0	19	16	54	34
MZ - MZ				-	50	54	17	76	-4
Mean	*3069*	*84*	*56*	*83*		*64*	*23*	*70*	*22*
LF field									
CP + MZ (R2)	731	23	58	19	50	14+10	12+6	54/63	45
SB - MZ	4676	106	87	131	0	118	26	81	13
GN - MZ	2235	55	76	60	0	14	15	49	46
MZ - MZ				-	50	34	17	67	16
Mean	*2547*	*61*	*74*	*70*		*48*	*19*	*63*	*30*
SED crop	366***	11***	8***	15***		9***	1***	3***	n.s.
SED fertility	n.s.	7*	7**	n.s.		6*	n.s.	2**	n.s.
NGS									
HF field									
CP + MZ (R2)	1768	56	40	30	25	34+0	22+0	61/0	21
SB - MZ	5095	118	67	110	0	137	27	84	-27
GN - MZ	1896	62	64	57	0	22	17	56	35
MZ - MZ					50	24	8	75	26
Mean	*2920*	*79*	*57*	*66*		*54*	*19*	*69*	*14*
LF field									
CP + MZ (R2)	1133	29	60	23	25	19+0	17+0	53/0	29
SB - MZ	4815	135	86	160	0	66	13	84	94[b]
GN - MZ	1173	34	90	43	0	17	13	57	26
MZ - MZ					50	7	5	58	43
Mean	*2374*	*66*	*79*	*75*		*27*	*12*	*63*	*48*
SED crop	322***	11***	n.s.	8***		6***	2***	3***	n.s
SED fertility	n.s.	n.s.	n.s.	n.s.		5**	2*	n.s.	9**
SED site	n.s.	n.s.	n.s.	n.s.		4**	1***	n.s.	n.s.

Shoot DM and shoot N yield of the CP + MZ (R2) are for the CP (cowpea) only.

[a] Soil N balance of cowpea-maize relay (cowpea + maize) in SGS combines the N balances of the cowpea and maize. N balance of cowpea-maize relay in the NGS does not include the N balance of the maize due to failure of maize to produce a grain yield. However, the first N dose of 25 kg ha^{-1} of urea N was applied to the relay maize in the NGS and added to the soil N balance of the cowpea-maize relay system.

[b] Soil N balance of soybean in the poorly fertile field in NGS was possibly an overestimation as destruction by free roaming livestock prior to harvest at maturity led to reduced grain yield and consequently smaller grain N.

* Significant at $P < 0.05$; ** Significant at $P < 0.01$; *** Significant at $P < 0.001$; n.s. = not significant.

The partial soil N balances of legumes were comparable between sites and among the different crops within site (Table 4.3) though there was a large variability within crops (data not shown). On the other hand, partial N balance of maize was 28 kg ha^{-1} greater ($P < 0.001$) in the NGS than in SGS. The cowpea-maize relay system had the smallest partial N balance in the NGS whereas the smallest partial N balance in the SGS was observed in the continuous maize system. The partial soil N balance was larger in the LF fields than in the HF fields at both sites (Table 4.3). Negative partial N balances were observed only in the HF fields (maize in the SGS and soybean in the NGS).

4.3.4. Cropping sequence, maize N uptake and grain yield in Year 2

Cowpea and groundnut grain yields were comparable between sites (Fig. 4.3). However, the mean grain yield of soybean was 0.69 t ha^{-1} and of maize 0.67 t ha^{-1} larger in the SGS than in the NGS (Fig. 4.3). Spatial arrangement of relay intercrops did not influence legume and maize grain yields (Fig. 4.3a, c). However, relaying cowpea into maize at 3 (R5) and 5 (R6) WAS maize led to a reduction in cowpea grain yield of 28 and 47%, equal to 0.18 and 0.26 t ha^{-1}, in the SGS relative to the mean yield of cowpea in treatments R1–R4 where cowpea was sown as the first crop (Fig. 4.3a). In the NGS, a 29 and 42% reduction in cowpea grain yield, equal to 0.18 and 0.24 t ha^{-1}, relative to the mean yield of cowpea in treatments R1–R4 was observed (Fig. 4.3c). Sowing maize into cowpea at 2 (R1 & R3) and 4 (R2 & R4) WAS cowpea resulted in a 14 and 39% (0.29 and 0.64 t ha^{-1}) reduction in maize grain yield relative to mean yield of maize in treatments R5 and R6 in the SGS (Fig. 4.3a). The yield penalty was more severe in the NGS where there was a 58 and 83% reduction (0.66 and 0.82 t ha^{-1}) in maize grain yield sown at 2 and 4 WAS cowpea compared with the mean yield of maize in R5 and R6 (Fig. 4.3c).

Grain yield of maize after natural fallow and in continuous maize did not differ (Fig. 4.3b, d). Maize grain yield increased by 0.89 t ha^{-1} when maize succeeded soybean and by 1.01 t ha^{-1} with groundnut as the preceding crop relative to continuous maize in SGS (Fig. 4.3b). In the NGS, soybean and groundnut increased the grain yield of a subsequent maize by 0.49 and 0.38 t ha^{-1}, respectively (Fig. 4.3d). Cowpea and soybean grain yields were larger in the HF than in the LF fields (Fig. 4.3; $P < 0.05$ in SGS; $P < 0.001$ in NGS). Groundnut grain yield was not affected by soil fertility (Fig. 4.3b, d). Soil fertility had no significant impact on maize grain yield in the SGS (Fig. 4.3a, b), while maize yield declined ($P < 0.001$) with decreasing soil fertility in the NGS (Fig. 4.3c, d).

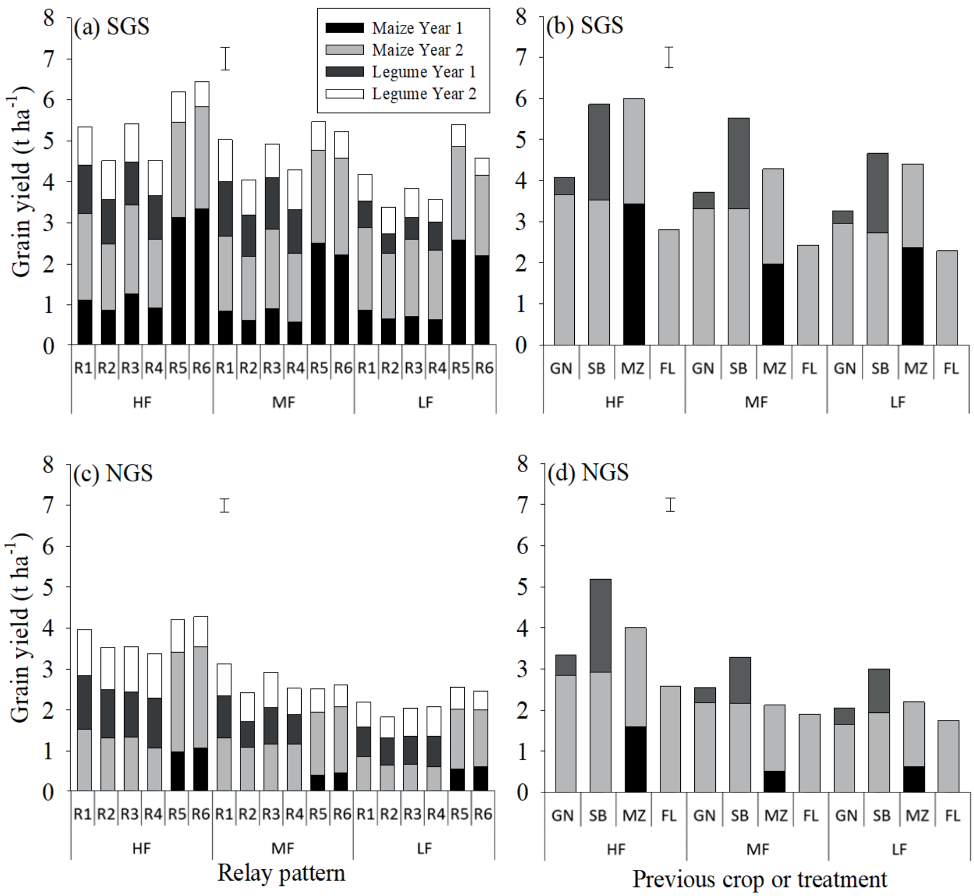

Fig. 4.3. Maize and legume grain yields as influenced by different relay and rotation cropping sequences and soil fertility status in both years in southern Guinea savanna (SGS) and northern Guinea savanna (NGS). Error bars indicate the combined standard error of differences between means for the different cropping patterns across soil fertility status.

N uptake by maize was greater in the SGS than in the NGS (Fig. 4.4). Grain yield of maize had a curvilinear relationship with maize N uptake and the yield seemed to reach a plateau at 80–120 kg ha^{-1} of N uptake, particularly in the SGS (Fig. 4.4a, c). The fitted model explained 87% (SGS) and 88% (NGS) of the variability in maize grain yield. The model suggested a maximum grain yield of 5.0 t ha^{-1} in the SGS and 5.9 t ha^{-1} in the NGS that can be achieved when N is not limiting on farmers' fields (Fig. 4.4a, b). Soybean and groundnut increased ($P < 0.001$) N uptake by subsequent maize compared with continuous maize in the SGS (Fig. 4.4a). In the NGS, only soybean stimulated a 33% larger uptake of N ($P < 0.001$) by the succeeding maize relative to continuous maize (Fig. 4.4b). Mean N uptake by maize following natural fallow was comparable with that of continuous maize at both sites. Relay maize sown at 4 WAS cowpea decreased maize N uptake by 36% in the SGS and 48% in the NGS compared with continuous maize (Fig. 4.4a, b). Crops in HF fields had a greater maize N uptake ($P < 0.05$ in SGS; $P < 0.01$ in NGS) than in LF fields (Fig. 4.4c, d).

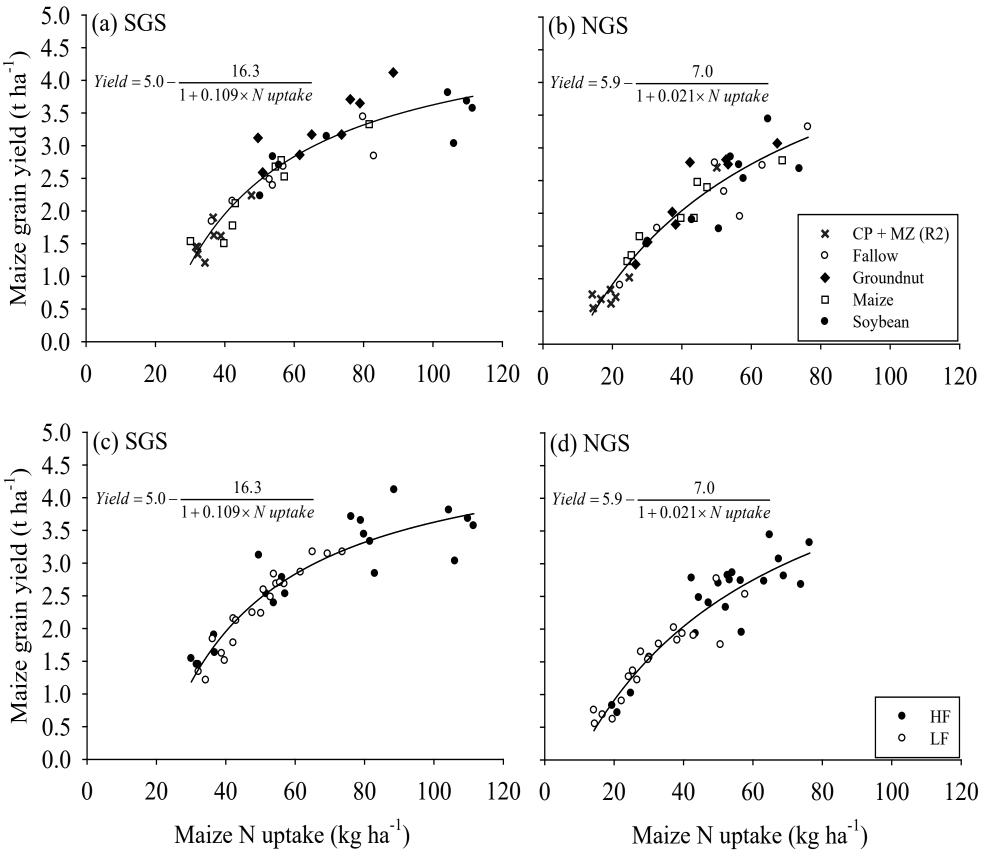

Fig. 4.4. Response of maize grain yield to maize N uptake as influenced by rotation with soybean, groundnut and natural fallow or relay with cowpea or continuous maize in (a) southern Guinea savanna (SGS), (b) northern Guinea savanna (NGS), and under different soil fertility status in the (c) SGS and the (d) NGS of northern Ghana. CP + MZ (R2) refers to the cowpea-maize relay treatment with maize sown 4 WAS cowpea.

4.3.5 Cumulative crop yields

Crops in the SGS provided more stover and grain yield than in the NGS over the two Years (Fig. 4.3, 4.5). The cumulative grain yield was comparable between relay treatments R5–R6 and soybean-maize rotation, while these treatments provided larger grain yields than the other cropping sequences (Fig. 4.3). The crops grown in the HF fields consistently yielded more maize and legume grain in rotation and in relay compared with the MF and LF fields at both sites (Fig. 4.3).

Cumulative stover yield followed a similar pattern as grain yield with more stover in the SGS than the NGS (Fig. 4.5), and declines in stover yield with decreasing soil fertility at both sites (data not shown). Soybean-maize rotation and relay R5–R6 provided larger cumulative stover yields than the other cropping sequences (Fig. 4.5).

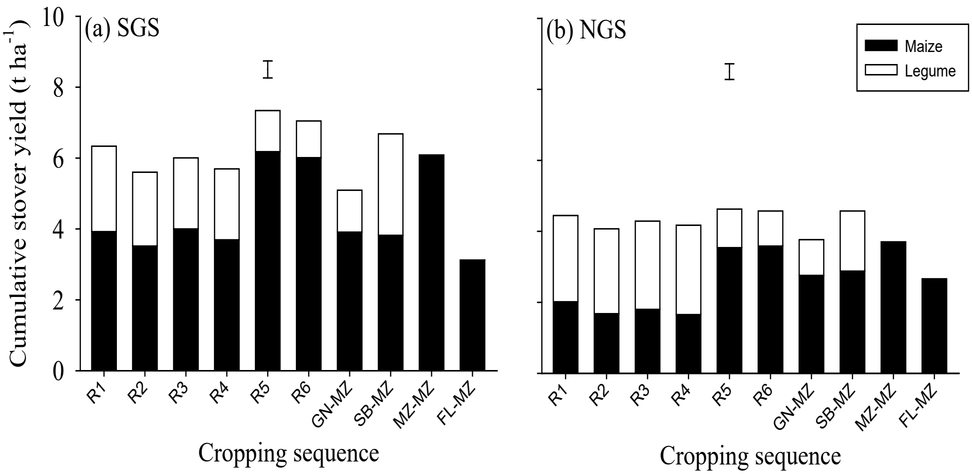

Fig. 4.5. Accumulated maize and legume stover yields over both seasons averaged across soil fertility for the different cropping sequences in southern Guinea savanna (SGS) and northern Guinea savanna (NGS). Error bars indicate the combined standard error of differences between means.

4.4. Discussion

4.4.1. N_2-fixation and net N contribution to the soil for a subsequent maize crop

The reference weed species had greater δ^{15}N values compared with the legumes which is likely to give reliable estimates of %Ndfa by the legumes using natural abundance method (Unkovich et al., 2008). The soil organic C and total N in the HF fields were larger than in the LF fields (Table 4.2) which may be the result of differences in the application of crop residues and mineral fertilisers affecting N turnover. This could account for the larger δ^{15}N enrichment of the reference weeds and the legumes in the HF fields compared with the LF fields (Fig. 4.2c, d; Unkovich et al., 2008).

