Benefits of new technologies for grain legume cultivation for smallholder farmers in northern Ghana, as promoted by the N2Africa project

Dorien Westerik
970525945090

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Instructor: Joost van Heerwaarden
Chair group: Plant Production Systems (PPS)

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1. Preface

As a final product of the BSc phase of Plant Sciences, a thesis is written. This study is supposed to be a logical consequence of all my previously gathered knowledge and skills. After I completed courses such as Introduction Quantitative Agroecology, Systems Analysis Simulation and Systems Management, Soil-Plant Relations and Crop Ecology, my particular interest in agricultural systems in developing countries was raised. N2Africa is a project which provides great opportunities for smaller studies concerning agricultural development. The agronomic knowledge that gathered throughout the completion of the previously mentioned courses will be helpful in the analysis of crop responses. Statistic skills that I developed in the course Advanced Statistics will be useful in the interpretation of the data. Courses like Global Food Security, African History and Globalization and Sustainability of Food Production and Consumption will contribute to the evaluation of the socio-economic aspects of this study. All in all, the knowledge and skills gathered throughout my study program are a fine base for the subject of this study: An analysis of the benefits of new technologies for grain legume cultivation for smallholder farmers in northern Ghana, as promoted by the N2Africa project. I want to thank my supervisor Joost van Heerwaarden for his continuous support and guidance during the study.

2. Abstract

Harsh climate conditions and poor soils pose challenges for agricultural production by smallholder farmers in Northern Ghana. N2Africa promotes interventions such as increased grain legume cultivation and application of mineral fertilizers and/or rhizobium inoculants, with the aim of improving soil fertility and increase yields. Little is known about the actual benefits and costs associated with the implementation of the promoted technologies for smallholder farmers. In this study, groundnut and soybean yields have proven to increase significantly when the new technologies are implemented. However, the variation in crop yields is high between districts in northern Ghana and between individual farmers. The variation in crop response to the new technologies can partly be explained by the variation in soil properties of the plots, and is expected to be influenced by climatic variability and adaptive capacity of the farmers. For most farmers in northern Ghana, the benefits of the crop responses to the promoted technologies outweigh the direct costs. However, the new technologies are relatively less cost-effective than the conventional technologies, due to the additional investment costs.

3. Introduction

3.1. Increasing agricultural productivity by means of new technologies

Raising agricultural productivity is essential for reducing poverty and increasing food security in developing nations. In contrast to many other regions, sub-Saharan Africa (SSA) has seen little increase in crop yields over the past decades (Ehui & Pender, 2005; Ray et al., 2012). Increased agricultural productivity and incomes of smallholder farmers in rural areas can drive poverty reduction and lead to structural economic change (Dorward & Kydd, 2005). In order to sustainably increase agricultural productivity of smallholder farms, it is essential to address problems associated with soil fertility and land degradation (Jama & Pizarro, 2008). The implementation of grain legumes in cropping systems can play an important role in maintaining soil fertility through biological nitrogen fixation (Wani, Rupela & Lee, 1995; Peoples, Herridge & Ladha, 1995). Grain legumes contribute to the uptake of essential protein and minerals in the diet, help in reducing pest and disease build-up, and enhance N availability for subsequent crops (Franke, van den Brand & Giller, 2014; Ncube et al., 2007; Peoples et al., 2009; Tharanathan & Mahadevamma, 2003).

In addition, there are multiple benefits to the implementation of new technologies such as Rhizobium inoculants and phosphorus fertilizers in the farming system. Rhizobia are nitrogen-fixing bacteria which are known to form a symbiotic association with the roots of leguminous plants. The bacteria provide the plant with a continuous supply of reduced nitrogen, biologically fixed from the air (Fatima, Zia & Chaudhary, 2007). The leguminous plant is thus provided with nitrogen by the presence of the bacteria. Yields are expected to increase in the presence of Rhizobia, even though the farmer does not have to apply expensive nitrogen fertilizers (Stacey & Upchurch, 1984; Young, Juang & Chao, 1988). In addition the treatment of seeds with Rhizobia, new technologies include the application of phosphorous (P) fertilizers in the soil. P fertilizers have shown to enhance biological nitrogen fixation in legumes and enhance yields (Ndakidemi et al., 2006; Kaizzi et al., 2012; Ikeogu & Nwofia, 2013; Tairo & Ndakidemi, 2013).

The N2Africa project promotes these promising legume technologies with the aim of improving nitrogen fixation by grain legumes on smallholder farms to improve income and soil fertility (N2Africa, 2017). Implementation of N2Africa technologies across countries in SSA has shown to increase yields by 13 to 138% compared to control plots (Ampadu-Boakye, Stadler & Kanampiu, 2017). However, the crop response to new technologies may vary strongly as a result of different climatic conditions (Antwi-Agyei, Stringer, & Dougill, 2014), soil types and agricultural practices (Concha et al., 2012). In addition, different farm types face different input costs, and net benefits of crop production can differ greatly per crop type (Franke, van den Brand & Giller, 2014). Grain legume technologies do not only need to fit within the biophysical environment of farming systems, but also within the market and institutional context of the value chain in a specific region (Farrow et al., 2016).

3.2. The case of Northern Ghana

This study proposes to study the cost-effectiveness of legume technologies and its variation among different types of farmers in Northern Ghana. Within this specific region, cultivation, annual rainfall, temperature and soil characteristics may vary greatly (Antwi-Agyei, Stringer, & Dougill, 2014; Callo-Concha, Gaiser & Ewert, 2012). Main cereal crops are maize, sorghum, millet and rice. Groundnut is the main legume cultivated in the northern regions of Ghana, followed by other legume species like cowpea, soybean and Bambara bean. These crops are both cultivated in mixed cropping systems as well as in monocultures (Schindler, 2009). Although strongly varying across different regions, average yields appear to remain far below potential for all crops (Antwi-Agyei et al., 2012; Breisinger et al., 2011; Callo-Concha, Gaiser & Ewert, 2012; Franke, Rufino, & Farrow 2011).

Soils in the northern regions of Ghana are generally characterised by low levels of organic matter. This is due to high temperatures which lead to a rapid decomposition of organic matter in the soil, and cultivation practices like slash-and-burn systems (Dessalegn, 2006). Soil organic matter can decline even further due to a low organic input during the cropping season, leading to low levels of nutrients like N, P, K, S, and Zn. The soil texture is mainly sandy, generally has a low water-holding capacity in the top layers, and is very susceptible to erosion and compaction (Callo-Concha, Gaiser & Ewert, 2012).

The biophysical circumstances and low yields in northern Ghana make improved soil management of particular great importance. It is expected that a change in cultivation practices by implementation of the promoted technologies will lead to a structural improvement of soil quality, and thus higher yields. However, the question remains whether the implementation of the promoted technologies is economically feasible for individual smallholder farmers. In other words: whether an increased yield and associated economics benefits of improved soil quality outweigh the costs of the required inputs.

3.3. Cost-effectiveness of new technologies

Many factors can determine whether a new technology can be successfully implemented. However, it is essential that a new technology is economically feasible for a farmer. Farmers are likely to adopt new technologies only when the benefits outweigh the costs, i.e. when new technologies are cost-effective. However, it is expected that cost-effectiveness varies strongly among different types of farmers (Franke, van den Brand & Giller, 2014). Insight on potential profit can be gained by assessing the crop responses to new technologies and comparing these to the crop response to conventional technologies.

For a technology to be profitable, it first of all needs to offer a distinct yield advantage over existing technologies. The extent to which this is the case may depend on biophysical constraints as well as on agronomic constraints due to a lack of labour, inputs etc. Even if a yield advantage is obtained, profitability may be reduced by socio-economic factors. Particularly for farmers with small profit margins, small costs associated with technology implementation, marketing of produce, and accessing inputs may add up to make investments in improved productivity unattractive. Therefore, it is important to evaluate the constraints on adoption of new technologies by smallholder farmers in the widest sense, including both biophysical, management and economic conditions.

Farmers participating to the N2Africa project received input packages containing legume seed (cowpea, soybean, groundnut), mineral fertilizer and/or rhizobium inoculants (Ray et al., 2012; Stadler, van den Brand & Adjei-Nsiah, 2016). For a subset of these farmers, yield data was collected on both N2Africa trial fields, and the farmers' own main fields. Also managemental practices and farm and household characteristics were recorded. This data is highly suitable for assessing the distribution of agronomic responses among different types of crops and farm types. However, cost effectiveness is not only dependent on yield, but is also determined by socio-economic factors. Little is known about the actual profit that can be made with increased yield in the specific context of northern Ghana. Therefore, it is important to gain insight in the actual farmgate prices for selling agricultural produce as well as in costs going along with the implementation of the promoted technologies.

Determining cost-effectiveness can be complex, as many aspects are involved including farmers' willingness to pay for new technologies, variation in (market) prices for purchasing technology options, varying (farmgate) prices for selling agricultural produce, and factors influencing these costs and benefits. Also, implementation of the promoted technologies are expected to influence crop yields for subsequent years (Peoples et al., 2009). For this study, time and means are not sufficient to go in depth on all aspects and will therefore mainly focus on the direct agronomic benefits of the promoted technologies for separate years, and their economic value. Only direct costs like fertilizers, inoculants and other input prices will be taken into consideration. The study will focus on the cost-effectiveness of the promoted technologies in the northern regions of Ghana, one of the eleven areas where N2Africa operates. Agricultural growth in these regions has mainly been driven by land expansion, but land productivity has barely increased over the past decades and yield gaps are high for many important crops (Breisinger et al., 2011). Room for agricultural improvement combined with abundantly available data and knowledge, makes this area a suitable example for the assessment of agronomic benefits and the economic value of technologies promoted by the N2Africa project. Although this study will thus be performed within the specific context of northern Ghana, it can serve as an example for countries in SSA with similar agronomic and socioeconomic contexts.