The observed %Ndfa values (Table 4.3) are in line with findings by others (e.g. Kermah et al., 2017b; Giller, 2001) that poor soil fertility stimulates grain legumes to rely more on atmospheric N_2-fixation for growth. The amount of N_2 fixed by a legume is related to the %Ndfa as well as shoot biomass and N yield (Giller, 2001; Peoples et al., 2009; Kermah et al., 2018). As a result of the large shoot biomass and shoot N yields in the HF fields, the mean amount of N_2 fixed was comparable in the HF and the LF fields at both sites, despite a greater %Ndfa of legumes in LF fields (Table 4.3).

The negative soil N balances of cowpea in HF fields at both sites and of soybean in the HF field in the NGS reflected their %Ndfa being smaller than the NHI (Table 4.3). A maize crop succeeding a grain legume only benefits from a fixed-N effect if the preceding grain legume relies more on atmospheric N_2-fixation than on soil N for its growth (Giller, 2001). Nevertheless, N sparing by a grain legume could also result in enhanced N availability to a succeeding crop or a crop grown in association with a grain legume, despite a negative soil N balance of the grain legume. Although the soil N balance of soybean in the HF field in the NGS was negative, the following maize had a grain yield comparable with that of maize after groundnut that had a positive soil N balance. This suggests that the increased maize grain yield after soybean in the HF field in the NGS was largely due to non-N benefits (e.g. increased soil microbial biomass and functioning, improved soil structure, improved N mineralisation) (Giller, 2001, Sanginga et al., 2002; Yusuf et al., 2009b; Franke et al., 2018). Residual effects of fixed N_2 on maize performance are likely to be more important in LF fields than in HF fields, but the results from the current trial do not provide clear evidence for this.

4.4.2. Performance of relay crops as affected by biophysical properties

The favourable soil fertility properties of fields in the SGS compared with the NGS, and in HF fields compared with LF fields resulted in a greater productivity of crops (Table 4.2; Fig. 4.3, 4.5). The LF field in the SGS was marked by poor drainage that may have led to denitrification, reduced nutrient availability and uptake by the crops. Maize in the MF field in the SGS was affected by *Striga hermonthica* which affected grain yield particularly in Year 1 (Fig. 4.3a, b). The MF field in the NGS was also characterised by poor drainage which may have restricted nutrient availability and uptake by the crops. Soil organic C, total N and available P appeared to be sub-optimal for crop growth in all fields (Fairhurst, 2012). However, the deficiencies of total soil N and available P were most probably corrected by P application in both Years, N application in Year 1 and residual N benefits in Year 2 (Table 4.3).

The present results show that the time of relay sowing of maize and cowpea had an overriding influence on grain yield, as grain yield declined consistently with a delay in sowing of the relay crops regardless of the within-row spatial arrangement of the crops (Fig. 4.3a, c). This overriding effect, in the case of maize could mainly be due to the decreasing amount of rainfall received by the relay crops for growth (Fig. 4.1; Table 4.1). In the case of the cowpea relayed into maize, shading of the cowpea by maize likely contributed to the observed cowpea grain yield reduction particularly in the SGS where the maize produced larger biomass evidenced by the greater maize stover yield (Fig. 4.5a). In this case, the first maize crop could be sown early in the season (with early onset of rainfall) and the relay cowpea sown when the maize leaves begin to senesce. This could reduce the shading of the relay cowpea by the maize which could improve the productivity of the cowpea and the overall relay system. Also, the cowpea in R1–R4 can be sown early in the season so that the relay maize could receive enough rainfall during the growing season to mature, which could improve the yield and the productivity of that relay system. In such instances, the relay cowpea could be harvested early in the season to provide food for the farm households while awaiting the main harvests later in the season.

However, early sowing of cowpea could result in flowering, pod setting and maturation coinciding with the peak of rainfall in August leading to high diseases and pests pressure reducing the yield in addition to poor drying of pods. The ideal sowing times of the relay crops is also likely to vary from season to season and between sites in the Guinea savanna depending on the onset of the rainy season. This could affect the relative productivity of the different cropping sequences, particularly the relay cropping patterns. Therefore, a modelling work based on our results is needed to explore and possibly identify ideal sowing times and associated risks for the different sites in the Guinea savanna.

The failure of the relay maize sown at 3 and 6 WAS cowpea in the NGS in Year 1 was mainly due to the poor quality of the seeds used for sowing compounded by insufficient rainfall. Insufficient rainfall largely accounted for the failure of the relay cowpea sown at 6 and 9 WAS the maize in Year 1 in the NGS as only 209 mm (R5) and 130 mm (R6) rainfall were received (Fig. 4.1b). In the SGS, the relay cowpea failed in Year 1 due to severe infestation by bacteria blight disease (*Xanthomonas axonopodis* pv. *vignicola* (*Xav*). The infestation presumably resulted from infected seeds and secondly infections after germination proliferated due to the consistent rainfall during the early stages of growth (Fig. 4.1a; de Lima-Primo et al., 2015). These show the difficulty in identifying the optimal sowing time for cowpea in the Guinea savanna as the crop could be affected by too little or too much rain which can possibly lead to crop failure. The broad range of causes of crop failure also highlights the usefulness of crop diversification in smallholder farming systems in the Guinea savanna.

4.4.3. Effect of cropping sequence on crop productivity

The apparent plateauing of maize grain yield at 80–120 kg ha^{-1} of N uptake in the SGS (Fig. 4.4a, c) suggest that increased supply of N beyond that rate may not lead to appreciable maize grain yield increases. Marginal increases and subsequent plateauing of maize grain yield after N input of 30–40 kg ha^{-1} on a highly infertile soil have been reported in the Guinea savanna of Nigeria (Franke et al., 2004) and in East Africa (Ndungu-Magiroi et al., 2017). Groundnut and soybean induced 9–13 kg ha^{-1} more N uptake in the subsequent maize relative to continuous maize in the SGS (Table 4.3), indicating that N seemed to be less limiting for maize yield in the groundnut/soybean-maize rotation than in the continuous maize system.

Comparable yield of maize following a natural fallow and a continuous maize rotation has previously been reported in the Guinea savanna of Nigeria (Franke et al., 2008a; Yusuf et al., 2009a, b). This implies that a one-year fallow period in the Guinea savanna is not suitable for soil fertility regeneration to increase and sustain crop yields. This is presumably because a one-year fallow is too short to restore soil fertility when the growing season is short (Franke et al., 2008; Yusuf et al., 2009b). Maize grain yield did not differ significantly between maize succeeding soybean or groundnut, suggesting that the choice of a grain legume species as a preceding crop was not an important factor in this study, as also observed by Sauerborn et al. (2000) in the Guinea savanna of northern Ghana. The better maize grain yield in Year 2 compared with Year 1 in the NGS (Fig. 4.3c, d) was largely the outcome of better quality seeds used for sowing in Year 2. The decline in grain yield of continuous maize in Year 2 relative to Year 1 in the SGS could be attributed to negative (HF field) or smaller (LF field) soil N balance in Year 1 (Table 4.3).

The superior maize grain yield induced by soybean and groundnut as preceding crops compared with continuous maize and the other cropping sequences (Fig. 4.3b, d) stresses why legume-maize rotation predominates smallholder farming systems in the Guinea savanna. However, despite the relay cowpea in R5 and R6 failing to produce yield in Year 1, the R5 and R6 relay treatments accumulated similar yield as soybean-maize rotation over both Years and was superior to the other rotation systems (Fig. 4.3, 4.5). The poor yield of groundnut (Fig. 4.3b & d, 4.5) was due to the late sowing of groundnut as a result of late onset of rainfall. This led to a smaller productivity of the groundnut-maize rotation relative to the soybean-maize rotation and the R5 and R6 relay systems. The present results indicate that sowing maize first and relaying cowpea into it (R5 & R6) represents an alternative to the legume-maize rotations for smallholder farmers in the Guinea savanna. Nonetheless, the soybean-maize rotation provided more legume grain than the relay systems (Fig. 4.3) which is vital for household nutrition and income as legume grain has higher nutritional and economic values than that of maize.

4.5. Conclusions

Low soil fertility stimulates grain legumes to rely more on atmospheric N2-fixation than on soil N for growth resulting in larger partial soil N balances of grain legumes grown in the LF fields. A rotation of soybean or groundnut with maize is superior in increasing subsequent maize yield than natural fallow rotation and relay cropping of maize and cowpea. Relaying cowpea into maize is more productive than relaying maize into cowpea. The productivity of relay cropping where maize is sown first and cowpea planted much later seems a promising ecological intensification option alternative to the dominant legume–maize rotation in the Guinea savanna. Relaying cowpea into maize is thus recommended in the Guinea savanna when the growing season is short due to late onset of rainfall as was observed during this study.

Acknowledgements

The first author was funded through the Netherlands Fellowship Programme (NFP) of the Netherlands Organization for International Co-operation in Higher Education (NUFFIC). We are grateful for additional support for the field work provided by the Bill & Melinda Gates Foundation through the N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa project to Wageningen University. We thank the CSIR-Savanna Agricultural Research Institute, Tamale for the use of its facilities to conduct this work, and Wytze Marinus and Susana Kwofie for their active support in preparing and conducting the field trials.

Chapter 5

Sustainable crop intensification and diversification to increase household food self-sufficiency in the Guinea savanna of Ghana

To be submitted in modified version as:

Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., Sustainable crop intensification and diversification to increase household food self-sufficiency in the Guinea savanna of Ghana.

Abstract

The Guinea savanna area of Ghana is characterised by high food insecurity among the dominant smallholder farm households due to poor crop yields. This, coupled with unpredictable climate and rapid population growth, necessitates sustainable intensification and diversification with grain legumes to improve soil fertility, grain yield and food self-sufficiency. However, insights are required on the diversity of resources availability and allocation in contrasting regions and the impact of intensification and diversification on food self-sufficiency, which was the focus of this study. The baseline data of N2Africa Ghana project from surveys conducted in 2010 in seven districts spanning 29 villages and 400 farm households was used: 151 in Northern (NR), 120 in Upper East (UER) and 129 in Upper West (UWR) regions. Data on soil fertility, rainfall and population were from secondary sources. Maize, cowpea, groundnut and soybean were targeted for intensification and diversification in three Scenarios: I – intensification of grain legumes alone with 30 kg P ha^{-1}; II – intensification and diversification through additive intercropping of maize with each grain legume, 50 kg N, 30 kg P and K ha^{-1} for maize and only P and K for legumes; III – intensification of both maize and grain legumes to achieve 80% of maximum yield of each crop in the baseline. Food self-sufficiency was estimated as the ratio of total annual energy produced by farm household to the total annual energy requirement of the household. The results show that 56% of households in NR and just 45% in UER and UWR were food self-sufficient in the baseline, with one-third surviving on own food for half a year or less. Combined for all three regions, intensification and diversification increased the share of food self-sufficient households by 25, 36 and 43% in Scenarios I, II and III, respectively relative to the baseline. The households with only 6 months or less of food-sufficiency decreased to 7% in UWR and 15% in UER but just 3% in NR due to comparative advantage in soil fertility, rainfall and 1.2 ha more land cultivated. These indicate that sustainable intensification with grain legumes is a promising pathway to achieve food self-sufficiency though improved access to market and credit are vital to acquire the needed inputs. Further, in densely populated areas with limited land access, off-farm income will be needed to procure additional food.

Key words: Farming systems; regions; resources diversity; intensification scenarios; smallholder farms

5.1. Introduction

Despite the steady increase in food security in Ghana as a whole (WFP, 2009), food and nutrition security remains a critical concern among households in northern Ghana (de Jager et al., 2017; 2019; WFP, 2009; 2013). The Comprehensive Food Security and Vulnerability Analysis (CFSVA) by the World Food Programme, WFP (2009) revealed 453,000 people, representing 60% of the rural population in northern Ghana to be food insecure. The WFP (2013) analysis identified over 680,000 people in northern Ghana as food insecure (NR – 10%, UER – 28%, UWR – 16%). The numbers of food insecure people are likely to increase considering the population growth rate of 1.2 – 2.9 % in northern Ghana (GSS, 2013). Such rapid growing population in northern Ghana, and in general in West Africa (United Nations, 2017) means increased demand for food, increased pressure on arable land and necessitates sustainable intensification of crop production (Vanlauwe et al., 2014).

In rural sub-Saharan Africa, the households' own food production is critical to food security as food purchases contribute only about a quarter (12 – 27%) to food security (Frelat et al., 2016). This indicates the need for increased food production by smallholder farm households in order to be food self-sufficient. The uncertainties and variability in biophysical and socio-economic resources among smallholder farms impact on decision making and give rise to complexity and diversity of farming systems at temporal and spatial scales (Tittonell et al., 2009; 2010; Giller, 2013; Whitfield et al., 2015). Consequently, blanket recommendations to improve crop productivity cannot work for all farm systems within a large geographical landscape like the Guinea savanna of Ghana (Giller et al., 2011). Likewise, it is neither possible nor desirable to make specific recommendations for individual farms or fields to improve productivity. What is essential is a basket of sustainable intensification and diversification options from which farmers can choose that could increase crop production and contribute to meeting the food demand of the rising population.

Grain legumes are important for sustainable intensification and diversification to increase crop production as they contribute to soil fertility and household food and nutrition security (Giller, 2001; Kerr et al., 2007; de Jager et al., 2019). It is vital to have a greater insight into how grain legumes are integrated in the farming systems. This is necessary for the design of legume-based sustainable intensification and diversification options that could be compatible with the biophysical and socio-economic resources of smallholder farms in contrasting sites in the Guinea savanna. For this purpose, knowledge of the pattern of resources availability, diversity and allocation as well as production objectives of smallholder farms is required (Weber et al., 1996; Frelat et al., 2016) but generally lacking in the Guinea savanna of Ghana. Given that these may be variable across sites, a better understanding of such diversity in contrasting sites in the Guinea savanna of Ghana and the impact on food self-sufficiency is needed. Hence this study focused on providing:

i) enhanced understanding of the diversity and pattern of resources availability and allocation to major crops and the influence on food self-sufficiency;
ii) insights on the impact of intensification and diversification with grain legume production on household food self-sufficiency.

5.2. Materials and methods

5.2.1. Study locations and data sources

The study was conducted in the Northern region (NR), Upper West region (UWR) and Upper East region (UER) in northern Ghana. A total of 400 farm households were surveyed during the cropping season of 2010, with 151 in the NR, 129 in the UWR and 120 in the UER. The study involved seven districts (Chereponi, Savelugu, Tonlon in NR; Nadowli, Wa East in UWR; Kassena-Nankana East, Bawku West in UER). Twenty-nine villages were selected from these districts, 13 from NR and eight each from UWR and UER. Purposive sampling was used to select the districts based on the importance or potential of grain legume in the farming systems, the consumption of legume grain in households and access to markets for sale of produce and purchase of required inputs (Franke and de Wolf, 2011). Households were then selected though random sampling in the field (Franke and de Wolf, 2011).

The sites in the NR and UWR are located in the southern Guinea savanna (SGS) agro-ecological zone, while those in the UER are within the northern Guinea savanna (NGS). The mono-modal rainfall regime permits a single cropping season in a year in each region. The season starts early (May-June) in the NR and UWR in the SGS, lasting approximately 150 – 200 days and late in the UER in the NGS (June-July) for about 150 – 160 days. Soils in all locations are classified mainly as Savanna Ochrosols and Groundwater Laterites formed over granite and Voltain shales (Adjei–Gyapong and Asiamah, 2002).