3.4. Objectives and hypothesis

The main goal of the paper is summarized in the following research question:

To what extent do new farming technologies, as promoted within the N2Africa program, increase yield and benefits for smallholder farmers in northern Ghana?

In order to create an outline for this paper and provide with a well-supported answer to this question, a number of sub questions are formulated:

I. *What are the average crop yields using the promoted new technologies, and do they exceed average crop yields under conventional technologies?*
II. *Are crop responses consistent with the expected responses given the local biophysical conditions and according to literature?*
III. *How are the crop responses distributed amongst farmers, and can the differences in responses be explained by biophysical, management, household or farm characteristics?*
IV. *Do the benefits of the crop responses to new technologies outweigh the direct costs?*

First of all, it is hypothesized that the average crop yields using the promoted new technologies do exceed yields under conventional technologies. It is expected that observed yield response to inputs is correlated with the potential response determined by climatic conditions and soil properties, and will be similar to what is reported for comparable treatments in the literature. Furthermore, it is hypothesized that there is a large distribution in responses amongst farmers, partly due to variability in soil properties and climate, agricultural practices, and household or farm characteristics. Ultimately, it is expected that the benefits due to the increased crop yield using the new technologies outweigh the additional direct costs.

4. Material and methods

4.1. Site description

The N2Africa project targeted farmers in the three Northern regions of Ghana; namely Chiriponi, Savelugu and Yendi districts in the Northern region, Binduri, Bawku-West districts in the Upper East region, and Nadowli and Wa-West districts in the Upper West region (Farrow et al., 2015) . The annual mean temperature in this region is between 25°C and 30°C. Precipitation is annually between 100 and 1500 mm, but is lowest in the Upper East and Upper West region (Farrow et al., 2015; Antwi-Agyei et al., 2012). Climatic conditions and soil types may vary highly across the regions, which will be taken into consideration during the study.

4.2. Data collection

During the course of the N2Africa project primary data of crop production, agricultural practices, demographic and biophysical variables in the study areas were collected by short questionnaires to the farmers. The goal of the questionnaires is to evaluate the performance and adaptation of the proposed technologies under farmer's management and to observe how household characteristics and management practices affect the performance of the new technologies (Bravo, 2017). In the Northern regions of Ghana, 171 focal farmers were selected in 2016 for more intensive data collection done under supervision of N2Africa staff. Data was collected with the use of mobile forms following standardized protocols, so the data collected across all focal farmers can be combined and compared (Bravo, 2017). Two observations were taken on each farm: one on the farmers' main field, where crops were grown with conventional technologies (will be referred to as Own treatment). The other observation was taken on an intervention test plot on the farm, where new technologies were implemented (will be referred to as N2Africa treatment). Data was included of groundnut (*Arachis hypogaea)* and soybean (*Glycine max)*, being two of the most widely grown legumes by smallholder farmers in Northern Ghana. The N2Africa fertilizer pack contained TSP (Trisodium Phosphate) fertilizer, and improved soybean and groundnut varieties which were bred for higher yields. In the case of soybean, the pack also contained Rhizobium inoculants of the brand LegumeFix (Ampadu-Boakye, Stadler & Kanampiu, 2017). TSP fertilizer was consistently applied at the N2Africa test plots, as well as the improved varieties. The improved soybean varieties used in the N2Africa test plots were Afayak and Soungpoung, the improved groundnut varieties were Samnut 22 and 23. The inoculants were applied at some N2Africa test plots, but were not consistently applied at all plots. In the analysis of the average crop responses (section 4.3.1) there will be no distinction between these plots, and will be considered as one treatment. Later on in the study, the potential effects of inoculation on soybean yield will be discussed.

4.3. Methods

4.3.1. Analysis of average crop responses to new technologies

Prior to the statistical analysis of the data, the dataset was cleared from observations with missing yield data points. Only farms with observations for both treatments 'Own' and 'N2Africa' where used in the analysis. Grain yield (in kg ha^{-1}) was calculated from the observed grain weight and plot area, and was taken as a measure for the crop response to either of the treatments.

Grain yield was modelled as a function of different terms (Table 1): the different technologies (Name_treatment, with levels Own and N2Africa); the different crops (Pack_species, with levels Groundnut and Soybean); the different districts (Lga_district_woreda, with levels Savelugu, Binduri, Yendi, Bawku Municipal, Wa-West, Nadowli, Bawku West), and the individual farms (Farm_ID).

Table 1: Overview of the terms used in the statistical analysis of crop responses

Model terms	Data type	Levels	Unit	Fixed/random terms
Estimated.grain.yield_kg_ha	Numeric variable	-	kg ha^{-1}	-
Name_treatment	Factor	2: Own, N2Africa	-	Fixed
Pack_species	Factor	2: Groundnut, Soybean	-	Fixed
Lga_district_woreda	Factor	7: Savelugu, Binduri, Yendi, Bawku Municipal, Wa-West, Nadowli, Bawku West	-	Fixed
Farm_ID	Factor	118: Individual farms	-	Random

The analysis will be done in R studio, in which a linear mixed-effects model will be used (1).

lmer (estimated.grain.yield_kg_ha ~ name_treatment * lga_district_woreda * pack_species + (1|farm_id) , data=dat) (1)

The two-sided linear formula describes both the fixed-effects and random-effects part of the model, with the response (estimated.grain.yield_kg_ha) on the left, and the fixed-effect terms (name_treatment, lga_district_woreda and pack_species) and random-effect terms (farm_id) on the right. The fixed effects have levels that are of primary interest, while the random-effect terms levels are rather thought of as a random selection from a much larger set of levels and are not of primary interest. The linear mixed-effects model is fitted to the data via restricted maximum likelihood.

The lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017) will be used to calculate Analysis of Variance (ANOVA) Tables for model 1, providing inference on the fixed-effect terms. The lmerTest package provides ANOVA tables of type III, which is not dependent on the order in which the fixed-effect terms are entered in the model. The package uses Satterthwaite approximation for denominator degrees of freedom for F-tests, in order to estimate the significance of the fixed-effect terms. The predictmeans package (Luo et al., 2014) will be used to make inferences from the linear mixed-effect model. This includes the calculation of the model means, SED of the means and LSD's for the different levels of the terms.

The calculated model means will be used to calculate the absolute response to the N2Africa treatment for both crops in all districts. The response is calculated as the absolute difference between the N2Africa treatment and the Own treatment.

4.3.2. Comparing the crop responses with the expected responses

In order to evaluate whether the observed grain yield responses to the N2Africa treatment would meet up to the expectations, the crop responses will be compared to responses to similar treatments in literature, namely the application of P fertilizer on both crops, and the inoculation of soybean. There will be distinguished between soybean responses to a treatment with or without the inoculation with Rhizobium. The literature that will be taken into consideration covers a wide range of countries in SSA, soil types, P application rates, crop cultivars and years. The means of the observed crop responses in literature will be compared to the means of the crop responses as calculated in section 4.3.1.

In addition, it will be evaluated whether the crop responses complied with the soil properties in Northern Ghana with the help of a system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). The QUEFTS system is designed to calculate crop yields as a function of the status of N, P and K in the soil, with calculated yields of unfertilized maize used as a yardstick. Crop yields are calculated by the QUEFTS model in four steps: The maximum quantity of these nutrients that can be taken up by maize is calculated from the potential supply if no other nutrients or factors are yield-limiting. Thereafter, the actual uptake of each nutrient is calculated from the potential supply of that nutrient, while taking into account the potential supply of the other two nutrients. Next, three yield ranges are calculated from the actual uptakes of N, P and K, and are combined in pairs. Finally, the ultimate yield estimate is calculated from the average of the yield estimates of the pairs (Janssen et al., 1990). For this study, crop-specific parameters for soybean and groundnut and average soil properties of the northern regions were obtained (personal communications with Joost van Heerwaarden) and will be implemented in the QUEFTS model.

The nitrogen fixation rate of groundnut is estimated at 101 kg ha^{-1} (Dakora et al., 1987). The nitrogen fixation rate of soybean was estimated at 111 kg ha^{-1}(Salvagiotti et al., 2008). Rhizobium inoculants are expected to increase the nitrogen fixation rate of soybean and increase yields (Stacey & Upchurch, 1984). However, it is uncertain how much Rhizobium inoculants exactly contribute to nitrogen fixation. For the scope of this study, the nitrogen fixation rate of soybean in combination with Rhizobium inoculants is estimated at 125 kg ha^{-1}. Water limited yield was set at 4000 kg ha^{-1} (personal communications with Joost van Heerwaarden), and average daily temperature was set at 27 °C. The application rate of P in the N2Africa treatment was estimated at 25 kg ha^{-1} (personal communications with Joost van Heerwaarden). The average yields of the farmers' own plot and average QUEFTS calculated yields without additional P will respectively be used as a control treatment. The absolute response to the treatment will be calculated by as the absolute difference between the average control yield and the average treatment yield (treatment-control).

As exact soil properties of the N2Africa intervention plots and farmers' own plots are unknown, it is not possible to calculate the expected crop responses for the locations used in section 4.2 and 4.3.1. However, specific soil properties from other plots (80 plots in total) in northern Ghana are available (personal communications with Joost van Heerwaarden). The soil properties of the N2Africa intervention plots and farmers' own plots are likely to fall within the same range as the available soil data. The QUEFTS model will therefore be applied to the available soil data in which P ranges between 0,6 and 34,6 mg kg^{-1}; K ranges between 0,05 and 0,32 mmol kg^{-1}; pH ranges between 6,0 and 7,8; and Soil Organic Content (SOC) (calculated from the amount of N in the soil) ranges between 2,5 and 8,5 g kg^{-1}. The QUEFTS calculated responses will also give insight in the individual effect of P, K, Soil Organic Content and pH on the crop responses to the N2Africa treatment. The effect of the variability of the soil properties on the distribution of the crop response to the treatment will be estimated. Afterwards, the assumptions and accuracy of the QUEFTS model will be evaluated.

4.3.3. Analyzing and explaining the distribution of crop responses among farmers

After analyzing the average crop responses to the new technologies (i.e. the N2Africa treatment), the extend of variation amongst farmers will be analyzed. Crop responses are calculated as the absolute difference between the estimated model means of the N2Africa treatment and Own treatment (N2Africa-Own). The variation in response will be expressed in terms of standard deviation and range, and visualized by a histogram. Subsequently, it will be investigated whether the response is randomly distributed, or may (partly) be explained by the effect of biophysical, socio-economic or managemental factors. At first, this is done by reviewing literature to invest whether it is plausible that these factors influence crop responses. Thereafter, factors potentially influencing crop responses will be implemented in a linear mixed-effect model (2) as fixed-effect terms and ANOVA tables will be computed to checking for a significant effect on the crop response.

lmer (estimated.grain.yield_kg_ha ~ name_treatment * factor (x) + (1|farm_id) , data=dat)

(2)

If factor (x) shows a significant effect on the crop response, it will be further examined by calculating the model means.

4.3.4. Benefits and direct costs

A cost-benefit analysis will be made in order to evaluate whether the benefits of the crop responses to the new technologies (TSP and Rhizobium inoculation) are sufficient in order to compensate for the investment costs. Only the expected direct costs and benefits will be taken into consideration.

Direct costs include the purchase of improved and local seed varieties for new and conventional technologies respectively. For an estimation of the costs of new technologies, the purchase of TSP inputs and Rhizobium inoculants are also taken into consideration. Because the costs of the improved seed varieties are unknown, they are estimated as a twofold of the costs of the conventional seed varieties. The costs are calculated in USD ha^{-1} $season^{-1}$, derived from the costs per kg input, and the amount of input used per hectare. Seed, fertilizer, and inoculant prices are provided by personal communications with Mats Hoppenbrouwers (2017).
Direct benefits are based on the average crop yields of both new and conventional techniques (calculated as described in section 4.3.1.) and an estimation of the farmgate prices in the three northern regions. Farmgate prices are provided by personal communications with Mats Hoppenbrouwers (2017).

An overview of the expected costs and benefits will be provided to give insight in the numbers used to calculate the cost-effectiveness.

An estimate of the cost-effectiveness of the new technologies is calculated from the profits (benefits minus costs) of both technologies, according to formula (3).

$$(Benefits_{new}-Costs_{new})-(Benefits_{conventional}-Costs_{conventional}) \quad (3)$$

Furthermore, the relative benefits (in USD) per USD invested in inputs will be calculated by dividing the benefits by the costs, according to formula (4).

$$(Benefits_{new}/Costs_{new})-(Benefits_{conventional}/Costs_{conventional}) \quad (4)$$

The overview of the expected costs and benefits will give insight in the extra costs coming along with the new technologies. To compensate for the extra costs, the benefits from additional grain yield caused by the implementation of the new technologies need to be sufficiently high. The threshold level will be calculated, and will be compared to the N2Africa trial data in order to gain insight in the proportion of farmers with sufficient yield increase.

5. Results

5.1. Crop responses to new technologies compared to conventional technologies

As described in section 4.3.1, the crop responses to the new and conventional technologies are estimated by a linear mixed model (1). The model estimated the grain yield response to the 'N2Africa' treatment for both groundnut and soybean in different districts of northern Ghana. The 'N2Africa treatment included the application of TSP, and in some cases also the inoculation of the seeds with Rhizobium. The model terms are significant, which means that there are significant differences between the levels of a single model term (Table 2). More precisely, there are significant differences between 'Own' and 'N2Africa' (P<0,0001), between groundnut and soybean (P=0,018), and between the districts (P<0,0001). The interaction between the districts and the treatment are significant (P=0,0074), as well as the interaction between the districts and the crops (P=0,00097). The presence of one of these terms may change the interpretation of the other.

Table 2: Analysis of Variance Table of the model (1). Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

Analysis of Variance Table of type III with Satterthwaite approximation for degrees of freedom

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	
name_treatment	104417	104417	1	104.99	213.762	< 2.2e-16	***
lga_district_woreda	86782	14464	6	105.00	29.610	< 2.2e-16	***
pack_species	2819	2819	1	105.00	5.770	0.0180554	*
name_treatment:lga_district_woreda	9165	1527	6	104.99	3.127	0.0073593	**
name_treatment:pack_species	727	727	1	104.99	1.488	0.2252178	
lga_district_woreda:pack_species	12023	2004	6	105.00	4.102	0.0009727	***
name_treatment:lga_district_woreda:pack_species	1264	211	6	104.99	0.431	0.8565992	

Model means were calculated for both groundnut and soybean (Figure 1 and 2). The average groundnut yield response (N2Africa-Own) is significant (LSD=387 kg ha^{-1}). On average, the groundnut grain yield was estimated by the model at 940 kg ha^{-1} for the Own treatment and 1459 kg ha^{-1} for the N2Africa treatment. This results in an average increase in yield of 519 kg ha^{-1} or 155% as an effect of the treatment.

The difference between the treatments is however not significant for Bawku-West, Nadowli, and Savelugu (LSD=387 kg ha^{-1}). Furthermore, large variation between the different districts is visible for both the N2Africa treatment and the Own treatment.

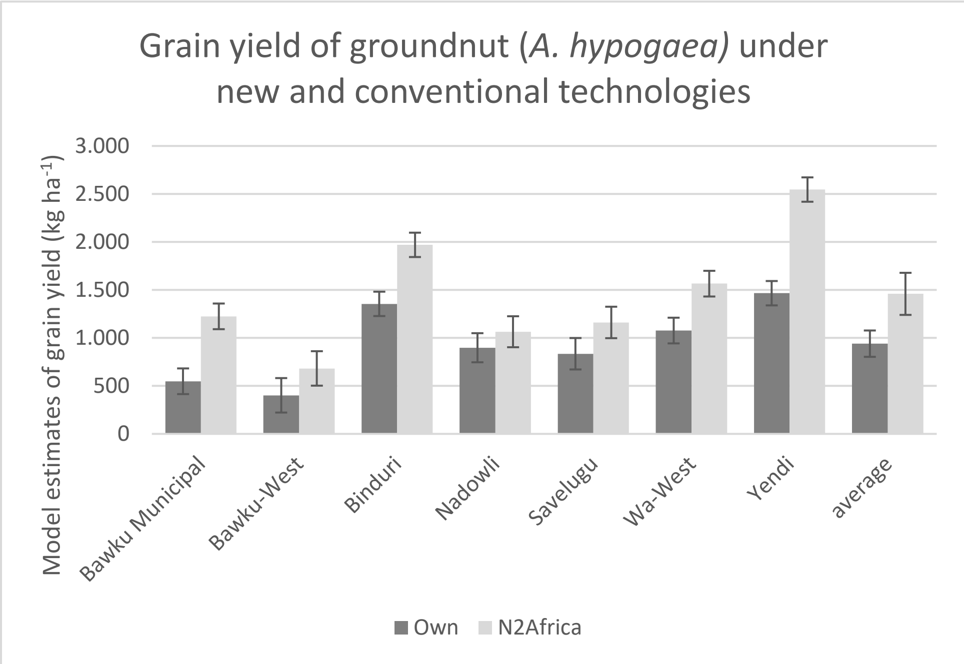

Figure 1: Comparison of model estimates of groundnut (*A. hypogaea*) grain yield under conventional technologies (Own) and new technologies (N2Africa) on plots in different districts in the three northern regions of Ghana in 2016. Error bars represent the Standard Error of the Mean (SEM).

The estimated soybean grain yield response to the N2Africa treatment is significantly higher (LSD=387 kg ha^{-1}) than to the Own treatment. On average, the soybean yield was estimated by the model at 820 kg ha $^{-1}$ for the Own treatment and 1222 kg ha^{-1} for the N2Africa treatment. An average increase in yield of 402 kg ha^{-1} or 149% is estimated by the model due to the N2Africa treatment. As well as for groundnut, large variation between the districts is visible for both treatments. The effect of the N2Africa treatment is not significant for Bawku-West, Nadowli and Savelugu (LSD=387 kg ha^{-1}).