Data collection was done with a farm characterisation protocol developed for the N2Africa project (Putting nitrogen fixation to work for smallholder farmers in Africa; https://www.n2africa.org) with methodologies from the AfricaNUANCES (Nutrient Use in Animal and Cropping systems – Efficiencies and Scales) project (Franke and de Wolf, 2011). The data obtained and used in this study formed the baseline data for the N2Africa Ghana project. Main themes contained in the questionnaire related to:

Biophysical characteristics

Arable landholding, number of fields and field sizes (measurement of field size was based on farmers' estimation), management strategies, main crops grown and cropping pattern; total grain production, livestock ownership (type and number owned), fertiliser and agrochemical usage. Grain production data were based on farmers' estimates in bags or other local units and converted to kg grain produced per household using standard conversion factors. For each household, grain yield per hectare for each crop was calculated as the total grain produced (in kg) divided by the total land area (in ha) used in producing it. For soil fertility analysis, one soil sample each was taken from 57 fields in 8 locations (villages) in NR, 52 fields from 7 locations in UER and 9 fields from 6 locations in the UWR. The soil samples did not form part of the N2Africa baseline data as they were taken during agronomic trials of the N2Africa project after the baseline survey was conducted.

Socio-economic characteristics

Ownership of farm tools (e.g. donkey-cart, tractor, tri-cycle, etc), household composition, labour use, income generating activities (categorised into main sources of income) and markets.

During data collection, the area of crops intercropped was not recorded separately for each of the component crops. No information on the specific planting configuration, seeding rates and relative plant densities of the component crops in the mixture was recorded. In such cases, Kelly et al. (1996), Fermont and Benson (2011) and GSARS (2017) suggested the use of a ratio to share the area among the component crops. When many crops are involved in the mixture, Kelly et al. (1996) proposed that the area is shared among the main crop and at least two other important crops to ensure that at least 90% of the total intercropped area and production value is captured.

In northern Ghana, cereals, particularly maize, are the dominant crops and occupy a large part of the area when intercropped with legume. However, there are circumstances where a grain legume (e.g. groundnut, soybean, cowpea) is sown as the main crop and occupies a larger area than a cereal. With cereal-cereal intercropping, maize is the main crop and occupy larger area. Based on the above discussion the following attribution patterns were used to apportion intercropped area among the component crops:

i) 60% of the area was allocated to a cereal (either maize, millet or sorghum) when intercropped with one of the main grain legumes (cowpea, groundnut or soybean), but 80% to the cereal if a less important legume (e.g. Bambara nut) was involved. If more than one legume was involved, the remaining 40% area was shared equally among them. If one of the two legumes was less important, that was allocated 10% of the remaining area and 30% to the main grain legume.

ii) If an important grain legume was indicated as the main crop, the area allocation as in (i) above was reversed. In this case, the main legume was allocated 60% of the area and the remaining 40% shared equally among the other components (whether legume or cereal).

iii) If only two cereals were intercropped, the area was shared equally among them in the case that maize was not the main crop. If maize was recorded as main crop, then 60% of the area was allocated to the maize.

iv) If only two of the three most important grain legumes were intercropped (cowpea, soybean, groundnut), each was allocated 50% of the area. But if one of them was a less important legume (e.g. Bambara nut, etc), that was reduced to 20% of the area.

5.2.2. Household food self-sufficiency assessment

The energy contents of the major grain legumes and cereals used in estimating total energy production of households were taken from a standard nutrient profile data developed by the United States Department of Agriculture (https://fdc.nal.usda.gov/index.html). Per capita daily energy requirement of 2,500 kcal for an active adult (following Hengsdijk et al., 2014; Frelat et al., 2016) was used in estimating a household's total energy need. Children 16 years and below and elderly persons 60 years and above were assumed to consume half the energy requirement of adults.

Food self-sufficiency was calculated as the ratio of the total energy produced by a farm household to the total energy requirement of the household over a period of 12 months (daily adult equivalent energy requirement of all members of a household multiplied by 365 days). This excluded the amount of food households may have purchased with on-farm or off-farm income (Waha et al., 2018). A ratio of 1.0 indicates that the household is food self-sufficient, below 1.0 the household is food deficient while 0.5 and below means the household is unable to meet half of its annual food requirement. Food self-sufficiency was calculated separately for grain legumes and cereals to show their relative contributions under the different scenarios, and then added to obtain the total food self-sufficiency ratio. Production and consumption of livestock products were not taken into account when calculating household food availability and self-sufficiency. Livestock products are not consumed daily or regularly in farm households in all regions. Sale of livestock forms only a small portion of the annual household incomes (Franke and de Wolf, 2011) as this is done occasionally to cover certain pressing financial needs such as school fees, funerals or consumed during festive periods.

5.2.3. Crop diversification and intensification scenarios

A base scenario and two others were tested. The baseline scenario conforms to the current farm practices and outcomes (grain yields and total food production) of farm households and differs between regions. The other scenarios were set similarly for all regions to provide an insight on the relative role of grain legume in the farming systems and contribution to food self-sufficiency. Cowpea, groundnut and soybean were the grain legumes considered in the scenarios as all the other grain legumes combined, formed less than 5% of the total cropped area across all regions. The choice of maize, millet and sorghum was based on the principle of these being the most important cereals (in terms of area and food production) grown in each region. Details of the scenarios are provided below.

Baseline scenario: current cropping practices

No fertiliser (mineral or organic) or inoculant applied to grain legume in all regions, current crop management practices of farmers land allocation pattern as shown in Fig. 5.1 are maintained. Food self-sufficiency calculation is based on present grain yield and total grain production of cereals and legumes by households in each region. The mean grain yields of the different crops are presented in Table 5.1. The minimum grain yield of 0 kg ha^{-1} observed in the baseline indicates crop failure in a sole crop system. A maize-grain legume intercropping helps in mitigating the risk of crop failure, such that if one crop fails to produce yield the other could provide food for the farm household (Rusinamhodzi et al., 2012; Kermah et al., 2019).

Scenario I: intensification of grain legume production through P and inoculant application

Current land area allocated to cereals and grain legumes, cropping practices and grain yield of cereals as in the baseline are retained in each region. Grain legume production is intensified with application of 30 kg P ha^{-1} to cowpea, groundnut and soybean (soybean seeds inoculated with 7 g of inoculant per kg seed) in sole cropping systems (Adjei-Nsiah et al., 2018). An overview of the increase in grain yield assumed in the scenario is shown in Table 5.1.

Scenario II: intensification and diversification through additive intercropping

The area cultivated to each crop, present cropping practices and grain yield of millet and sorghum remain the same as in the baseline and Scenarios I and II. Maize is selected for intercropping with cowpea, groundnut and soybean over millet and sorghum since it is the major food security crop and occupies a larger portion of the total cropped land in each region. The choice of an additive design in this Scenario is to maintain the area of land allocated to maize as farm households may be reluctant to sacrifice the maize area for grain legumes. Nitrogen is applied at 50 kg ha^{-1} to maize while 30 kg ha^{-1} each of P and K is applied to both maize and each grain legume (soybean inoculated with 7 g inoculant per kg seed).

Intercrop grain yields of maize, cowpea, groundnut and soybean each sown at half the recommended density as reported by Kermah et al. (2017) who conducted a maize-grain legume intercropping study on farmers' fields in northern Ghana are used in this Scenario. However, with the additive intercropping method used in this Scenario, it is assumed that maize and each grain legume is sown at 100% its recommended sole crop density (cf. Rusinamhodzi et al., 2012). Hence, the intercrop grain yield of each crop from Kermah et al. (2017) is multiplied by two (2) to get an assumed grain yield at 100% density for each crop. However, to account for the yield penalty for the grain legumes due to the increased competition and possible shading by maize in this additive design, additional yield reductions ranging from 28% for cowpea, 29% for groundnut to 46% for soybean are assumed (Kermah et al., 2017). It was also assumed that the maize may not suffer further yield penalty as it the dominant crop. The study of Kermah et al. (2017) did not cover the Upper West region. Therefore, the assumed grain yields in the Upper East region are used in the Upper West since both regions have similar baseline yields for the different crops. Table 5.1 shows the yield increases.

Scenario III: intensification of grain legume and cereal production to achieve 80% of the maximum grain yield observed in the baseline

Allocation of land area to both cereals and grain legumes, and yields of millet and sorghum in the baseline is maintained in each region. Grain yield increases of maize, cowpea, groundnut and soybean are assumed to reach 80% of the maximum yield achieved per ha for each crop in the baseline as shown in Table 5.1. This is assumed to happen through:

- increased use of inputs (e.g. recommended 90 kg N ha^{-1} for maize, at least 30 kg ha^{-1} each of P and K for both legumes and maize, and soybean seeds inoculated with at least 7 g of inoculant per kg seed)
- efficient crop management practices (e.g. recommended plant density, sowing and weeding times; timely and efficient fertiliser application methods such as split doses and in furrows covered after application; use of improved varieties and seeds)
- rotation of maize with grain legumes in sole cropping systems for maize to benefit from residual N and non-N effects of rotating legumes and cereals.

Table 5.1. Grain yield (kg ha^{-1}) as affected by intensification and diversification with grain legume in the different Scenarios in Northern, Upper East and Upper West regions of Ghana.

	Baseline					Scenario I	Scenario II	Scenario III
Region	Mean	Range Min	Range Max	Median	s.e.m.	Mean	Mean	Mean
Northern region								
Maize	1215	6	5733	860	86	1215	4019	4586
Millet	801	129	1733	700	265	801	801	801
Sorghum	485	54	1740	400	70	485	485	485
Cowpea	375	29	1661	240	39	1496	1085	1329
Groundnut	564	5	2323	465	39	2504	1032	1858
Soybean	713	10	1920	593	62	1748	1724	1536
Upper East region								
Maize	841	0	2866	750	86	842	2091	2293
Millet	393	0	1040	297	41	393	393	393
Sorghum	621	75	2080	506	96	621	621	621
Cowpea	529	0	2880	328	94	1203	1335	2304
Groundnut	636	0	2667	457	64	880	1051	2134
Soybean	628	0	2165	392	117	1696	1213	1732
Upper West region								
Maize	525	1	3332	383	70	525	2091	2666
Millet	381	4	1522	259	45	381	381	381
Sorghum	400	1	1769	301	80	400	400	400
Cowpea	361	0	2400	254	43	1018	1335	1920
Groundnut	619	0	3375	445	55	1469	1051	2700
Soybean	612	0	2600	474	70	762	1213	2080

5.2.4. Data analysis

The data were analysed with GenStat (version 19.1, VSN International Ltd). Data for each region were analysed separately with farm household and crop type as factors. Thereafter, the data for all three regions were combined and analysed with the linear mixed model structure with region as a fixed factor.

5.3. Results

5.3.1. Resources availability and allocation pattern

The Upper East region (UER) has a high population density, over 2-fold that of the Northern region (NR) and Upper West region (UWR) (Table 5.2) and 15% greater than the national average (103 persons km^{-2}). However, the fragmented family and/or dwelling units led to smaller household sizes compared with the other two regions. A similar proportion of households in each region was engaged in agriculture. The NR has more rainfall and more rainy days during the cropping season than the UER and UWR (Table 5.2). Soils seem to be more fertile in the NR (e.g. organic carbon, total N and K) compared with the UER and UWR. Soil pH, exchangeable K, Ca and Mg data are within the range favourable for crop growth in all regions with reference to the critical soil fertility values for sub-Saharan Africa (Fairhurst, 2012). By contrast, organic carbon, N and available P could be limiting for crop growth as respective levels are below the critical values.

Farm households in NR cultivate more land than their counterparts in the other two regions (Table 5.2). Specifically, the area cropped per household in the NR was on average 1.3 ha (37%) and 1.1 ha (30%) more with respect to land cultivated by households in the UWR and UER, respectively. The area cultivated to a grain legume per farm generally tend to be smaller than that allocated to a cereal. For instance, the mean area per farm for cowpea, groundnut and soybean was 0.1 ha, 0.3 ha and 0.7 ha smaller than the mean of maize, millet and sorghum in NR, UWR and UER, respectively.

Table 5.2. Selected features that characterise the differences in farms in Northern (NR), Upper East (UER) and Upper West (UWR) regions of Ghana.

Farm characteristic	NR	UER	UWR
House characteristics (source: GSS, 2013)			
Household size *(from survey data)*	10.3	6.5	7.7
Population growth rate	2.9%	1.2%	1.9%
Population density (persons/km^2)	35.2	118.4	38.2
Households engaged in agriculture (%)	76	77	84
Rainfall (mm) (source: Ghana Meteorological Agency)			
Annual mean (1961 – 2014)	1,153	977	1,013
Seasonal mean (1990 – 2011)	1,020	867	827
Seasonal rainy days (1990 – 2011)	85	66	69
Soil fertility (source: survey data)			
pH	6.0 (0.5)	5.7 (0.5)	6.1 (0.3)
OC (g kg^{-1})	8.3 (2.0)	5.6 (1.5)	6.4 (2.5)
Total N (g kg^{-1})	0.8 (0.2)	0.5 (0.2)	0.5 (0.2)
P (mg kg^{-1})	4.2 (1.8)	7.3 (4.5)	6.3 (5.9)
K (cmol$_+$ kg^{-1})	0.4 (0.1)	0.3 (0.1)	0.1 (0.0)
Ca (cmol$_+$ kg^{-1})	1.8 (1.1)	1.3 (0.7)	2.0 (0.7)
Mg (cmol$_+$ kg^{-1})	0.8 (0.3)	0.5 (0.2)	0.8 (0.3)
Cropped area (source: survey data)			
Mean area cropped (ha farm^{-1})	4.8	3.7	3.5
Mean area (ha crop^{-1} farm^{-1})			
Maize	1.4	1.4	0.9
Millet	0.8	0.9	1.0
Sorghum	0.8	1.6	1.0
Groundnut	1.2	0.8	0.8
Cowpea	0.6	0.4	0.6
Soybean	0.9	0.7	0.6
Rice	1.5	0.5	0.6
Roots & tubers	0.5	0.0	0.5
Other crops	0.5	0.4	0.5
Total	**0.9**	**0.7**	**0.7**

Note: The data in brackets for soil fertility parameters represent the standard deviation

Farm households in the three regions allocate the available lands differently among the main crops (Fig. 5.1). The total land cropped to cereals (maize, millet, sorghum) and grain legumes (cowpea, groundnut, soybean) was similar within NR and UWR (Fig. 5.1a, c). In the UER, the land cultivated to cereals was twice the total land used for grain legume production. Combined for all regions, the proportion of total land allocated to each crop point to maize, groundnut, millet, rice, sorghum, soybean and cowpea in a descending order as the main crops grown in the Guinea savanna of Ghana (Fig. 5.1).

Maize dominates the farming system, occupying 24% of the cultivated farmland across all regions. The dominance of maize differs among the regions. For example, the total land cropped to the three main grain legumes in NR and UER was nearly the same as that occupied by maize alone (Fig. 5.1a, b). By contrast, the total land area cultivated to the main grain legumes in UWR was 22% greater than that of maize alone (Fig. 5.1c). Roots and tubers and other crops (Bambara nut, cotton, vegetables, etc) together were grown on less than 10% of the cultivated land. The marked disparity in household composition, climate, soil fertility and land area cropped highlight the diverse opportunities and constraints to intensification and diversification of crop production among farms across the different regions.