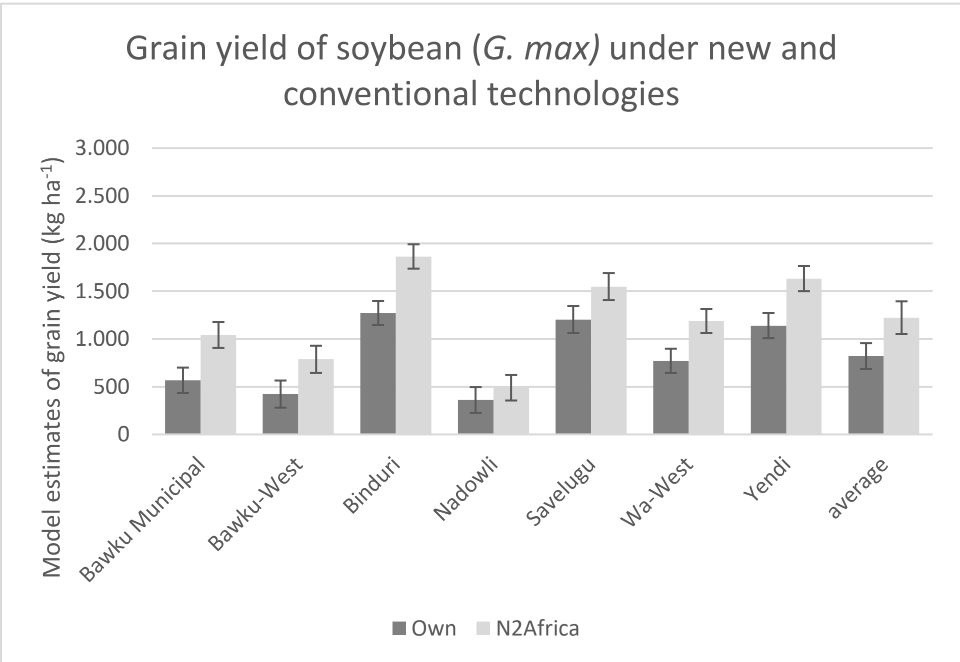

Figure 2: Comparison of model estimates of soybean (*G. max*) grain yield under conventional technologies (Own) and new technologies (N2Africa) on plots in different districts in the three northern regions of Ghana in 2016. Error bars represent the Standard Error of the Mean (SEM).

5.2. Comparison between the crop responses and expected responses

5.2.1. Literature review

The soybean and groundnut responses to new and conventional technologies (section 5.1) are compared to combined responses to similar treatments (P application and Rhizobium inoculation) in literature (Appendix 8.1 and 8.2). The literature taken into consideration covers a wide range of countries, soil types, P application rates, crop cultivars and years.

The literature shows an average increase of 252 kg ha^{-1} groundnut yield due to P application (averagely 27,3 kg ha $^{-1}$) compared to the control treatment without P application. The observed response of 519 kg ha^{-1} from the N2Africa data is thus slightly higher than the increase found in literature.

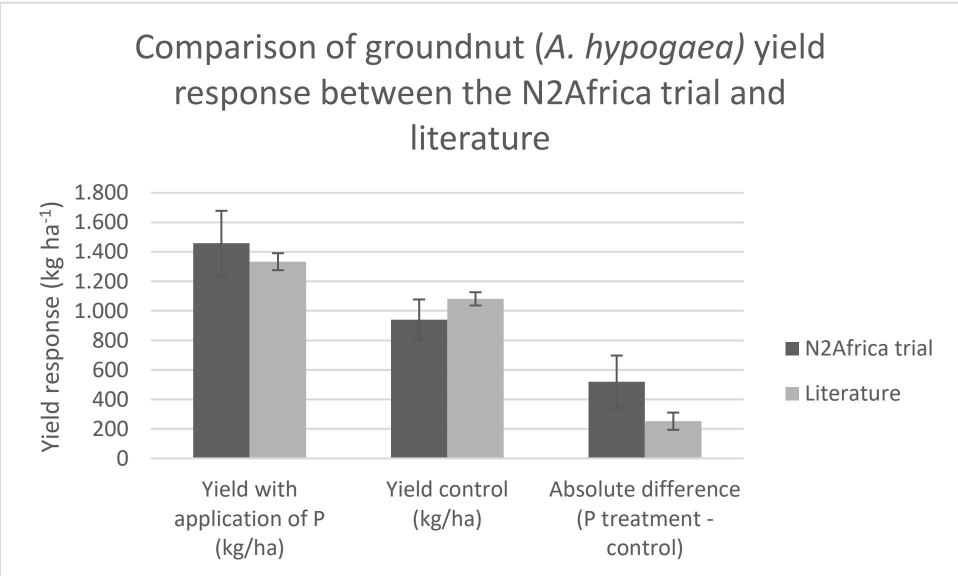

Figure 3: Comparison of groundnut yield response to P treatment in literature and N2Africa treatment in own analysis. In literature, the average P rate is 27,3 kg ha^{-1}. Error bars represent the Standard Error of the Mean (SEM).

The literature shows an average increase of 525 kg ha^{-1} soybean yield due to P application compared to the control treatment without P application. The P application rate is averagely 24,7 kg ha^{-1} in combination with applicated Rhizobium inoculants, and 30,0 kg ha^{-1} when no Rhizobium inoculants are applied. The observed response to the P treatment of 214 kg ha^{-1} in the N2Africa trial is lower than could be expected based on literature. However, the reference yield (no P application) for the farmers in the N2Africa trial is higher than the average reference yield from the reviewed literature.

According to literature, the effect of P application combined with Rhizobium inoculation of the seeds is found to be slightly higher, even though less P is applied on average. The observed response of 337 kg ha^{-1} from the N2Africa trial is lower than could be expected based on literature, where an average response of 600 kg ha^{-1} is recorded. Again, the reference yield (no P application and no Rhizobium inoculation) is higher for the farmers in the N2Africa trial than the average reference yield from the reviewed literature.

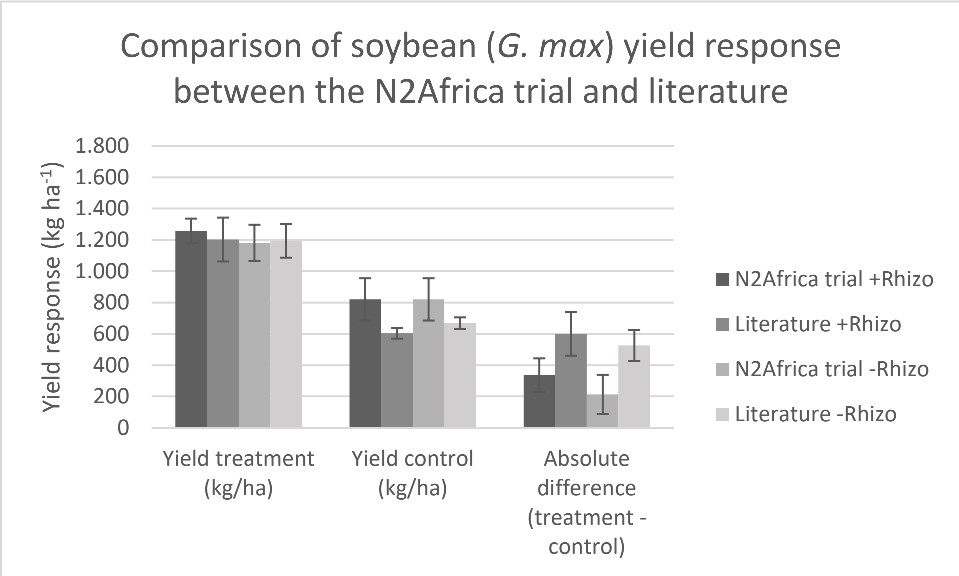

Figure 4: Comparison of soybean yield response to P treatment and inoculation with Rhizobium in literature and N2Africa treatment in own analysis. In literature, the average P rate is 24,7 and 30,0 kg ha^{-1} for treatments with and without Rhizobium inoculants respectively. The error bars represent the standard error of the mean.

5.2.2. QUEFTS model

As explained in section 4.3.2, responses to a P treatment of 25 kg ha^{-1} are calculated by the QUEFTS model as a function of the acidity, soil organic content (SOC) and P and K status of the soil. The means of the QUEFTS calculated responses are compared to the soybean and groundnut responses to new and conventional technologies (Section 5.1).

The crop responses from the N2Africa trial do generally comply with expected responses according to results from similar P and inoculant treatments in literature and the QUEFTS model. The QUEFTS calculated groundnut yields are slightly lower than the actual yields from the N2Africa trial. The differences are however not significant, and the absolute response as a result of the N2Africa treatment is in accordance with what could be expected based on the QUEFTS calculated response.

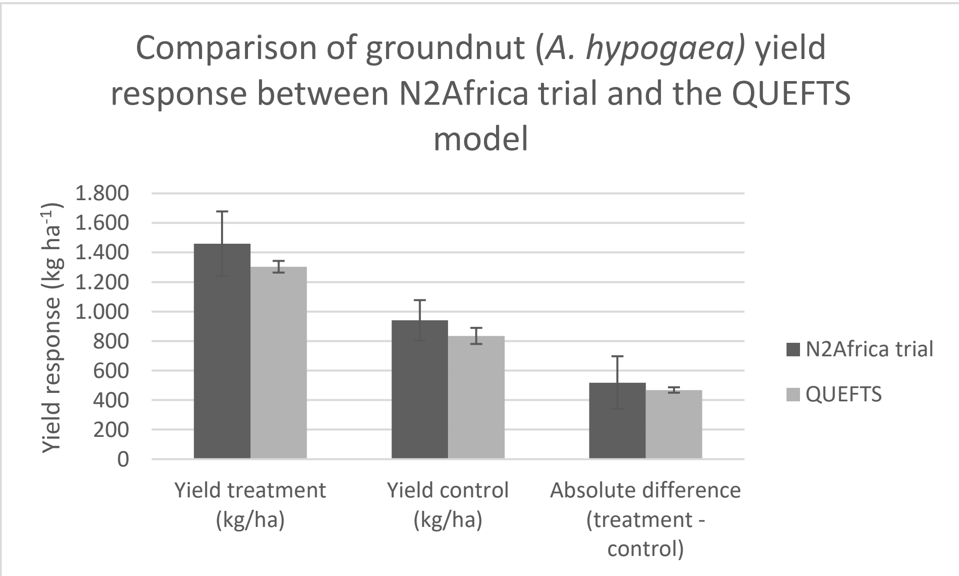

Figure 5: Average groundnut yield response to a P treatment of 25 kg ha^{-1} as calculated by the QUEFTS model compared to the average response to N2Africa treatment in own analysis. The error bars represent the standard error of the mean.

The QUEFTS calculated soybean yields are slightly higher than the actual yields from the N2Africa trial. The increase in yield as a result of the N2Africa treatment is therefore smaller than could be expected based on the QUEFTS calculation. Besides, the effect of Rhizobium inoculants as calculated by the QUEFTS model is found to be lower than the effect found in the N2Africa trial.

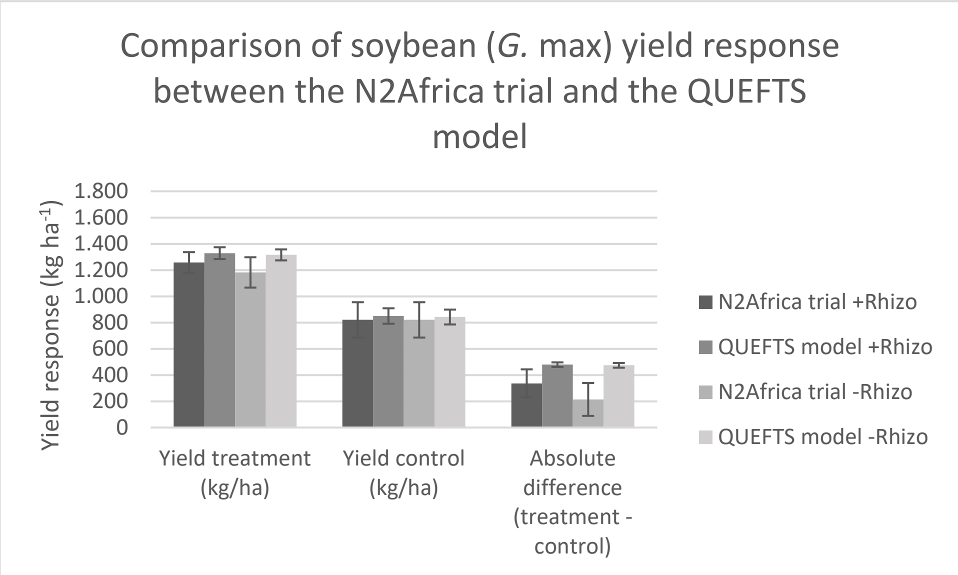

Figure 6: Average soybean yield response to a P treatment of 25 kg ha^{-1} as calculated by the QUEFTS model compared to the average response to N2Africa treatment in own analysis. The error bars represent the standard error of the mean.

According to the model, the response of groundnut and soybean are very similar (Figure 7), resulting from corresponding crop parameters inserted in the model. The response of soybean with Rhizobium inoculants is calculated to be slightly higher than soybean without Rhizobium, and both are calculated to be higher than the groundnut response. These small differences result directly from a different estimated N fixation rate, being the only distinction between the crop parameters in the model.

The average QUEFTS calculated responses to a P treatment of 25 kg ha^{-1} are based on a range of different soils in northern Ghana, which are highly variable in pH and P, K and organic matter content. Calculated responses are highly affected by these soil properties.

If soil P is low, the effect of the P treatment is expected to be high. The effect of the P treatment is linearly decreasing as the amount of P in the soil increases. For K, the opposite is expected to be true: if soil K is low, the effect of the P treatment is expected to be low. The response to the P treatment is expected to be lower when pH is above 7, according to the model. A pH value ranging between 6 and 7 is not expected to influence the response. The effect of the P treatment is linearly decreasing as the amount of SOC (estimated from the amount of N in the soil) increases: if SOC is low, the effect of the P treatment is expected to be high and vice versa.

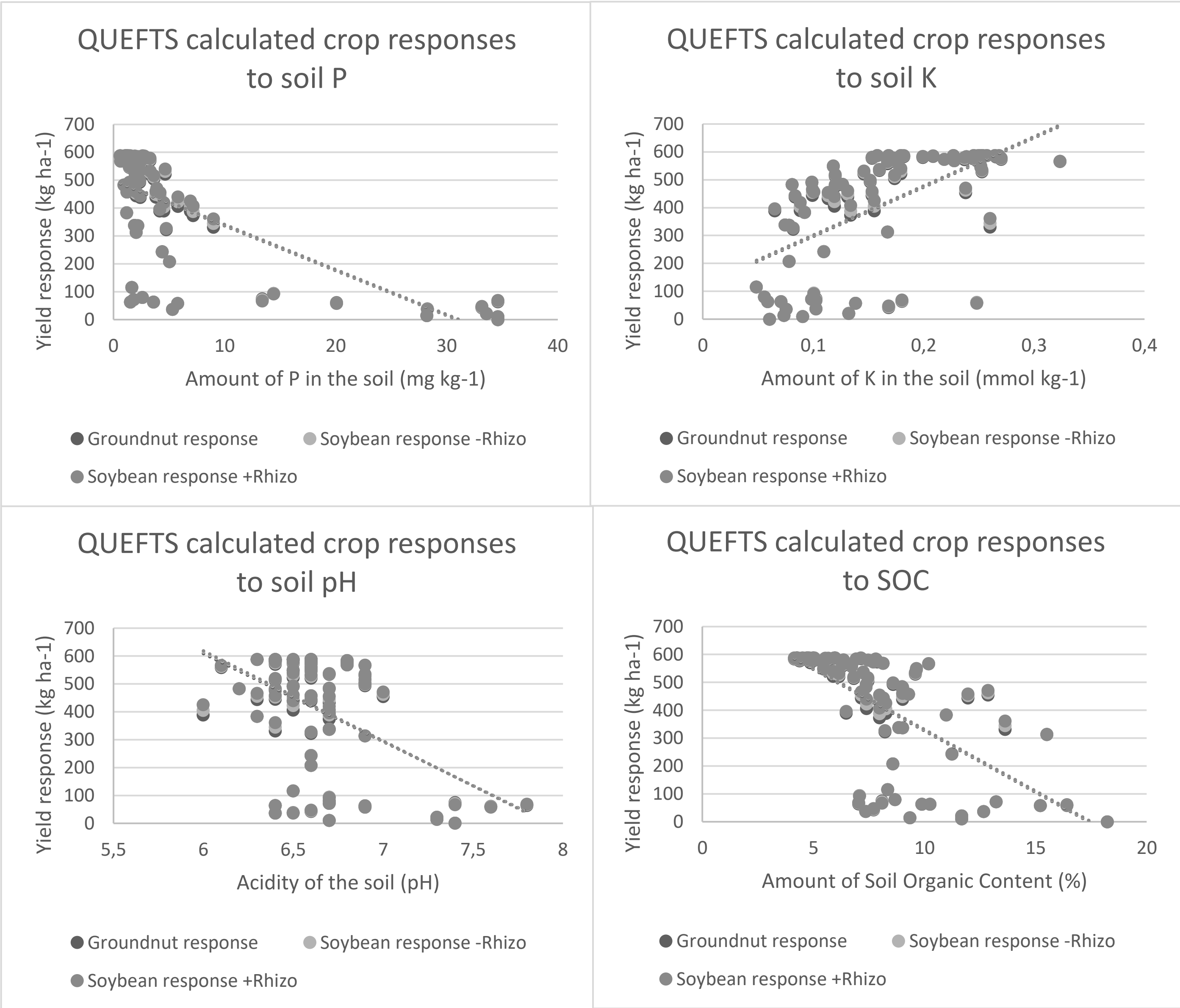

Figure 7: Visual representation of the effect of different soil properties (pH, P, K and SOC) according to the QUEFTS model used to estimate the expected response (section 5.2.2). The y-axis represents the QUEFTS calculated crop response to a P treatment of 25 kg ha^{-1}. The x-axis represents the range of the different soil properties.

5.3. Analyzing and explaining distribution of crop responses

5.3.1. Distribution of the crop responses in the N2Africa trial

The calculated crop responses from the N2Africa estimated means range between -511,1 kg ha^{-1} and 2450 kg ha^{-1} for groundnut, and between -41,7 kg ha^{-1} and 1590,0 kg ha^{-1} for soybean. A negative crop response value means that the yield is lower under new technologies than under conventional technologies. The standard deviations of the mean are 568,3 kg ha^{-1} and 291,4 kg ha^{-1} respectively.