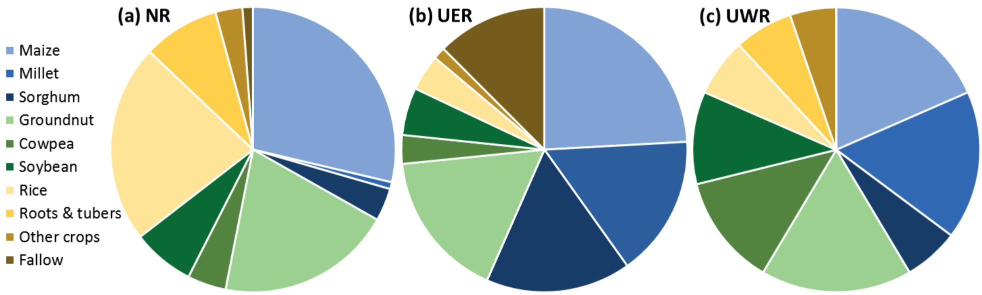

Fig. 5.1. Allocation of arable land to the different crops in (a) Northern (NR), (b) Upper East (UER) and (c) Upper West (UWR) regions of Ghana. The data show the proportion (%) of total cropped land (all households) allocated to each crop.

Organic fertilisers provided only a small proportion of the nutrients applied, except in the UER where they accounted for about 40% of the total fertiliser applied (Fig. 5.2). The allocation of fertilisers to crops followed similar pattern as land allocation with 94 – 99% of available fertiliser applied to cereals in all three regions. Maize alone received 70 – 90% of the applied fertiliser with the combined allocation to grain legumes being negligible.

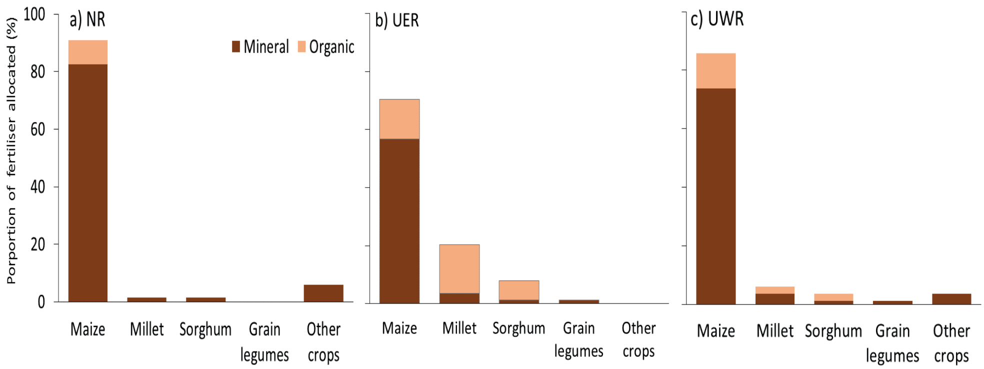

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Fig. 5.2. Allocation of fertiliser to the main crops grown in (a) Northern (NR), (b) Upper East (UER) and (c) Upper West (UWR) regions of Ghana. The data represent the proportion (%) of the total number of fertiliser (both mineral – NPK, urea, sulphate of ammonia; and organic – cattle manure, farmyard manure, compost) applied by all households irrespective of the application rate.

In all regions, farm households earned their largest share of income from either on-farm alone or farm related activities (Fig. 5.3), though variation exists in the relative proportions between regions. In NR, nearly 60% of farm households earned income from on-farm activities alone which largely involved selling of crop produce. Additionally, less than 5% of the households in NR earned income from off-farm activities compared with 17% in UER and 23% in the UWR. Such off-farm income generating activities generally included petty trading, remittances, paid salaries and family labour sold to other farms. These disparities mirrored the differences in production orientation of farm households shown in Fig. 5.5a–c, where households in NR sold much of their grain produced for income.

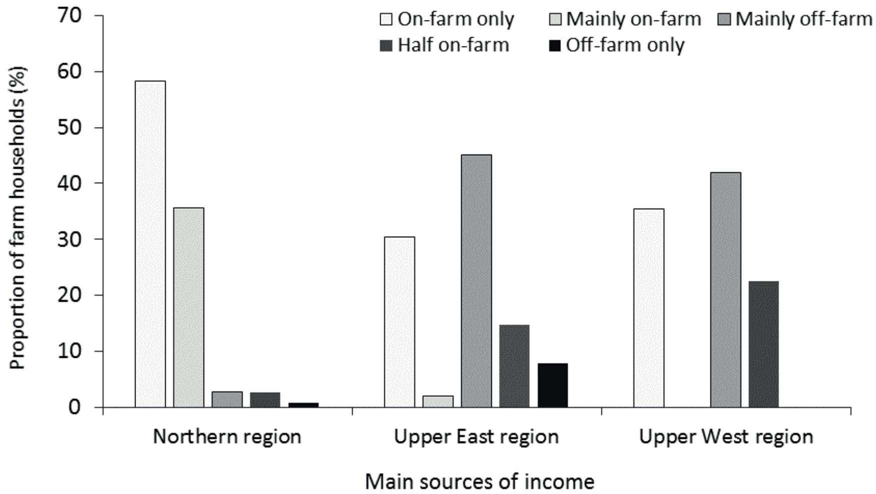

Fig. 5.3. Classification of income sources of farm households in Northern (NR), Upper West (UWR) and Upper East (UER) regions of Ghana.

5.3.2 Production objective of farm households

Households in NR produced more cereal grain than in UWR and UER (Figure 5.5d–f). The total amount of legume grain produced per farm is similar between NR and UWR (Fig. 5.5a–c) but both are larger than what was produced in the UER (Fig. 5.5b). Across the three regions, farm households exhibit different objectives for the production of cereal and legume grain. Households in NR generally orient legume grain for the market, selling over 70% of the produce. In the UWR and UER, a considerable amount of the legume grain is earmarked to support household food security though a sizeable share was also sold on the market in UWR. Cereals are produced to support household food security in all regions (Fig. 5.5d–f).

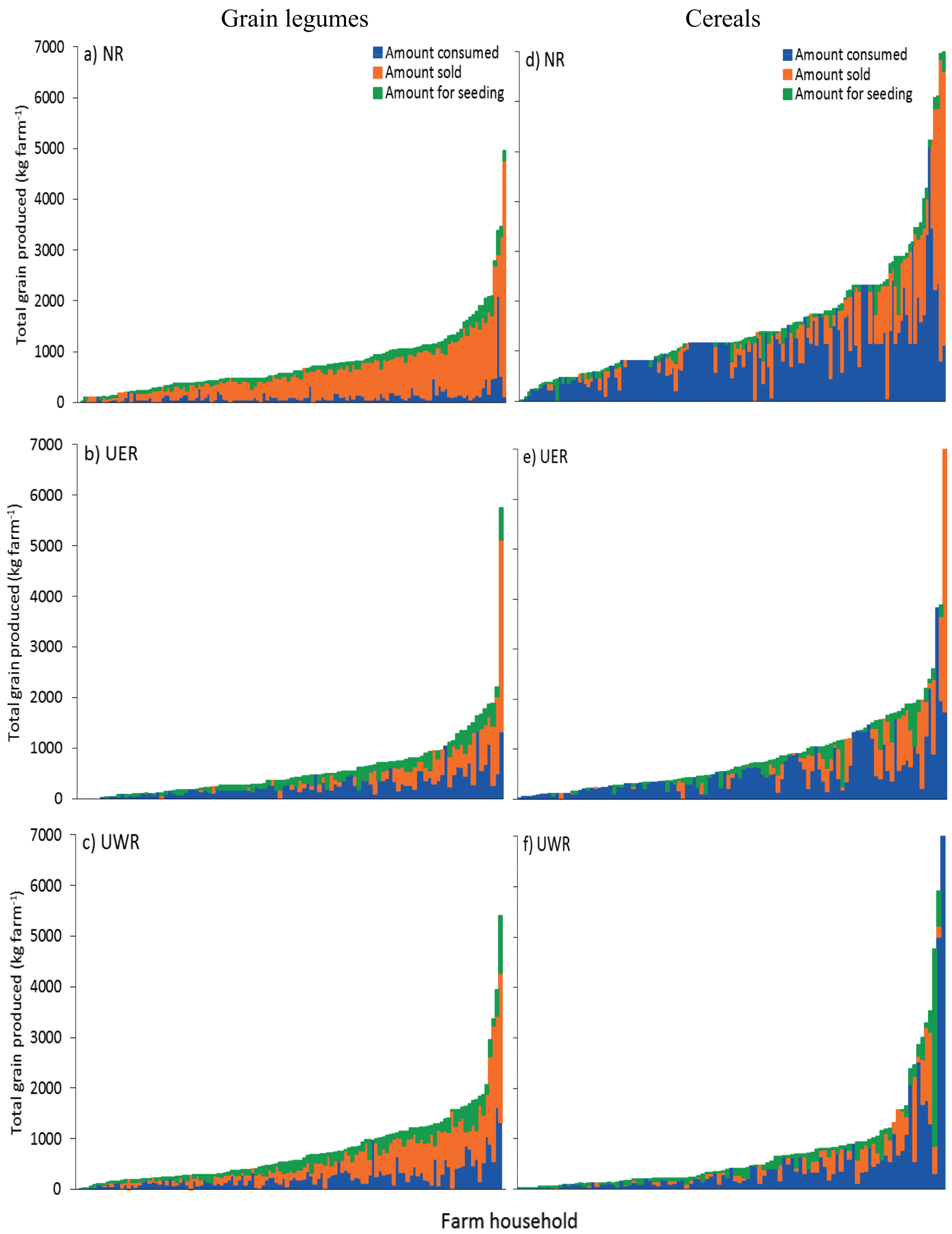

Fig. 5.4. Production objectives of farm households as indicated by the proportion of total grain production of grain legumes (a–c) and of cereals (d–f) consumed in the household, sold or used for sowing in the following season in Northern region (NR), Upper East region (UER) and Upper West (UWR) of Ghana.

5.3.3. Household food self-sufficiency

The mean food sufficiency ratios of 1.21 (NR), 1.16 (UER) and 1.20 (UWR) in the baseline indicate enough food available per farm household member in each region (Fig. 5.5a, d, g). These hide the disparity between regions, and the large variation between farms within each region. For instance, a little more than half (56%) of households in NR were food sufficient (food self-sufficiency ratio ≥ 1) but less than half of households in the UER and UWR (45% each) were able to meet their annual food requirements. Additionally, about a quarter of households in NR and one-third in both the UER and UWR could only meet half or less of their required annual food needs (food self-sufficiency ratio ≤ 0.5).

Intensification and diversification of crop production substantially increased the baseline mean food self-sufficiency ratios to 2.94, 4.05 and 4.97 (NR), 1.68, 2.68 and 3.82 (UER) and 2.32, 3.11 and 5.07 (UWR), respectively for Scenarios I, II and III. These improvements led to a considerable increase in households that were food sufficient and a decrease in the proportion of households that had food deficits for up to half a year. Combined for all the regions, the share of households who achieved 12 months of food self-sufficiency increased by 25% in Scenario I, 36% in Scenario II and 43% in Scenario III compared with the baseline. Similarly, the households who were self-sufficient in their own food production for a maximum of half a year reduced by 19%, 24% and 27% in Scenarios I, II and II, respectively.

Despite the overall improvement in food self-sufficiency due to intensification and diversification, the impact was variable among farm households within each region and between regions. In NR, the food sufficient households increased to 85% in Scenario I, 96%in Scenario II and 98% in Scenario III with food deficient households ranging from just 1% in Scenario III to 6% in Scenario I (Fig. 5.5b-d). In UWR, 76% households became food self-sufficient in Scenario I, 82% in Scenario II and 94% in Scenario III while the households with food deficits decreased to 2 – 12% across the three Scenarios (Fig. 5.5j-l). The situation was however different in UER where 63%, 75% and 83% of households, respectively in Scenarios I, II and III achieved 12 months of food-sufficiency (Fig. 5.5f-h). Of particular concern, roughly a quarter of households had enough food for the members up to half a year only in Scenario I, though in Scenarios II and III, such households were about one-tenth.

Sustainable intensification and diversification resulted in most food sufficient households producing huge food surpluses. This is indicated by the general trend across all the three regions where the food self-sufficiency ratios of most households in Scenarios I to III were much greater than the threshold of one (1) (Fig. 5.5). These could attract food marketers and open up farm villages for increased economic activities and create jobs.

The farm household size and the total land cultivated have influence on food self-sufficiency though these vary between regions as shown in Fig. 5.6. Household size seemed to have no bearing on food self-sufficiency in the UER (Fig. 5.6e) but the impact was more visible in the other regions where households that could only achieve 6 months or less of food sufficiency had 1.4 (NR) and 1.1 (UWR) more persons per household than the food sufficient ones. The impact of total land cropped on food self-sufficiency was stronger and consistent in all regions compared with the effect of household size (Fig. 5.6a-c). On average, the households that were food self-sufficient cultivated 2.0 ha more land than those that were self-sufficient in own food production for half a year or less in each region.

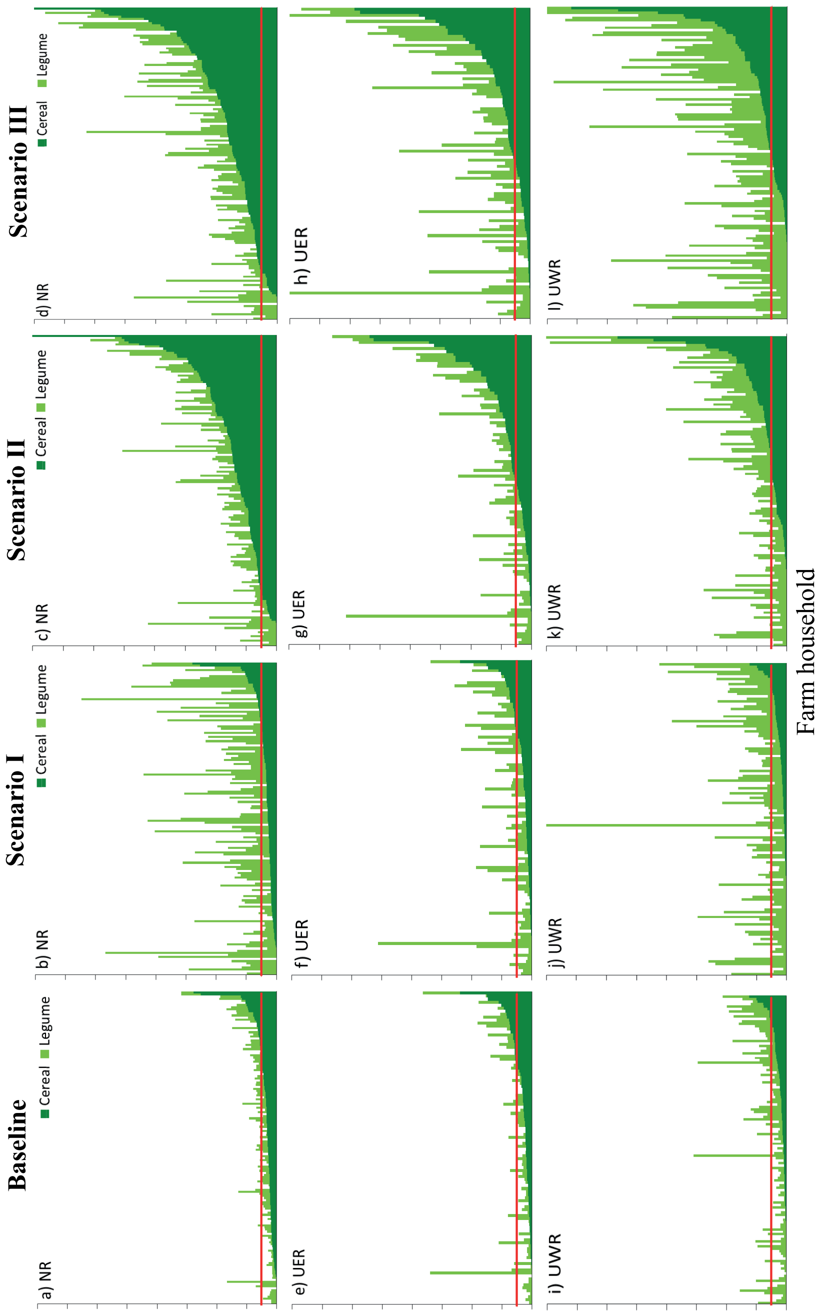

Fig. 5.5. Food self-sufficiency of farm households in the baseline situation, and as influenced by grain legume intensification alone in sole cropping (Scenario I), intensification and diversification of maize with grain legumes in additive intercropping (Scenario II), and intensification of both grain legumes and maize in sole cropping to reach 80% of maximum yields in the baseline (Scenario III) in Northern (NR), Upper East (UER) and Upper West (UWR) regions in the Guinea savanna of Ghana. The red line shows the food self-sufficiency threshold, above it a farm household is able to meet its annual household food requirement and below it the household is food deficient.