Table 3: Numeric representation of the distribution of the calculated responses of groundnut and soybean to the 'N2Africa' treatment (Response='N2Africa'-'Own').

	Groundnut response (kg ha^{-1})	*Soybean response (kg ha^{-1})*
Mean	589,6	406,7
Standard deviation	568,3	291,4
Minimum	-511,1	-41,7
25th percentile	259,0	222,5
Median	490,0	360,0
75th percentile	749,0	547,5
Maximum	2450,0	1590,0

The responses are normally distributed around a mean increase of 589,6 kg ha^{-1} and 406,7 kg ha^{-1} due to the N2Africa treatment for groundnut and soybean respectively.

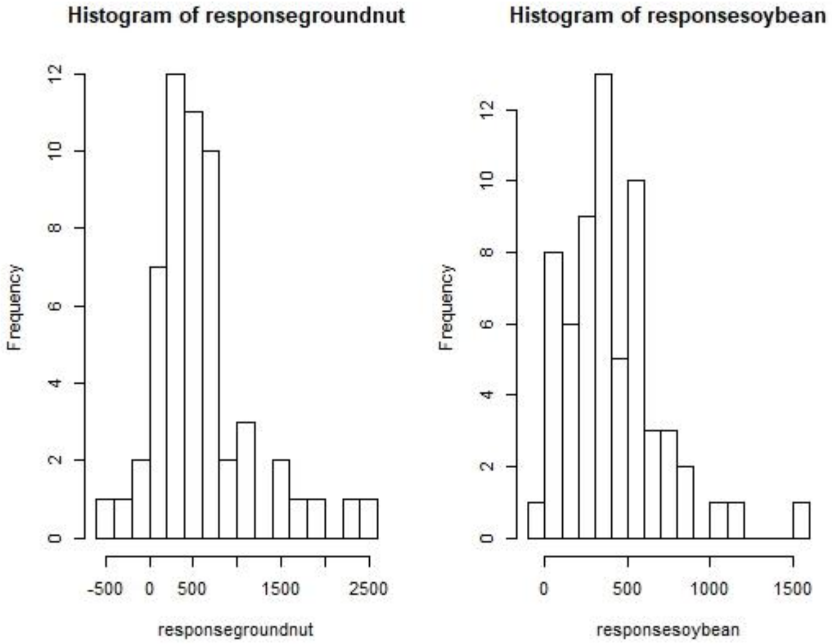

Figure 8: Visual representation of the distribution of the calculated responses of groundnut and soybean to the N2Africa treatment (Response='N2Africa'-'Own').

5.3.2. Soil properties as a possible cause of variability in crop responses

The QUEFTS model calculates the expected crop response based on a wide range of soil properties (as described in section 5.2.2). According to the QUEFTS model, the responses of both crops to the P treatment of 25 kg ha^{-1} are varying between 0 and 587,5 kg ha^{-1} as a result of varying soil properties. The standard deviations of the crop responses are estimated to be 204,3, 2015,7 and 205,1 kg ha^{-1} respectively for groundnut and soybean with and without the application of Rhizobium inoculants (Table 4).

Table 4: Numeric representation of the distribution of the QUEFTS calculated responses of groundnut and soybean to the P treatment of 25 kg ha^{-1}.

	QUEFTS modelled groundnut response (kg ha^{-1})	*QUEFTS modelled soybean response +Rhizo (kg ha^{-1})*	*QUEFTS modelled soybean response -Rhizo (kg ha^{-1})*
Mean	405,9	411,1	408,8
Standard deviation	204,3	205,7	205,1
Minimum	0	0	0
25th percentile	320,2	323,2	323,6
Median	486,6	488,8	488,4
75th percentile	578,1	580,7	580,3
Maximum	587,5	587,5	587,5

Varying soil properties may thus partly contribute to the variability of the crop responses to the treatment. The variability of the crop responses in the N2Africa trial is found to be much higher than could be concluded based on varying soil properties. The next sections will elaborate on other possible causes of variations in crop response.

5.3.3. Literature review of possible causes of variability in crop responses

Crop responses to the N2Africa treatment are -in addition to variability in soil properties- subject to a wide range of variabilities which might influence the response. These variabilities can have a biophysical or socioeconomic nature, and can occur regional or farm level.

Increasing climate variability and erratic rainfall patterns are often mentioned as a main cause for yield instability or crop failure in all the northern regions of Ghana (Antwi-Agyei, Stringer, & Dougill, 2014; Callo-Concha, Gaiser & Ewert, 2012; Rademacher-Schulz, Schraven, & Mahama, 2014). Antwi-Agyei et al. (2012) state that the Northern, Upper West and Upper East regions of Ghana have the highest level of crop production vulnerability. According the Antwi-Agyei et al., this results from a low adaptive capacity due to low levels of social, economic and physical assets. Different levels of vulnerability were observed among the various districts within these regions. The economies in these regions are based on rain-fed agriculture, and crop yields are thus subject to recurring droughts and unpredictable rainfall patterns (Antwi-Agyei et al., 2012).

In addition, it is stated that continuous cropping without the addition of appropriate soil amendments has resulted in soils of low fertility, especially in regions with high levels of poverty (Antwi-Agyei et al., 2012). Higher levels of poverty constrains the capability of communities in northern Ghana to cope with drought, as it limits the amount of capital assets that may be necessary to reduce the impact of recurring droughts.

5.3.4. Explaining distribution of the crop responses based on N2Africa trial

General assumptions made in the previous section do not necessarily apply to all farmers in the N2Africa trial in 2016. Therefore, in this section there will be looked at some biophysical and socioeconomic factors which could potentially contribute to the crop response variability in the N2Africa trial. As can be found in section 5.1 and 5.3.1, there is a large variance in crop yields between individual farms and between the plots in different districts. Grain yield significantly differs among the districts ($P<0.0001$). Moreover, the significant interaction between treatment effect and district ($P=0,0074$) illustrates the effect of district on the response to the N2Africa treatment (section 5.1, Table 1).

Soybean yields on the N2Africa intervention test plots do vary partly as a result of the inconsistent application of Rhizobium inoculants. The term 'N2Africa treatment' includes both TSP application with and without inoculation, resulting in divergent yield responses (5.2.1).

There is found to be an effect of the severity of drought (as experienced by the farmer, with levels absent, mild, moderate or severe) on grain yield (P=0,011). The interaction between the severity of the drought and the N2Africa treatment effect is also significant (P=0,0015). However, when looking at the average yields of both groundnut and soybean in all districts, the effect proves to be negative (Figure 9). Average grain yields of both treatments are observed to increase when the experienced severity of drought increases. The crop response to the N2Africa treatment is similar when the severity of drought is experienced as absent, mild, or severe (respectively 306,64; 448,81 and 487,23 kg ha^{-1}). When the severity of drought is experienced to be moderate, the crop response to the N2Africa treatment is high (1044,8 kg ha^{-1}). The crop response is only significant when drought is experienced as moderate or severe (LSD=444,8 kg ha^{-1}).

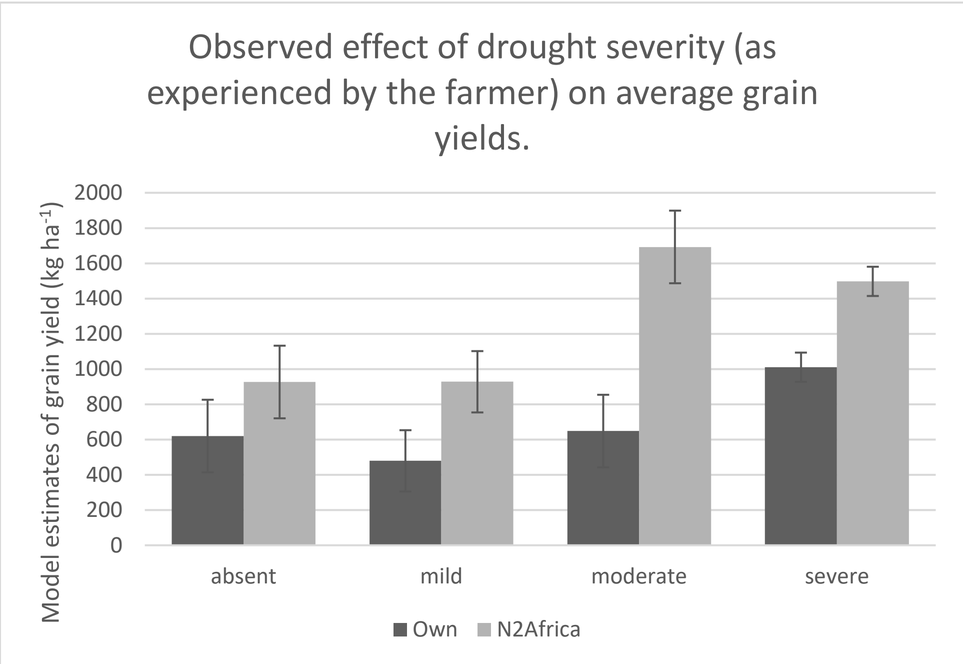

Figure 9: Average grain yields under new and conventional technologies, as a function of the experienced severity of drought. The calculated grain yields include both groundnut and soybean in all districts in the N2Africa trial. The error bars represent the standard error of the mean.

There is also found to be a significant effect of estimated wealth levels (very poor, poor, medium or wealthy) on grain yield (P=0,053), and a significant interaction between the estimated wealth levels and the N2Africa treatment effect (P=0,93). When looking at the average yields of both groundnut and soybean in all districts, the effect of the wealth levels is not so clear (Figure 10). The crop yields under conventional technologies seem to increase when wealth levels increase. Crop yields under new technologies seem to be especially high compared to crop yields under conventional technologies when the estimated wealth level is medium. However, the crop response to the N2Africa treatment is not significant for any of the wealth levels (LSD=648,1 kg ha^{-1}).

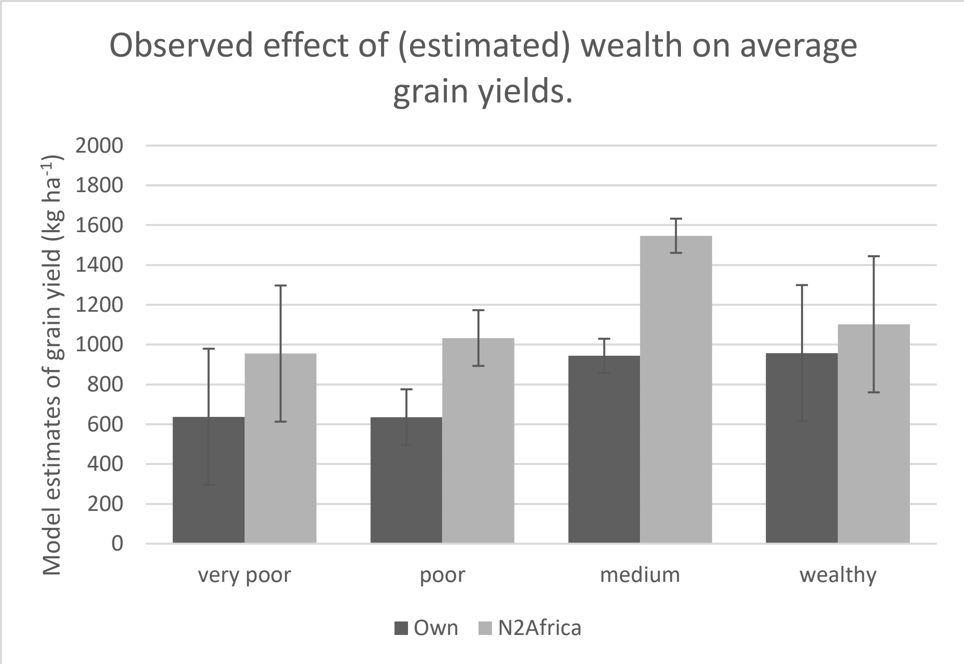

Figure 10: Average grain yields under new and conventional technologies, as a function of the estimated wealth levels. The calculated grain yields include both groundnut and soybean in all districts in the N2Africa trial. The error bars represent the standard error of the mean.

Some other factors which were thought to potentially have an effect on the grain yield (variety, application of inoculants, household size, altitude of the plot and planting density), but no other significant effects were found.

5.4. Direct costs and benefits

A cost-benefit analysis is performed as described in section 4.3.4. The input costs and farmgate prices are provided through personal communications with Mats Hoppenbrouwers (2017).

For groundnut, the cost-effectiveness (benefits-costs) of the new technologies is higher than the cost-effectiveness of the conventional technologies, respectively 292,22 and 245,40 USD ha^{-1} $season^{-1}$. This results in an absolute difference of 46,82 USD ha^{-1} $season^{-1}$ between the new and conventional technologies (Table 5). As investment costs of the new technologies are higher, the relative benefits per USD invested in inputs are higher under conventional technologies.

Table 5: Cost-benefit analysis of the expected costs and benefits involved in groundnut cultivation under both new technologies (as promoted by the N2Africa project), and conventional technologies (used by farmers in the northern regions of Ghana) . All values are expressed in USD ha^{-1} $season^{-1}$.

GROUNDNUT

New technologies	USD kg^{-1}	required/produced kg ha^{-1}	USD ha^{-1} $season^{-1}$
Improved groundnut variety	1,76	20,23	35,61
TSP input	0,55	148,00	80,66
TOTAL COSTS			**116,27**
Average groundnut yield	0,28	1458,91	408,49
TOTAL BENEFITS			**408,49**
Cost-effectiveness of new technologies (Benefits-Costs)			**292,22**
Benefits per USD invested in new technologies (Benefits/Costs)			**3,51**

Conventional technologies	USD kg^{-1}	required/produced kg ha^{-1}	USD ha^{-1} $season^{-1}$
Local groundnut variety	0,88	20,23	17,81
TOTAL COSTS			**17,81**
Average groundnut yield	0,28	940,04	263,21
TOTAL BENEFITS			**263,21**
Cost-effectiveness of conventional technologies (Benefits-Costs)			**245,40**
Benefits per USD invested in conventional technologies (Benefits/Costs)			**14,78**

Difference in cost-effectiveness per ha (new-conventional)	**46,82**
Difference in benefits per USD invested (new-conventional)	**-11,27**

For soybean, the cost-effectiveness (benefits-costs) of the new technologies is higher than the cost-effectiveness of the conventional technologies, respectively 278,91 and 242,79 USD ha^{-1} $season^{-1}$. This results in an absolute difference of 36,12 USD ha^{-1} $season^{-1}$ between the new and conventional technologies (Table 6). As investment costs of the new technologies are higher, the relative benefits per USD invested in inputs are higher under conventional technologies.

Table 6: Cost-benefit analysis of the expected costs and benefits involved in soybean cultivation under both new technologies (as promoted by the N2Africa project), and conventional technologies (used by farmers in the northern regions of Ghana) . All values are expressed in USD ha^{-1} $season^{-1}$.

SOYBEAN			
New technologies	USD kg-1	required/produced kg ha-1	USD ha-1 season-1
Improved soybean variety	0,88	7,28	6,41
TSP input	0,55	148,00	80,66
Rhizobium inoculants	16,50	0,04	0,60
TOTAL COSTS			**87,67**
Average soybean yield	0,30	1221,94	366,58
TOTAL BENEFITS			**366,58**
Cost-effectiveness of new technologies (Benefits-Costs)			**278,91**
Benefits per USD invested in new technologies (Benefits/Costs)			**4,18**

Conventional technologies	USD kg-1	required/produced kg ha-1	USD ha-1 season-1
Local soybean variety	0,44	7,28	3,21
TOTAL COSTS			**3,21**
Average soybean yield	0,30	819,99	246,00
TOTAL BENEFITS			**246,00**
Cost-effectiveness of conventional technologies (Benefits-Costs)			**242,79**
Benefits per USD invested in conventional technologies (Benefits/Costs)			**76,75**

Difference in cost-effectiveness (new-conventional)	**36,12**
Difference in benefits per USD (new-conventional)	**-72,57**

The additional direct costs of the new technologies are 98,47 and 84,47 USD ha^{-1} $season^{-1}$ for groundnut and soybean respectively (Table 5 and 6). Farmers need to compensate for the extra costs accompanying the implementation of new technologies, which is 351,66 and 281,55 kg ha^{-1} for groundnut and soybean respectively (Table 7). When looking at the yield response to the new technologies in the N2Africa trial, the groundnut yield increases sufficiently for 60% of the farmers. The soybean yield response to the new technologies is sufficiently high for 63% of the farmers in the N2Africa trial.

Table 7: Overview of extra costs coming along with the implementation of new technologies (acquired from table 3 and 4), and the required groundnut and soybean yield response to the new technologies.

	GROUNDNUT	SOYBEAN
Extra costs of new technologies (USD kg ha-1)	98,47	84,47
Benefits per kg yield (USD)	0,28	0,3
Required yield increase to compensate for extra costs (kg ha-1)	351,66	281,55
Farmers above this threshhold (%)	**60**	**63**

6. Discussion

6.1. Crop responses to new technologies compared to conventional technologies

We hypothesized that the average crop yields using the promoted new technologies would exceed yields under conventional technologies, and this was indeed confirmed by our analyses. Overall, the average yields on the N2Africa trial plots were found to be significantly higher than the average yield on the farmers' own plots.

However, both the farmers' own plot, and the N2Africa intervention test plot showed a high variability between the districts. The average increase in yield was not significant in every district, namely not in Bawku-West, Nadowli and Savelugu for both groundnut and soybean. For groundnut, Yendi and Binduri district showed much higher yield levels compared to the other districts. It is especially interesting that the yield levels of both treatments are significantly higher in Binduri than in Bawku Municipal and Bawku-West. As these districts are geographically very close, the climatic conditions are expected to be very similar. This indicates that other factors may cause variation between these districts. The same pattern is observed for soybean, where again grain yields are much higher in Binduri compared to Bawku Municipal and Bawku-West. Another interesting difference is found between Nadowli and Wa-West. The average soybean yield in Nadowli is extremely low, and the response to the N2Africa treatment is negligible. In Wa-West the crop responses are around average, although these districts are geographically close. This underlines the statement that something other than climatic variability between the districts is causing the variation in yield. In section 6.3 will be elaborated on possible causes for variation between the districts.