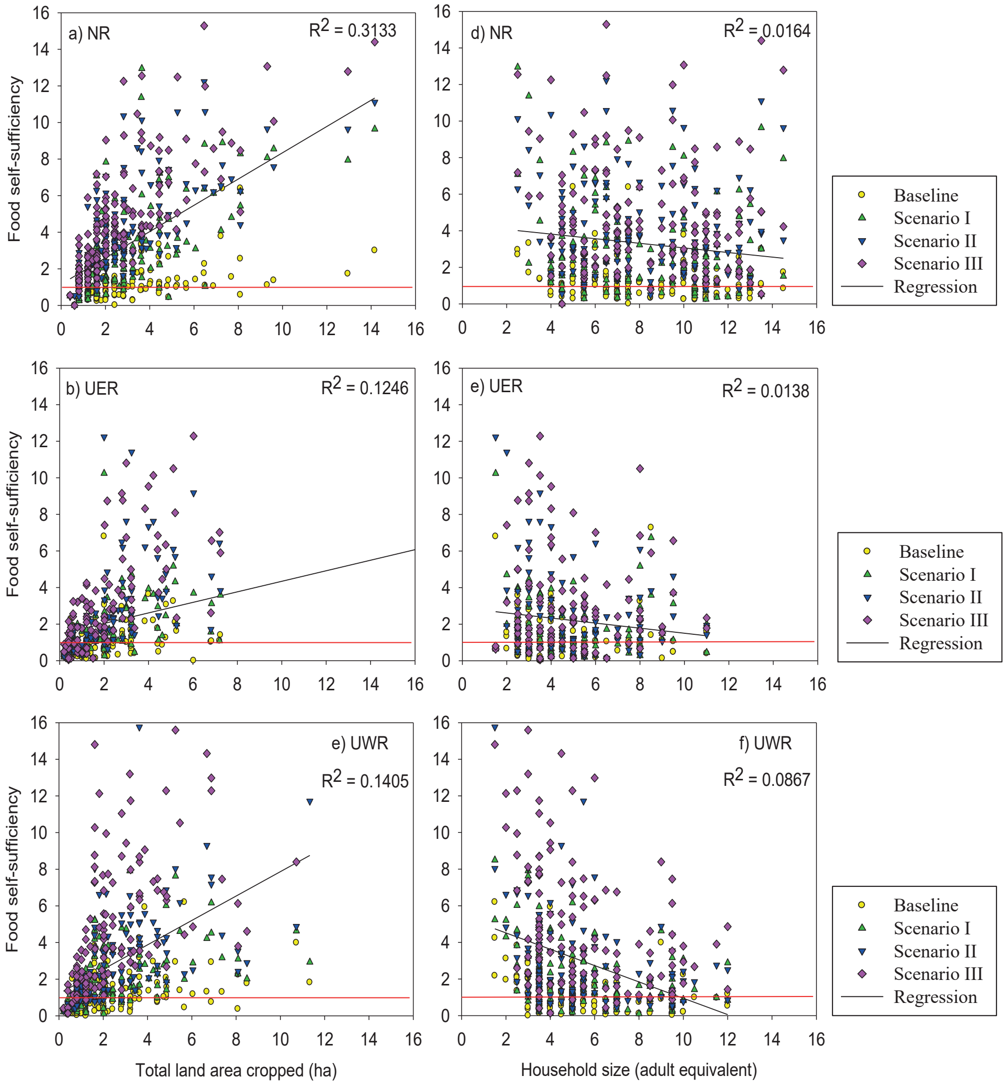

Fig. 5.6. Relationship between household food self-sufficiency and total land area cropped per household (a-c) and household size (d-f) in the Northern (NR), Upper East (UER) and Upper West (UWR) regions on northern Ghana. The red line denotes the food self-sufficiency threshold, above it a farm household food sufficient and below it the household is food deficient.

5.4. Discussion

5.4.1. Resource diversity and food self-sufficiency under baseline situation

The rainfall and soil fertility data cannot be linked directly to the specific sites where grain yields were measured. Yet, they offer a useful overview of the regional variation and explain the associated differences in grain production, particularly the larger yield and total grain production per farm in NR (Table 5.1). The greater land area cultivated per farm in NR explained the larger total grain production.

The large food insufficiency in northern Ghana (about half the farm households across all regions) could be largely attributed to the current relatively small grain yield per ha for both cereals and grain legumes (Table 5.1) relative to the national average (SRID, 2016). Poor grain yield leads to smaller total food production per household and eventually creating food deficits (van Ittersum et al., 2016). The food self-sufficiency results corroborate the findings of the World Food Programme, WFP (2009; 2013) that reported a greater concentration of food insecurity in northern Ghana, particularly in the UER and UWR. The regional disparities could be associated with the comparative advantage of farm households in the NR in terms of soil fertility, rainfall and rainy days, as well as a greater land availability and area cropped (Table 5.1). These resources advantage enabled the greater total food production per household (Fig. 5.4a, d) that overrode the large household sizes (Table 5.2; Fig. 5.6d).

The situation necessitates vigorous and innovative production systems to substantially increase grain production in these regions (Vanlauwe et al., 2014). This applies to the NR as well, since just over half the households were food self-sufficient there. The large population growth rate (2.9%; cf. national average of 2.5%) has a negative implication for future household food self-sufficiency. Also, farm households in NR rely more on on-farm income (Fig. 5.3) for household needs (Al-Hassan and Poulton, 2009) which explains why they sell more of their legume grain (Fig. 5.4a). Though there are more food sufficient households in this region (Fig. 5.5a-d), the objective of selling more of the legume grain could have a consequence for year-round food availability (Frelat et al., 2016). Most households could run into food deficits at some point in the year if a large part of the income generated from the crop sales is not used to acquire additional food. This is somehow complicated as farm incomes are meant for non-food needs as well (e.g. children school fees, medical care, clothing, funerals, etc). Hence only a small share may be spent on acquiring extra food (Frelat et al., 2016).

Most farm households in northern Ghana experience insufficient food between April to August each year (WFP, 2013). The period corresponds to six months after the closure of a current cropping season and the mid of the following season. This affirms the result of this study that one-third of households in the baseline situation could only survive on their own food production for a maximum of six months (5.5a, e, i). The period is characterised by high food prices, especially in June and July due to food shortage (WFP, 2013). Farm households generally sell their produce immediately after harvest. Consequently, they may not be able to afford the price hikes when additional foods need to be purchased.

5.4.2. Impact of grain legume intensification and diversification on food self-sufficiency

The discussion above suggests that much greater grain yields of both cereals and grain legumes than what are presently achieved by farms are required to offset all or part of the food deficits and improve food self-sufficiency. Intensification and diversification options with grain legume represent promising strategies to contribute to improved food security (Vanlauwe et al., 2014) in the Guinea savanna, as demonstrated by the enhanced food self-sufficiency in Scenarios I to III. These resulted from the comparatively greater grain yields than what is achieved with the current cropping practices, which occurred through input use and N_2-faxation by grain legumes and the subsequent residual N benefit to maize (Franke et al., 2014; 2017; Kermah et al., 2019).

Through sustainable intensification and diversification, a majority of food sufficient households could generate huge food surpluses that can be marketed to earn farm income (Fig. 5.5b-d, j-l, g-h). This offers opportunity for farm households to store their surplus produce and take advantage of the price hikes during the off-season to earn greater incomes. In addition, these have the propensity to attract food marketers or companies, input suppliers and credit agencies, generally open up farm villages for increased economic activities and create jobs which would be useful in earning off-farm income. This is of particular relevance in areas with high population densities and land scarcity (e.g. UER with more food deficient households) as they require off-farm income to secure extra food when needed.

Nevertheless, intensification and diversification options will require socio-economic and biophysical considerations (Vanlauwe et al., 2014; Frelat et al., 2016; Waha et al., 2018). First, improved market access and availability of the relevant inputs (especially inoculant and P) are needed. Secondly, the economic capacity of farm households or access to finance are crucial to acquire the needed inputs. Also, more labour may be required to support intensification and diversification activities, particularly in Scenario III (e.g. planting, weeding, fertiliser application and harvesting) (Rusinamhodzi et al., 2012). On the other hand, the intensification and diversification options appear feasible under the prevailing agro-ecological conditions in each region. For instance, the mean seasonal rainfall amounts (827 – 1,020 mm; Table 5.2) are adequate with reference to the rainfall needed as potential condition for such intensification of crop production in sub-Saharan Africa (Waha et al., 2018). The soil nutrient limitations (Table 5.2) remain a concern, especially in Scenarios II and III that involves intensification of maize as well. However, modest applications of N and P can possibly offset the nutrient imbalances to some extent and give appreciable grain yield increases leading to improvement in food sufficiency as established in Scenarios I to III. Soil partial N balances for similar intensification and diversification systems studied by Kermah et al. (2018; 2019) in northern Ghana were generally positive and provide hope for farm households to intensify.

In UER where arable land is less available, grain legume and cereal sole crop intensification systems are of utmost importance to increase food production per unit area in order to increase food sufficiency (Vanlauwe et al., 2014). However, diversification through intercropping of maize with grain legume is valuable for food diversity (de Jager et al., 2017; Waha et al., 2018), increased yield as shown in Scenario II. Diversification is also essential for insurance against climate stresses and crop failure (Rusinamhodzi et al., 2012; Kermah et al., 2019) as observed in the baseline.

Despite these benefits, it appears that in densely populated and land limited regions like the UER, it will take more than crop intensification for most households to achieve food security. Intensification and diversification could enhance crop yield per unit area but more land is required to take advantage of such yield enhancement to increase the total food production per household (Fig. 5.6a-c). Perhaps in those areas other farm related activities within the value chain of the different crops (e.g. processing, produce marketing) or off-farm jobs would be necessary to obtain additional income and support households' own food production.

5.4.3. Methodological limitations

The approach used provides useful insights into the potential of intensification and diversification to improve the food security of rural households in northern Ghana. However, the methods used have some shortcomings. For example, the method used to attribute the area to component crops in intercropping is somewhat subjective. Therefore, the total area allocated to a particular intercrop component may have been over- or underestimated which can affect the estimated total cultivated area for a particularly cereal or grain legume. It can influence the baseline grain yield per ha and eventually impact on the calculated food self-sufficiency ratios per farm household.

Post-harvest loses were not considered in accounting total grain production and estimating household food self-sufficiency. Additionally, other crops such as rice, roots and tubers and Bambara nuts were not considered in the determination of household food self-sufficiency. Rice in particular is occupies about 20% of cultivated land in NR (though grown basically in in-land valleys) while roots and tubers produced only NR and UWR are allocated about 8% of land. If included the baseline food self-sufficiency conditions in these regions would change.

5.5. Conclusions

Grain yields of cereals and grain legumes are presently low in the Guinea savanna of West Africa leading to high food insufficiency among smallholder farms. The large diversity in resources availability and allocation pattern among smallholder farms in contrasting regions give rise to different opportunities in achieving year-round food self-sufficiency. Sustainable intensification and diversification with grain legumes is a promising strategy for smallholder farm households in the Guinea savanna to achieve food self-sufficiency in the face of rapid population growth. Through such systems, farm most households could produce enough food that meet their annual food requirements and also generate substantial surpluses for market to earn income to finance non-food household needs. Intensification and diversification require the appropriate biophysical and socio-economic considerations to succeed. Functional markets are needed to acquire the needed inputs and sell surplus grain while the total size of land cultivated by a farm household also matters. Hence in densely populated areas with less land cropped per farm household, it will take more than intensification of crop production to be food sufficient. In such areas, off-farm work will be vital to earn income in order to purchase additional food that may be needed.

Acknowledgements

We are grateful to the Bill and Melinda Gates Foundation for the funding support provided through a grant to Wageningen University for the project N2Africa: Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (www.N2Africa.org). We thank the farmers in the Northern, Upper East and Upper West regions participating in the household surveys. We also thank Eva Thuijsman and Joost van Heerwaarden for the support in accessing the data.

Chapter 6

General discussion

6.1. Introduction

Achieving household and income security in smallholder farming systems in the Guinea savanna of West Africa remains a critical concern. A web of biophysical (e.g. poor soil fertility, erratic rainfall) and socio-economic (e.g. low income, lack of credit, shortage of labour) constraints combine to stifle the capacities of smallholder farms in producing enough for their households or purchasing the needed supplemental food. On top of these, the rising population puts pressure on the already fragile arable lands and creates additional burden for farm households to be food and income secure (Vanlauwe et al., 2014). Sustainable intensification of crop production to increase crop yield per unit area has become inevitable even with the prevailing biophysical and socio-economic limitations (Vanlauwe et al., 2014).

Solutions that contribute to addressing these challenges need to be rigorous to tackle and resolve multiple constraints. Therefore, I explored a diversity of legume-based intensification and diversification options that could have such attributes. The overall purpose was to test opportunities to enhance resource use efficiency and corresponding increase in yields of main cereal and grain legume crops, mitigate the risk of crop failure in sole cropping, while sustaining soil fertility under on-farm conditions. These are geared towards increasing food self-sufficiency and income of smallholder farms in the Guinea savanna.

In this chapter, I synthesize the main findings and draw conclusions on the potential of the tested intensification and diversification options under the diverse biophysical and socio-economic contexts of smallholder farming systems in the Guinea savanna, and the impact on household food self-sufficiency. In addition, I synthesize the key findings in the context of climate variability and change in the savanna region of West Africa, the needed institutional environment and the long-term sustainability of such intensification and diversification options. I also explore the possibilities of further enhancing and safeguarding crops yields, food self-sufficiency and farm income through emerging digital technologies.

6.2. Key findings of intensification and diversification options with grain legumes

The biophysical and socio-economic limitations in smallholder farming systems have both space and time dimensions (Ojiem et al., 2006). Spatial and temporal considerations are thus important in exploring intensification and diversification systems. For instance, rainfall is variable throughout the growing season and differs between locations in the Guinea savanna, so does soil fertility, land and credit access and labour availability. In following sub-Sections, I discuss the potential of maize-grain legume intensification and diversification options for increasing crop yields and improving farm income and household food self-sufficiency.

6.2.1. Legume-cereal rotation: sustainable intensification pathway to increase crop yields

Legume-cereal rotations are well known for increasing yields of cereals that succeed the legumes even without applying N fertiliser to maize. A systematic review of literature on this system by Franke et al. (2018) revealed a mean of 0.49 t ha^{-1} increase in yield of cereals rotated with legumes relative to continuous cropping of cereals in sub-Saharan Africa. In the Guinea savanna of West Africa, research attention has focused largely on this system owing to the opportunity of increasing yields of the main food security crops without additional N fertiliser cost to farmers (e.g. Agyare et al., 2006; Franke et al., 2008a; Oikeh et al., 1998; Sanginga et al., 2002; Yusuf et al., 2009a, 2009b). In Chapter 4, we showed that grain yield of maize that followed soybean and groundnut in rotation can increase by 0.69 t ha^{-1} in the Guinea savanna without any N fertiliser input (Fig. 4.4). The mechanisms explaining the strong effect of legume-cereal rotations on cereal yields are discussed in detail in Chapter 4.

Grain legumes seldomly receive fertilisers in smallholder farming systems in the Guinea savanna with resultant poor yields in farmers' fields as shown in Chapter 5, Table 5.1. Application of 25 kg P ha^{-1} and 30 kg K ha^{-1} to grain legumes in Chapters 2, 3 and 4 increased the yields considerably compared with the current farmers' yields. The results are similar to those reported by Adjei-Nsiah et al. (2018) who investigated the response of the same grain legumes to 30 kg P ha^{-1} in the Guinea savanna of Ghana. In a low population density area such as the Northern region of Ghana, the total area allocated to grain legumes is proportional to that of the cereals (Fig. 5.1a, c). This indicates the popularity of legume-cereal rotation with farm households.

6.2.2. Crop diversification for resource use efficiency and insurance under climate shocks

Considering that seasonal climate stresses are unavoidable in the Guinea savanna, and there is only one cropping season in a year, crop failure could have serious consequence for household food self-sufficiency and income. The Comprehensive Food Security and Vulnerability Analysis by the World Food Programme, WFP (2013) revealed that 40% of households in northern Ghana experienced food difficulty due to crop failure from erratic rainfall. We also showed crop failure in Chapter 4 (Fig. 4.4) for the drier Upper East region, and in Chapter 5 (Table 5.1) for both Upper East and Upper West regions with less rainfall and rainy days. In these areas, farmers usually intercrop albeit with no input use and inefficient crop management practices resulting in poor yields. In Chapter 5 (Fig. 5.1b) we demonstrated that only 25% of the total cereal area is potentially rotated with grain legumes in a season in Upper East region in the northern part of the Guinea savanna. This stems from the fact that grain legumes occupy only 25% of the total cultivated land, and that is half the area allocated to the main cereals. Under such adverse climatic conditions and land scarcity emanating from high population density, crop diversification systems would be more suitable options. The Guinea savanna of West Africa has a wide sowing window for the main cereals and grain legumes, which can be exploited for intensification and diversification. However, this is not straight forward and proper timing will be essential.

The wide sowing window, end of May to early July is based on the onset and regularity of rainfall (Adu et al., 2014) which in itself is a trap for many farm households. Delays in sowing due to the inability to acquire relevant seeds and other inputs on time would make households prone to poor yields or crop failure. Double cropping can be done to obtain food in mid-season (Franke et al., 2004) when households face the greatest food difficulties and food prices are high. Though this is promising, it means that there should be early onset and regularisation of rainfall. Also, suitable crop choices will need to be made. For example, early sowing of cowpea is tricky as consistent rainfall in mid-season causes yield reduction, poor drying of pods resulting in poor grain quality (Chapter 4) with negative consequence for food sufficiency.

Conversely, the extensive sowing window also offers an opportunity to explore intensified cereal-legume diversification options that would be resilient to climate shocks and safeguard food self-sufficiency. In Chapter 4, we demonstrated that cereal-legume relay intercropping is a viable ‘shock absorber’ for smallholder farms under adverse climatic conditions. In the drier Upper East region (northern Guinea savanna), inadequate rainfall caused the failure of cowpea relayed into maize sown from the onset of the season. Yet, the maize provided 1.81 t ha^{-1} of grain (Fig. 4.4c), which is 0.97 t ha^{-1} greater than current farmers yield (Table 5.1). In the wetter Northern region (southern Guinea savanna), the maize produced 2.28 t ha^{-1} grain and that is 1.06 t ha^{-1} larger than what farmers achieve though the relayed cowpea failed because of disease infestation (Fig. 4.4a). This shows that maize yield can be increased substantially with fertiliser application. In Central Mozambique, Rusinamhodzi et al. (2012) reported a similar case of cowpea intercropped with maize providing food when the maize failed to yield due to prolonged drought, highlighting the resilience of maize-cowpea intercropping.

Simultaneous intercropping of maize with grain legumes led to more efficient and productive use of land and consequently yield advantage ranging from 26% – 46% (LER of 1.26 – 1.46) compared with the respective sole crops (Chapter 3; Table 3.7). The mechanisms for this efficiency and yield advantage have been discussed in Chapter 3, sub-Section 3.4.3. The intercropping systems were not only more productive, but also provided larger net benefits (Chapter 3, Fig. 3.7). However, farm households may be reluctant to reduce the area cultivated to maize, the main food security crop. Furthermore, the two cereal-legume diversification options (relay and replacement intercropping) are more labour intensive than sole cropping due to more time needed for sowing, weeding and harvesting (Rusinamhodzi et al., 2012).

6.2.3. Soil fertility and sustainability of intensification and diversification with grain legumes

Intensification of crop production brings about increased grain yields and food self-sufficiency. However, it also comes along with increased soil nutrient uptake which can lead to depletion of nutrient stocks. Already, the Guinea savanna soils generally have negative soil nutrient balances due to continuous practising of unsustainable cropping systems (Bationo et al., 1998; Stoorvogel and Smaling, 1990; Yusuf et al., 2009a; 2009b). An intensification option has to be sustainable in itself to prevent further soil fertility decline and to allow for its longer-term practice and productivity. For this purpose, we assessed the agronomic sustainability of the tested intensification and diversification options through partial soil N balance estimations (Chapter 2 and 4). Though the partial N balance indicator has its own shortcomings (as discussed in Chapter 2), it gives an indication of the status of soil N fertility.

The partial soil N balances for the different intensification and diversification options tested were generally positive (Chapter 2, Fig. 2.2; Chapter 4, Table 4.3), suggesting that our systems were not nutrient exhaustive and could be sustainable by themselves. This was possible because the grain legumes fixed up to 183 kg N ha^{-1} in sole cropping (Chapter 4, Table 4.3) and up to 97 kg N ha^{-1} in intercropping (Chapter 2, Table 2.3) and these were achieved in fertile fields with corresponding greater grain yields (Chapter 2, Table 2.4; Chapter 4, Fig. 4.4). In the poorly fertile fields, the grain legumes fixed less N but relied more on atmospheric N for growth leading to a more positive soil N balance than in fertile fields, both in intercropping and sole cropping. Especially with intercropping, we showed that grain legumes become more competitive in poor soils because in such case the maize is unable to shade them, and also the legumes fix N_2 which they use for growth. In the end, the intercropping advantage as discussed in sub-Section 6.2.2 was larger in poorly fertile fields due to a larger contribution of legumes to the productivity of the intercrop systems. It means that with appropriate integration of grain legumes into the cereal-based cropping systems, crop intensification and associated increased yields can be achieved in both fertile and infertile fields. At present, it appears that the tested intensification systems are sustainable. However, on the long term, it is uncertain whether soil nutrient balances remain positive to allow continues intensification of crop production. Therefore, a modelling work would be necessary to explore the long-term feedbacks, particularly relating to N and C stocks and to advise accordingly.

It is pertinent that crop residues, especially those of the legumes be retained in the fields to achieve positive N balance (Fig. 2.2), allow for benefits of the residual N to the cereals grown in rotations or in association with the legumes. However, this brings the key challenge of crop residue deployment in smallholder farming systems. Groundnuts are mostly taken home for threshing hence the residues would naturally be used to feed livestock. Cowpea and soybean residues are left in the field in the Northern region but not evenly spread, especially soybean (Fig. 6.1) contributing to within-field variability in soil fertility. Also, the residues when left in the fields may be grazed by stray livestock (Fig. 6.1). In the Upper East region, the fields are just behind the homesteads so farmers can afford to collect the residues to feed livestock and return the manure to the fields. This strategy is complicated to implement in the Northern region of the southern Guinea savanna where most fields are located further from the homesteads and would require more labour from the farmers.

Fig. 6.1 Crop residue use to build soil fertility remains a challenge in smallholder farming systems in the Guinea savanna of Ghana

Also, in the Northern region farm households who own cattle give them to the Fulani herdsmen to herd for them. Consequently, the real cattle owners do not have access to the manure that may be collected. These challenges limit intensification of mixed crop-livestock systems. The competing claims for grain legume residues are understandable because the livestock population has increased consistently over the last three decades in Ghana (Fig. 6.2) and livestock farmers need to feed their animals. At the same time, there is import of soybean meal for feeding in intensive livestock systems (Fig. 6.3). This presents an opportunity for farmers to intensify production of soybean to supply the increasing market for soybean products. For that, digital technologies and other opportunities discussed in the other Sections below are essential.

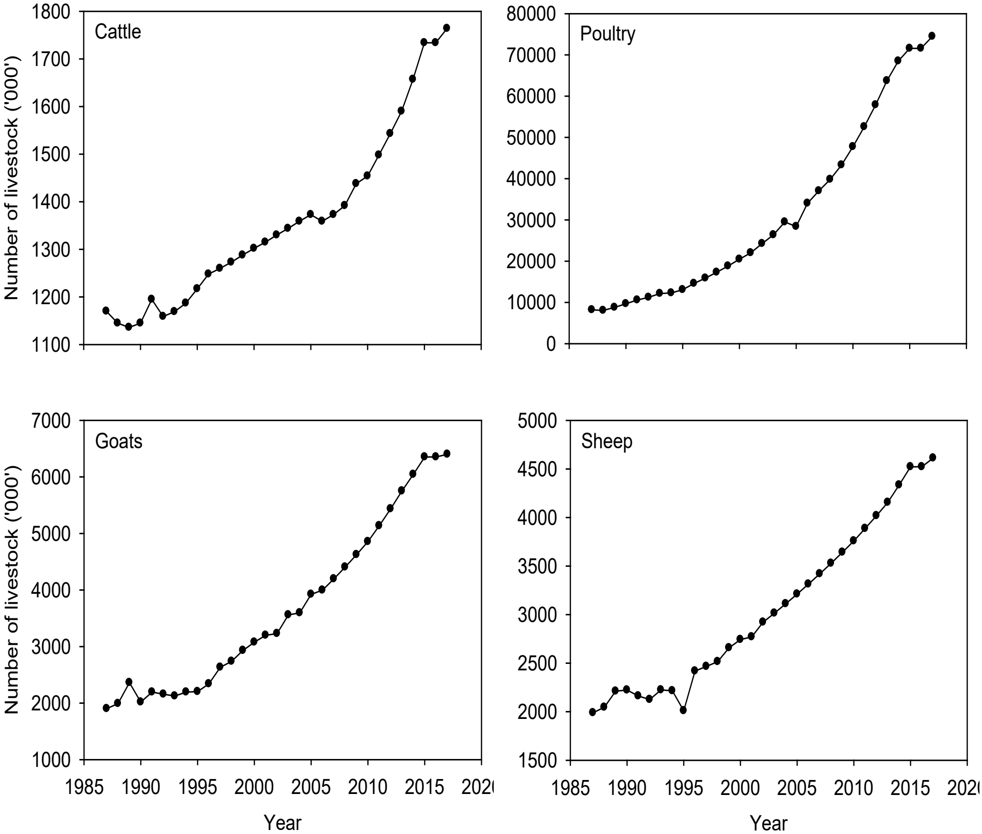

Fig. 6.2 Livestock population trend over the last three decades in Ghana (Source: FAOSTAT)

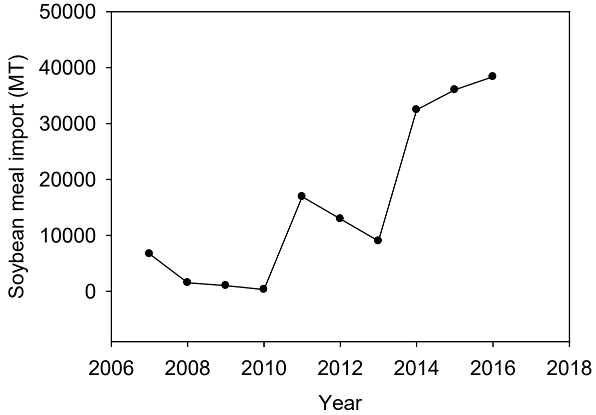

Fig. 6.3 Trend of soybean meal imports for livestock feeding in Ghana (Source: SRID, 2016)

6.3. Achieving food self-sufficiency in the Guinea savanna under a changing climate

Smallholder farm households in the Guinea savanna of West Africa, and in Africa in general have been at the mercy of climate variability and change due to the overwhelming reliance on rainfed agriculture. This in addition to poor fertility of soils and the subsequent adverse impact on crop yields make the achievement of food security by most farm households a distant target (Frelat et al., 2016; Waha et al., 2018). The single cropping season in the Guinea savanna makes the impact of climate variability and change a more critical concern for achieving food self-sufficiency. At present, seasonal rainfall in the different regions in the Guinea savanna of Ghana, 827 – 1020 mm (Table 5.2; Fig. 6.4c) constitute roughly 80 – 90% of the annual rainfall. The rainfall amounts are adequate for smallholder farms to take advantage of the tested intensification and diversification options (Critchley and Siegert, 1991) to achieve food self-sufficiency as demonstrated in Chapter 5 (Fig. 5.5).

However, Roudier et al. (2011) reported a –13% reduction in staple crop yield decline induced by changes in rainfall and temperature in smallholder farming systems in the West African Guinea savanna. A 22-year climate data (1990 – 2011) for the Guinea savanna of Ghana indicate visible increases in temperature with no particular trend for rainfall (Fig. 6.4a-b). Future climate change projections by the Environmental Protection Agency of Ghana, EPA (2015) suggests an increase of 1.6 and 2.8 °C in minimum temperature by 2040 and 2060 while maximum temperatures are projected to increase by 1.7 and 3.1 in 2040 and 2060, respectively. Projections for rainfall did not show any consistent pattern. The indication is that further yield reductions due to climate variability and change is to be expected. This means that suitable adaptation measures feasible within the biophysical and socio-economic capacities of smallholder farms are required.

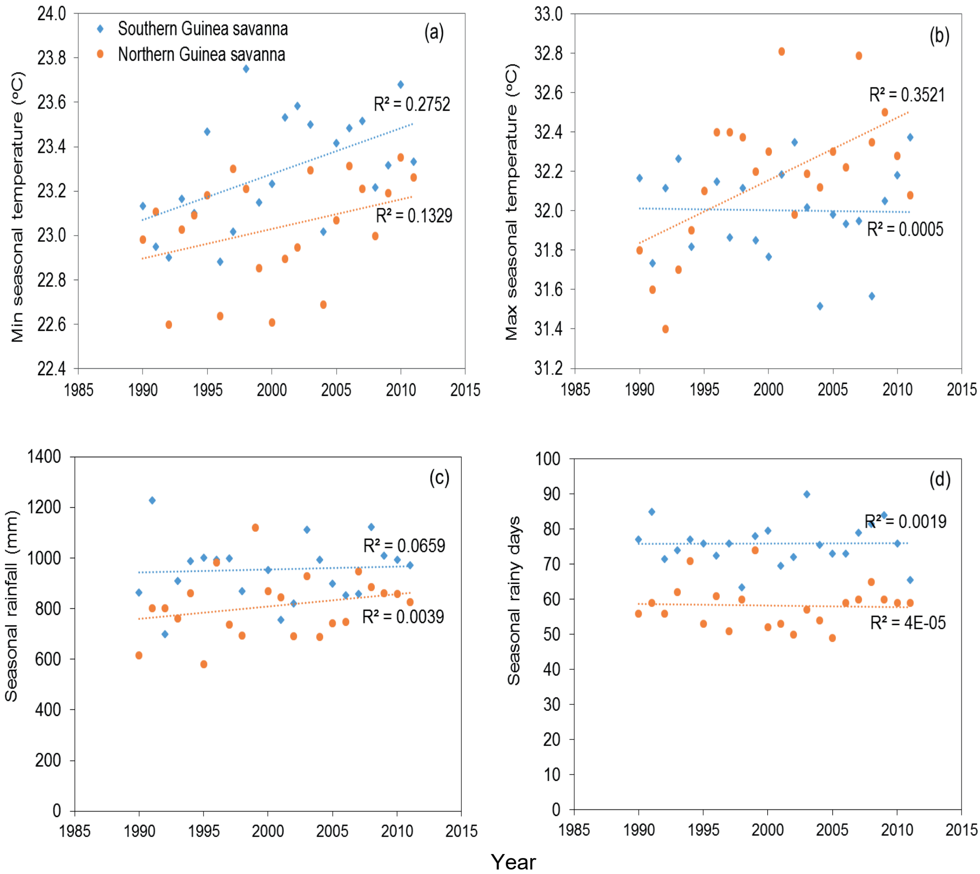

Fig. 6.4 Seasonal changes in climatic variables over a 22-year period in the Guinea savanna agro-ecological zone of Ghana. (Data source: Ghana Meteorological Agency).

More drastic adaptation measures are needed in smallholder farming systems. This is because the negative consequences of future climate change on yield reduction and food self-sufficiency is expected to be more pronounced for smallholder farms (Traore et al., 2017). However, the weak economic conditions translating to inability to finance or adopt more rigorous adaptation measures make them vulnerable to climate variability and change. Households' own food production is key to achieving food self-sufficiency in smallholder farming systems since food purchases contributes only a quarter to household food availability (Frelat et al., 2016). It follows that strategies that could increase food production by households are valuable adaptation measures. Early sowing, use of drought tolerant varieties and adequate fertiliser application are adaptation measures for smallholder farms in adverse climates (Traore et al., 2013; 2017). Early sowing is an interesting option given the wide sowing window in the Guinea savanna but greatly depends on early onset and regularisation of rainfall, which is not certain due to lack of adequate evidence on future trend. Model analysis of future climate variability and change and impact on food self-sufficiency by Traore et al. (2017) suggests that even with early sowing and adequate fertiliser application, smallholder farms will struggle to achieve food sufficiency. These imply that climate pressures will have both short- and long-term negative consequences for food self-sufficiency for smallholder farm households in the Guinea savanna. However, relay intercropping with maize sown first and legume planted later or additive intercropping of maize with grain legumes sown at recommended sole crop densities as shown in Scenario II in Chapter 5, provide some hope for smallholder farms. Such intensified diversification options facilitate efficient use of scare resources to increase crop yield per unit area, increase total food production, are resilient to climate shocks (Chapter 4; Rusinamhodzi et al., 2012) and safeguard food self-sufficiency in the face of climate variability and change.

I think that though intercropping is helpful in mitigating total crop failure, current and future increase in temperature and uncertain rainfall could reduce the yield of both cereal and grain legume components and in the end reduce total food production and self-sufficiency. Nevertheless, from Chapter 5 (Fig. 5.5) we show that through additive intercropping of maize with grain legumes (Scenario II), food self-sufficiency ratios of 70 – 93% of households ranged from at least 20% to over 300% above the threshold of one (1). This means that majority of households can generate huge food surpluses through intensified diversification with grain legumes. Therefore, additive or relay intercropping of maize with grain legumes could be a solid adaptation measure for smallholder households to combat the negative impact of climate variability and change.

6.4. Digitalisation to transform smallholder agriculture and safeguard food sufficiency

Technology has been a key driver boosting the efficiency, productivity and profitability of many economic sectors globally. In Africa, emerging technologies are driving success of businesses outside the agriculture sector. To harness the benefits of emerging technologies, African agriculture and agribusinesses are currently undergoing digital transformation with ICTs, blockchains, satellites and drones being employed to boost food production, enhance market linkages and income. Smallholder farmers cannot be left out since they produce over 80% of the food needs of the African population but ironically, food insecure. Digitalisation for agriculture (D4Ag) could be relevant in improving the benefits and resilience of promising intensification and diversification options (Tsan et al., 2019).

Presently, over 30 million smallholder farmers across Africa have gone digital and registered with D4Ag solutions (Tsan et al., 2019) that provide tailored information and services along the value chains, from pre-production, production, harvesting, post-harvest and market linkages (Sotannde and Lohento, 2019; Tsan et al., 2019). This number is estimated to increase with annual growth rate of about 45% (Tsan et al., 2019). In Ghana, several D4Ag opportunities exist that can boost crop productivity in smallholder farming systems in the Guinea savanna. Currently, about 1.6 million farmers are using D4Ag solutions that provide diversity of use cases from production to marketing and financial access (Fig. 6.5) to increase production and income. Mobile money services currently allow smallholder farmers to pay for inputs and make other transactions without having to pay transport cost. Yara, a large fertiliser company in Ghana currently allows its farmer clients to register for mobile money and use the service. In the following sub-Sections, I discuss a few of these D4Ag opportunities in Ghana that could transform smallholder systems in the Guinea savanna to make farmers take advantage of promising intensification and diversification options and be food self-sufficient.

6.4.1 Digital service delivery solutions to increase crop productivity

At present, more than 50 D4Ag platforms are available in Ghana with 28 headquartered in the country (Fig. 6.5). Through partnership with agricultural organisations and mobile networks, they provide diversity of services for smallholder farmers ranging from weather forecasts, information on market prices and advises on optimal sowing times, and other efficient crop management practices that can boost crop productivity. Climate or crop insurance packages and weather forecasts are vital due to the unpredictability of rainfall in the Guinea savanna and its negative impact on crop yields and food-sufficiency. Also, the predicted future changes in climate in the Guinea savanna (Roudier et al., 2011; EPA, 2015) and elsewhere in the Sudano-Sahalien region (Traore et al., 2017) of West Africa make climate alert services crucial for the resilience of crop intensification production systems. Provision of market linkages by connecting farmers with potential buyers, could alleviate the challenge of finding access to markets, transporting produce and accessing better product prices.

Farmers also have the opportunity to order required inputs on mobile phones with no transport cost, which is helpful for smallholder farmers in the Guinea savanna with generally weak economic capacities and poor road networks. Interestingly, these services are tailored to the specific needs of smallholder farmers by taking into account location of farmers, the stage of production, and largely through voice messages in local languages. This particularly eliminates the previous key challenge of illiteracy associated with many smallholder farmers which made them unable to benefit from SMS services. The current service delivery form (voice messages) provide opportunity to access those digital services and to apply them to the promising intensification and diversification options identified in this thesis.

In addition, some digital solutions (e.g. *Farmerline, Esoko*) provide digital farmer profiling service for smallholder farmers. Digital profiling involves geo-referencing information about smallholder farmers, their production activities and their land. This creates traceability, enable farmers to use their land as collateral if desired (which they normally are unable to provide before) and improve their ability to access credit facilities to finance farm activities. This is of utmost importance since credit access is essentially needed for smallholder farmers to acquire the needed fertilisers, inoculants and seeds to intensify crop production. Digital farmer profiling also facilitates input supply and input subsidies for smallholder farmers (particularly in the case of *Esoko*), which is a great opportunity to source needed input for sustainable intensification of crop production. The technology excitement needs caution because most of these services are not entirely free. Yet, given the large surpluses that most farm households could generate due to the deployment of digital solutions in intensification and diversification (Chapter 5, Fig. 5.5), they could offset the digital costs, achieve food-sufficiency and make economic gains.

Fig. 6.5 The digital landscape of Ghana: Snapshot of D4Ag solutions smallholder farmers are currently accessing in Ghana. (Source: Tsan et al., 2019).

6.4.2 'Planting for Food and Jobs': Government's digitalisation for agriculture initiative

The Government of Ghana has embraced the digitalisation agenda and initiated some programmes to contribute to transforming smallholder farming in order to increase food and income security and create jobs. This has led to the establishment of the 'Planting for Food and Jobs' initiative, which includes a D4Ag opportunity for smallholder farmers. The programme is aimed at increasing food production towards food security with maize, sorghum and soybean among the target crops for intensification. In this line, the intensification and diversification options profiled through this thesis fits well within that framework. The initiative involves electronic registration of smallholder farmers willing to participate in the programme and benefit from:

- access to certified inputs (seeds and fertilisers) needed for intensification of crop production at subsidised prices. This includes information on appropriate and efficient use of these inputs and monitoring of agronomic performance of the inputs.
- provision of information on efficient agronomic practices to increase crop yields
- extension services tailored to the needs and challenges of beneficiary farmers.
- marketing of crop products through establishment of linkages between farmers, food marketers, public food programmes such as the Ghana School Feeding Programme, and livestock feed companies.

In addition, the initiative has an e-agriculture component that tracks distribution of the subsidised inputs to farmers, monitoring the progress and challenges of farmers, and detection of inputs (e.g. fertilisers, seeds, agrochemicals) that perform poorly in terms of improving crop yields in order to replace them (MoFA, 2017; Tsan et al., 2019). As at 2018, 677,000 registered smallholder farmers were participating in the 'Planting for Food and Jobs' initiative and the number is expected to increase yearly (Tsan et al., 2019). The projected grain yield per ha for maize is 5 t ha^{-1}, which closely aligns with what could be achieved through sustainable intensification and diversification with grain legumes demonstrated in Chapter 5 (Table 5.1).

The 'Planting for Food and Jobs' together with the other digital schemes are vital for farm households in the Guinea savanna if they decide to embrace the digitalisation agenda. It will enable them to acquire the relevant inputs and harness the potential of sustainable intensification and diversification options (Chapter 2 – 5) to boost crop yields and enhance food self-sufficiency and income. Marketing is crucial for smallholder farmers in the Guinea savanna who usually find it difficult to sell their products, especially soybean grain. At least, the surpluses from intensification can be marketed if farmers choose to go digital by registering with these innovative schemes.

Agriculture production and related activities are not motivating for youth due to low income levels. Youth are however more adventurous and are attracted by technology. Digitalisation could attract the youth into agriculture production, especially through sustainable intensification and diversification systems that has the potential to make them innovate and achieve food and income security. Eventually, this will lead to job creation along the agricultural value chains and contribute to poverty alleviation which is widespread in the Guinea savanna region of northern Ghana.

6.5. Concluding remarks and future research needs

This study explored spatial and temporal maize-grain legume intensification and diversifications options that offer opportunities that enhance resource use efficiency and crop productivity leading to increased household food self-sufficiency. The study also focused on assessing the ecological sustainability of the intensification systems in order not to deplete the soil nutrient stocks in farmers' fields in the Guinea savanna.

Intercropping can provide benefits to both smallholder farms with fertile fields as well as those with poorly fertile fields. Intercropping led to greater efficiency in resource and consequently larger intercrop productivity or yield advantage over sole crops. Also, I observed that poor soils stimulate grain legumes to rely on atmospheric N_2 for growth and in the end result in larger net N contribution to improving soil fertility. However, there is absolute greater grain yields in fertile fields which means that farmers with better fields are likely to enjoy greater economic benefits.

The intensification and diversification options explored give hope for farm households in the Guinea savanna to be self-sufficient in own food production and still generate substantial marketable surpluses to increase farm income. Rotation of grain legumes with maize gives best grain yield which is already well established in the Guinea savanna and sub-Saharan Africa. The tested intensification and diversification options require further socio-economic developments in order to succeed such as credit access to acquire the relevant inputs and functional markets for timely input supply and marketing of farm produce.

In the near future, a study to explore diversity of additive intercropping with differing population densities and within-row sowing configuration will be worthwhile to provide farmers with additional productive diversification options resilient to climate shocks. Also, I recommend a modelling work to investigate the long term impact of intensification on soil fertility to support continuation of intensified production systems.

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Summary

Food security is a critical issue in the Guinea savanna of northern Ghana where about 60% of the rural population mostly smallholder farmers are food insecure. Food security results from poor crop yields and the inability of households to purchase required supplemental food. Poor crop yields result from low soil fertility compounded by erratic rainfall in the single cropping season. Rapid population growth means that the numbers of food insecure people are likely to increase. This necessitates sustainable intensification and diversification to increase crop production per unit area of land to meet the growing food demand. This thesis focused on testing spatial and temporal intensification and diversification options suitable for the variable biophysical and socio-economic conditions of smallholder farming systems in the Guinea savanna to increase productivity, mitigate the risk of crop failure, and thus to increase food self-sufficiency and income of smallholder farms.

One site in the southern Guinea savanna (SGS: favourable soils and rainfall) and one in the northern Guinea savanna (NGS: poor soils, less rainfall) were used for the study. In each site, on-farm experiments were conducted on three fields differing in soil fertility (fertile, medium fertile, poorly fertile). The amount of N_2-fixed and N contributed by grain legumes (cowpea, groundnut, soybean) to soil fertility improvement in sole and intercropping were quantified. The potential of replacement intercropping of maize with grain legumes in increasing resource use efficiency and crop productivity relative to sole crops was determined. The productivity of relay (additive) intercropping relative to the more common legume-cereal rotation system was assessed. Thereafter, scenario analysis was performed with household data from the N2Africa Ghana project supplemented with data from the on-farm experiments and literature to test the potential impacts of intensification and diversification options on household food self-sufficiency. The scenarios included: I – intensification of grain legumes alone; II – intensification and diversification through additive intercropping; III – intensification of both maize and grain legumes to achieve 80% of the maximum yield of maize and the grain legumes under farmers' current practices.

Sole legumes fixed a larger amount of N_2 (up to 183 kg N ha^{-1}) than under intercropping (up to 97 kg N ha^{-1}). The soil N balance was generally positive and similar between intercrops and sole crops suggesting that both systems could be sustainable. Low soil N stimulated grain legumes in the poorly fertile fields and in the NGS with poorly fertile soils to rely more on atmospheric N_2 for growth. However, the larger production of biomass in fertile fields and in the SGS with generally more fertile soils and higher rainfall resulted in 11 to 31 kg ha^{-1} more N_2-fixed in fertile fields than in poorly fertile

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fields, and 9 kg N ha^{-1} more in the SGS than in the NGS. Nevertheless, larger biomass and grain yields in fertile fields and the SGS were achieved with greater uptake of N leading to more positive soil N balance in poor fields and the NGS.

Across all fields and sites, intercropping enhanced efficiency in the use of land and radiation resulting in a 26% to 46% yield advantage over sole cropping indicated by land equivalent ratios of 1.26 in maize-soybean intercropping to 1.46 in maize-groundnut system. Intercropping also gave generally larger net benefits than sole cropping of maize or grain legumes. Intercropping of maize and grain legumes within the same row was more productive and profitable than distinct alternate row arrangements of the two crops.

The legumes in poorly fertile fields were more competitive with the maize crop than in fertile fields due to the greater reliance on atmospheric N_2 for growth and less shading by maize leading to 23% greater intercrop yield advantage. The efficiency and productivity of intercrops were also 14% greater in the drier site in the NGS than in the wetter site of the SGS. Yet the absolute larger grain yields achieved in fertile fields and in the SGS with comparatively better soil fertility and rainfall resulted in greater net benefits. This suggests that intercropping is beneficial both in poor and fertile fields, and in favourable and adverse biophysical environments except that the benefits take different dimensions.

Legume-cereal rotation is superior in increasing the yield of maize without N fertiliser compared to relay cropping of maize and rotation of maize with a natural fallow. The yield of maize that succeeded groundnut and soybean in rotation without N fertiliser increased by 0.38 t ha^{-1} in NGS to 1.01 t ha^{-1} in SGS compared with continuous cropping of maize due to residual N and non-N benefits. Sowing of cowpea at the onset of the season and relaying maize at least 2 – 4 weeks later led to maize yield decline ranging from 0.29 t ha^{-1} in the wetter SGS to 0.82 t ha^{-1} in the drier NGS due to inadequate rainfall. When maize was sown at the beginning of the season and cowpea was relayed at least 3 – 5 weeks later, the cowpea yield reduction was similar between the SGS and NGS and ranged from 0.18 t ha^{-1} to 0.26 t ha^{-1}. Over two seasons, the cumulative grain yield of sowing maize first and relaying cowpea was similar to that of the legume-cereal rotation systems even though the cowpea failed to yield in the first season. This indicates that such relay cropping is a promising ecological intensification and diversification option suitable for increasing crop productivity in smallholder farming systems in the Guinea savanna and under adverse climatic conditions.

The scenario analysis showed high levels of food insufficiency with current farming practices (baseline) in the Guinea savanna as only 56% of farm households in Northern region and 45% each in Upper East and Upper West regions of northern Ghana achieved 12 months of food self-sufficiency. In addition, 21% of households in the Northern region and 37% each in Upper East and Upper West regions were food self-sufficient for six months or less. The tested intensification and diversification options with grain legumes increased the proportion of food self-sufficient households across the Guinea savanna by 25% in Scenario I, 36% in Scenario II and 43% in Scenario III compared with the baseline situation. The share of farm households that could survive on their own food production for a maximum of half a year decreased by 19%, 24% and 27% in Scenarios I, II and III, respectively relative to the baseline.

The food self-sufficiency ratios of 70 – 93% of food self-sufficient households across the three regions ranged from at least 20% to over 300% above the threshold of one (1). This suggests that through intensification and diversification with grain legumes, most farm households will be self-sufficient in food and also generate marketable surpluses to earn income. These potential benefits resulted from the comparatively greater grain yields from intensification and diversification compared to the current cropping practices. Therefore, grain legumes provide promising strategies to contribute to achieving household food self-sufficiency and improved income in the Guinea savanna. However, the total size of land cropped matters, and improved access to markets and credit are needed to acquire the relevant inputs. The long-term sustainability of the tested intensification and diversification options is not certain. For this reason, further research using simulation modelling work is required to assess long-term nutrient balances, especially of N, and to predict likely changes in soil organic carbon and sustainability of the benefits.

Acknowledgements

The successful completion of this PhD thesis was possible due to committed support of various forms from many individuals and some institutions. I would like to express my profound gratitude to the Netherlands Organization for International Co-operation in Higher Education (NUFFIC), N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa project, and the Centre for Sustainable Rural Agriculture & Development (CSRAD) for the extended support. I am also grateful to the CSIR – Savanna Agricultural Research Institute (SARI, Tamale) for making available its facilities to support my field work for two years.

To my Ghanaian supervisory team, Pastor Dr Benjamin D.K. Ahiabor, Prof. Robert C. Abaidoo and Dr Samuel Adjei-Nsiah, I cannot thank you enough! Dr Ahiabor, you organised all logistics needed to conduct my field experiments when I was struggling, you made sure I had unlimited access to the required facilities at SARI and your lab. Prof Abaidoo, you thought me to be strong personally and as a scientist and to learn quickly from the best scientists around me. Dr Adjei-Nsiah, you have been there for me since 2009 when I worked with you for my MSc thesis. I cannot forget your recommendation which was key in getting the NFP for my PhD, and the unending guidance during my field work. To all three of you, you were exceptionally supportive from the beginning to the end – this is the fruit and I will remain forever grateful.

To my co-promoter, Dr Angelinus C. Franke, I must say that you are a great scientist! Your thought provoking and constructive comments and/or criticisms as well as your multiple expertise was a valuable asset in shaping up my scientific thinking and helped me in putting this thesis into a proper context. I have learnt a lot from you, and I am thankful for your support from the start to finish.

My greatest gratitude goes to my promoter, Prof. Dr Ken E. Giller. In all honesty, I do not know how to thank you. You are an exceptional promoter and a mentor for me. It has been a long journey with you. We first met in 2009 in Wageningen University during an agroforestry course as part of my MSc study, and later at a thesis information market at the Forum. The result was my MSc thesis supervised by Dr Mark van Wijk and Dr Samuel Adjei-Nsiah and examined by you – the genesis of this PhD. Your exceptional guidance, comments, suggestions and support were key to the successful completion of my thesis. We did not envisage the journey to be this challenging and long, but you stood by me, encouraged and supported me to this joyous end. I cannot forget the special moments when you and Irene invited me to your home for dinner. I am eternally grateful.

I express my heartfelt thanks to Linda, Alex-Jan, Charlotte, Karen and Ria for their wonderful administrative and logistical support at various times during my PhD. I sincerely appreciate the staff and students of the Plant Production Systems Group for sharing offices with me and the chit-chats at the coffee corner. Notably, I want to appreciate Bouba, Leonard, Edouard, Jiska, Brain, Renske, Wytze, Ashenafi, Esther M, Joy, Esther R, Alain N, Bert R, Marcel, Joost, Eva H, Eva T, Katrien, Mink S, Antoine, Pytrik, Maja, Martin, Mink Z, Elias, Arouna, Wim, Linda V, Dennis, Comfort, Gerrie, Lotte W, Lotte K, Tom, Siriluk, Uta, Ali and many others for making my stay at PPS comfortable. Wytze, I cannot forget your excellent support during the first year of my field work, thanks for everything. Edouard and Brain, I am appreciative of the wonderful support and encouragement at different periods during this journey. Antoine, my paranymph, thanks so much for the great support. Thanks to Dr Mark van Wijk for the initial support prior to the start of this PhD. It is unfortunate you were not at PPS to work together.

My heartfelt gratitude to the hardworking farmers of Kpataribogu, Alhaji Alhasan Bawa and his family, Mr Abukari Akanbe, and Bundunia, Mr Johnson Aboya and his family, Mr Nobert Anua and Mr Collins Tibiru who offered their land and time to support my field trials. Special thanks to Issah (Agricultural extension officer, Kpataribogu), Wahab (Kpataribogu), David (Bundunia) and James (Agricultural extension officer, Bundunia) for committing so much time to support the organisation and management of my field trials. Issah, I cannot forget taking me on your motor bike for the one and half hour's journey to visit Kpataribogu for the first time. Thanks also to Musa, Baba, Iddrisu (SARI driver), Jonathan and Edwin (Dr Ahiabor's lab), Prosper (Soil Chemistry lab, SARI), Alhasan, the late Imam Alhasan, Clementina, Esther and Nathaniel for the different roles you played in supporting my field work. Sumaila, I still remember how you had to risk traveling on that small and old motor bike for close to two hours that fateful evening to rescue me by fixing my car, which broke down in the middle of nowhere on my way home from the field. Thanks so much. All the other farmers that participated in the data collection process deserve my commendation.

At the Technical Centre for Agricultural and Rural Co-orperation (CTA), I had the privilege to work with two wonderful supervisors: Ken Lohento (Senior Programme Coordinator, ICT4Ag) and Dr Benjamin Addom (Team Leader, ICTs for Agriculture) who did not only supervise my work at CTA but also showed concern for my PhD and allowed me space to finalise my thesis. Thanks so much Ken and Ben for this. Thanks also to Arsene, Kudzanai, Didier, Folake, Aichetou, Olivier, Imelda, Mejury, Mariam, Felix, Hilda, Shelly-Ann, Oluwaseun, Noldi, Marion and the other colleagues for the nice interactions and for making my stay at CTA comfortable and memorable.

My sincere thanks to the following former and current Ghanaian students of Wageningen University and Van Hall Larenstein: Linda, Mathew, Claudia, Adu-Gyamfi, Padlas, Pascal, Nelson, Ruth, Confidence (especially for mapping my trial sites), James, Kingsley, Kwame, Ellorm, Ernest and Daniel. Thanks for the great moments we had together.

Special gratitude to Dr Nashiru Sulemana, Mr Ebenezer C. Adebah, Pastor Justice A. Quarcoe, Mr Emmanuel Ahoa, Rev Jean Bille Acquah, Dr Alexander Nuer, Mr Daniel N. Bomah and Mr Kwasi for the tremendous support and encouragement at various stages during this PhD journey. Justice, you have always been a pillar behind me , thanks my big brother.

To my brothers from different mothers, Eric Menlah, Patrick Menlah, Geoffrey Agbodohu and Philip Ndede, let me just simply say thank you for the unending concern, the marvellous support for the field work and the encouragement from day one till now. I am grateful also to Richard, Martin, Rose, Martha, Rosemond, Francis C, Joshua, Linda, Mavis, Morkeh, Dorcas, James, Naomi, Festus, Ackon, Julie and Elvis for the endless support and encouragement. Francis Annor, it was always a pleasure for you to take me on your motor bike to anywhere and you really helped me to settle in Tamale, thanks so much.

To Susana Kwofie, I cannot thank you enough! For two and half yours in northern Ghana, you were there for me, from the shops and markets to get inputs and other materials, from the lab to the fields, from traveling the long hours from Tamale to Bundunia and Kpataribogu, and the whole day journeys from western to northern Ghana. You did these without asking for any reward. You are one of a kind and I am eternally grateful for being there for me from the onset to this end. Jemima Afari-Kwarteng! I don’t know how to thank you enough. You and Emmanuel gave me immeasurable support and encouragement. Jemima, during some difficult times in this journey, especially 2017 to 2019, you were there for me, you did everything to ensure that I had sound mind and concentration to work hard until I get to the finish line. I am finally at the finish line. You are special and I am forever grateful for everything.

My deepest gratitude to my family: Mr Kwaw Kermah, Miriam B. Kermah, Miezah Bomo, my lovely sisters, the late Janet Ebah Kermah, Ernestina Kermah, the late Augustina Morkeh and Doris Ndede for all the love, care and encouragement during this journey. Janet and Augustina, it is unfortunate you are not here to celebrate this achievement, but I know sincerely that you are proud of me. To my nephews and nieces, Ndede, Isaac, Godwin, Stephen, Gloria, Jemima, Bernice, Lydia, Vivian and the others, thanks for the support and for being there for me. Special thanks also to Mr Ernest Kouassi, Uncle Menlah and Egya Ndah for being there for me and my family, especially during the difficult times, I appreciate your advice and support.

Finally, I am eternally indebted to my children, Janice Ebah Kermah and Michael Kodwo Kermah Jnr for enduring so much during my long absence from home. Michael Jnr, at some point when I cannot give you a definite answer as to when exactly I will come home, you will get angry and smash the phone. It is finally done, and I know you both are now proud of me.

List of Publications

Peer-reviewed journal articles

Kermah, M., Franke, A.C., Ahiabor, B.D.K., Adjei-Nsiah, S., Abaidoo, R.C., Giller, K.E., 2019. Legume-maize rotation or relay? Options for ecological intensification of smallholder farms in the Guinea savanna of northern Ghana. Experimental Agriculture 55, 673–691.

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Basset, N., **Kermah, M.,** Rinaldi, D., Scudellaro, F., 2010. The net energy of biofuels. EPROBIO IP June 2010, Foggia, Italy.

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PE&RC Training and Education Statement

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Biological nitrogen fixation: implications for soil fertility management and food security for smallholder farmers in Ghana

Writing of project proposal (4.5 ECTS)

- Exploring legume-rhizobium symbiosis towards increasing crop production, food security and improved economic livelihoods in northern Ghana

Post-graduate courses (6 ECTS)

- Tropical farming systems with livestock; WIAS, WUR (2013)
- Statistics for the life sciences; WIAS, WUR (2017)
- Grasping sustainability; SENSE, WUR (2017)

Invited review of (unpublished) journal manuscript (11 ECTS)

- Field Crops Research: dry matter accumulation and grain filling features of soybean and maize in intercropping (2017)
- Agronomy for Sustainable Development: crop-livestock interactions in maize-based cropping systems (2017)
- Experimental Agriculture: climbing bean phenotypic features for selecting genotypes suitable for intercropping with maize (2018)
- International Journal of Agronomy: herbaceous legumes intercropping for weed management in coffee plantations (2018)
- Advances in Agricultural Science: influence of blended fertilisers on soil chemical properties (2018)
- Field Crops Research: seasonal and year-round intercropping systems for smallholder farmers (2018)
- Nematropica: prevalence and severity of damages caused by nematodes on yam (2018)
- Field Crops Research: doubled-up legume systems for production efficiency and economic returns (2019)

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- Agricultural Systems: ecosystem services provision of grain legume-cereal intercrop combinations (2019)
- Crop and Pasture Science: impact of root contact on nitrogen transfer in legume-maize intercropping systems (2019)
- Field Crops Research: improving crop yields and resource use efficiency through legume-maize intercropping (2019)

Deficiency, refresh, brush-up courses (10.5 ECTS)
- Quantitative aspects of crop production; HPP, WUR (2012)
- Systems analysis, simulation and systems management; PPS, WUR (2012)
- Basic statistics; Biometris, WUR (2012)

Competence strengthening / skills courses (1.8 ECTS)
- PhD Competence assessment; WGS, WUR (2013)
- Project and time management; WGS, WUR (2017)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)
- PE&RC Weekend (2012)
- PE&RC Day (2012)
- WGS PhD Workshop carousel (2012)

Discussion groups / local seminars / other scientific meetings (5.8 ECTS)
- CSRAD Seminars; Ghana (2013-2015)
- SIAS Meetings; the Netherlands (2016-2017)

International symposia, workshops and conferences (3.4 ECTS)
- Joint World Cowpea & Pan-African Grain Legume Research Conference (2016)
- N2Africa International Workshop (2016)

About the author

Michael Kermah was born on 7 March 1978 in Ngalekyi, a small coastal town in the Western Region of Ghana. He had his primary and Junior High School education in this town, and his Senior High School education at Nkroful Agricultural Senior High School. In November 1999, he enrolled for the Bachelor of Science degree in Agriculture at the University of Cape Coast in Ghana and graduated in June 2003. In November 2004, he joined the Ghana Education Service as an Agriculture and Integrated Science Teacher at Nkroful Agricultural Senior High School, the same institution where he did his National Service a year before. He later joined the 'Forest Livelihoods and Rights for Sustainable Forest Resources Management' project of CARE International Gulf of Guinea. He implemented this project in the Wassa Amenfi East Municipal in Ghana from June 2007 until July 2008 when he was awarded a Netherlands Fellowship Programme (NFP) to pursue MSc in Organic Agriculture at Wageningen University. He graduated in 2010 with specialisation in Agroecology and a minor specialisation in Environmental Policy. His MSc project focused on analysis of climate variability and change and the impact on changes in cropping systems in the forest-savanna transition agroecological zone of Ghana. After completing his MSc, he was awarded a Norman E. Borlaug Global Research Alliance Fellowship by the United States Department of Agriculture. The corresponding research focussed on assessing environmentally friendly cropping systems to reduce greenhouse gas emissions was conducted at the University of Hawaii in the USA. At the same period, he worked with the Centre for Sustainable Rural Agriculture & Development (CSRAD, formerly SARD Foundation), a national NGO as a Research Associate, held the same position after starting his PhD and was later made the Director. Michael has led several consultancies on environmental and natural resources management, sustainable agriculture and rural livelihoods for some national and international organisations. He is currently a Consultant (Junior Expert – Digitalisation for Agriculture) within the ICTs for Agriculture Team at the Technical Centre for Agricultural and Rural Co-operation (CTA) in Wageningen, the Netherlands.

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The research presented in this thesis was funded by the Netherlands Fellowship Programme (NFP) of the Netherlands Organization for International Co-operation in Higher Education (NUFFIC), and the Bill & Melinda Gates Foundation through a grant to Wageningen University to support the project N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa (www.N2africa.org).

Cover design
Proefschriftmaken (www.proefschriftmaken.nl)

Cover photos
Michael Kermah