For the analysis of the crop responses to the 'N2Africa' treatment and the 'Own' treatment, only data from one year (2016) was used. Climatic circumstances can be highly variable in northern Ghana (section 5.3.3), and may strongly influence crop yields. The observed crop response for one year may give an indication on the effect of the new technologies, but cannot be directly applied to subsequent years. For a more substantiated comparison of the crop responses, several years should be taken into consideration.

6.2. Comparison of the N2Africa trial to expected responses

6.2.1. Comparison to literature

Groundnut and soybean responses to improved technologies did not deviate strongly from crop responses to similar treatments in literature. These treatments include the application of P for both crops, and the application of Rhizobium inoculants for soybean. Small differences were visible between the N2Africa trial and the reviewed literature, as described in section 5.2.1. The groundnut response to the treatment is expected to be lower (based on the literature), than it appears from the N2Africa trial. For soybean, it is the other way around: the response to the treatment is expected to be higher (based on the literature), than it appears from the N2Africa trial. Improved varieties were used only in the N2Africa trial, whilst other varieties were used in literature. The effect of variety on yield can result in differences in the crop responses to P fertilizer and Rhizobium inoculants. It is remarkable that the differences in soybean response between the N2Africa trial and literature mostly seem to result from differences in the control yields.

Furthermore, it is striking that no differences are observed between 'N2Africa' treatments with or without the application with Rhizobium (Figure 4). This is in contrast with an hypothesized yield increase due to inoculation with Rhizobium (Fatima, Zia & Chaudhary, 2007; Stacey & Upchurch, 1984; Young, Juang & Chao, 1988) as described in section 3.1. It is possible that the presence of Rhizobium does not have the desired effect on soybean yield, but it cannot be concluded based on this study. , the observations of the treatments with or without the application of Rhizobium are done on different fields. The observations can therefore not be paired, making it difficult to find a significant difference between the treatments. In addition, he lack of response to the presence of Rhizobium may for example be caused by incorrect application of Rhizobium, or inaccurate recording of the application in the survey report.

It is however notable that also in the reviewed literature, no differences can be observed in the response to between treatments with or without the application of Rhizobium. This does not necessarily mean that the presence of Rhizobium does not have the desired effect on soybean yield, as the average amount of applied P fertilizer differs between the treatments. Moreover, the amount of literature taken into account in section 5.2.1 is not sufficient to conclude on the effect of Rhizobium on soybean yield and the variation within the reviewed literature is large.

Overall, the reviewed literature may give an indication on what could be expected in the N2Africa trial, but the conditions are very divergent: the literature taken into consideration covers a wide range of countries in SSA, soil types, P application rates, and years. In addition, the potential effect of improved varieties is not taken into consideration in the literature review. The conditions of the treatments in literature may thus differ from each other, and from the conditions in which the grain yield responses to the 'N2Africa' treatment were observed.

6.2.2. QUEFTS model

It was hypothesized that average response to P fertiliser would correspond well to the potential response as calculated by the QUEFTS model. As described in section 4.3.2, QUEFTS responses are calculated for a range of soils with different properties. When comparing the means of the QUEFTS calculated responses to the observed responses of the N2Africa trial, only small differences are visible for both crops. Overall, the observed responses of both crops do indeed correspond well with the QUEFTS calculated responses.

For soybean, the QUEFTS calculated response to the P treatment is slightly higher than was observed in the N2Africa trial. The P application rate was estimated at 25 kg ha^{-1} in the QUEFTS model, but the actual application rate in the N2Africa trial plots is unknown. It is possible that the assumed P application rate is higher than the actual amount applied by farmers, causing the small difference in response to the P treatment. However, it would then be likely that the same difference would be visible for groundnut, but this is not the case. The cause of the differences in soybean response to the P treatment between the QUEFTS model and the N2Africa trial is thus not so clear.

As the soil characteristics of the N2Africa trial plots are unknown, it is not possible to compare the crop response of an individual trial plot to the expected response based on the QUEFTS model. Therefore, the overall comparison was made with the assumption that the mean of the soil characteristics used in the QUEFTS model are comparable to the mean soil characteristics in the N2Africa trial plots. Although the overall average crop responses are indeed very similar, it cannot be certain that this results from the appropriate soil characteristics.

In addition to the overall of the mean soil characteristics, the individual effects of the soil characteristics (P, K, SOC and pH) on the crop response to the P treatment were reviewed in section 5.2.2. According to the QUEFTS model, the effect of the P treatment is expected to be lower as the amount of P in the soil increases. If P levels are high, the crops take up less P than is potentially available, probably because other nutrients become limiting to crop growth. This is in accordance with Liebig's law of the minimum (as explained by Janssen et al., 1990). This law states that plant growth is not determined by the total amount of nutrients available, but by the scarcest nutrient.

This is also illustrated by the fact that (according to the QUEFTS model) the crop response to the P treatment increases as K levels in the soil increase. If K levels are low, they may be limiting for the crop response, and the effect of the P treatment will be smaller. This emphasizes the importance of a soil with adequate levels of all essential nutrients in order for the new technologies to have the desired effect.

It is remarkable that a high soil organic content seems to lower the effect of the P treatment on the QUEFTS calculated crop response. It would be expected that soils with a high organic content would be rich in various nutrients, which would (according to Liebig's law of the minimum) positively contribute to the effect of the P treatment. The QUEFTS model may underestimate the long-term impact of soil organic content on other physical, chemical and biological indicators of soil quality. These indicators of soil quality are among others pH, nutrient availability, soil texture and structure, water holding capacity and microbial activity, which are important for maintaining soil quality in continuous cropping systems (Opala, Okalebo & Othieno, 2012; Reeves, 1997). In addition, the observed effect of SOC may be slightly misleading, resulting from the assumption that the soil organic content is directly linked to the amount of N content in the soil. Although the assumption seems reasonable, the formation of soil organic matter (Melilo et al., 1989) and other soil dynamics are often highly complex, and can hardly be comprised in a simple model like QUEFTS.

The pH of the soil is important for the crop response to the P treatment, according to the QUEFTS model. If pH is between 6 and 7, the crop response to the P treatment is expected to be highest. The acidity of the soil is known to influence the bioavailability of essential nutrients in the soil, which may cause the decrease in crop response as the pH increases. As mentioned earlier, the pH itself is also affected by the soil organic content. This illustrates the complexity of interactions in the soil, and the importance of a balanced composition of soil properties.

In summary, the QUEFTS model seems to give a good estimation for the crop responses to the P treatment. It also gives insight in the general effect of different soil types as well as in the effect of individual soil properties.

6.3. Variability in crop response to the N2Africa treatment

It was hypothesized that there is a large distribution in responses amongst farmers. As described in 5.3.1, there is a wide range in both groundnut and soybean response to the new technologies. On some plots, even a negative response to the new technologies is recorded. The crop response ranges between -266 and 2450 for groundnut, and between -41,7 and 1590 for soybean. The standard deviations of the mean are 568,3 and 291,4 kg^{-1} ha^{-1} for groundnut and soybean respectively. It can be stated that there is a large distribution of the crop response to new technologies amongst farmers.

It is not possible to explain the variance in the crop response entirely. However, based on the outcomes of the QUEFTS model, it can be concluded that a large part of the variability of the crop response is expected to be caused by variability in soil properties. In addition, other possible causes for variance are addressed in the sections 5.3.3 and 5.3.4. The general trend in the reviewed literature (Antwi-Agyei, Stringer, & Dougill, 2014; Callo-Concha, Gaiser & Ewert, 2012; Rademacher-Schulz, Schraven, & Mahama, 2014) is that crop production in the northern regions of Ghana is vulnerable, due to high climatic variability and a low adaptive capacity. The literature mainly focusses on erratic rainfall patterns and recurring drought as the main problem of crop vulnerability. According to Antwi-Agyei, Stringer, & Dougill (2014), engagement in various on-farm adaptational strategies such as changing the timing of planting, diversification of crops, planting early maturing varieties, planting drought-tolerant crops and the use of irrigation systems is necessary to cope with the impact of climate variability and drought in particular.

However, the studied literature concerns farmers in northern Ghana in general, and does not necessarily apply directly to farmers in the N2Africa trial. Furthermore, rainfall patterns for 2016 (the year in which the N2Africa data used for this study was gathered) are not taken into account in this study. When looking at the N2Africa trial data, there is found to be a significant effect of the severity of drought on grain yield. This supports the statement that climatic variability causes a high variability in crop yields, as was mentioned in the reviewed literature. However, when looking at the model means the effect is opposite to what could be expected based on the literature. Grain yield is higher for both treatments when drought is experienced as moderate or severe, and lower when drought is experienced as absent or mild. It should be emphasized that the level of drought severity is based on the experience of the farmer in the growing season, and is not based on actual rainfall data. The outcomes of this study are contradictory to what would be expected, and the implications of rainfall and climatic variability on the variability of grain yield of N2Africa farmers should be studied more broadly before actual conclusions can be drawn.

Overall, the crop response varies highly over the different districts, which could among other things be caused by the variability in the adaptive capacity of individual farmers in the districts. However, it is difficult to quantify the adaptive capacity as many aspects can be involved. Nonetheless, the estimated wealth level of an individual household could give some indication for the socio-economic status and adaptive capacity of a farm. There is found to be an effect of the estimated wealth level and grain yield in the N2Africa trial data. When looking at the model means, yield levels of both treatments are higher when the farmers' estimated wealth is medium or wealthy, as compared to farmers being poor or very poor. Wealth levels may thus cause part of the variability in grain yield, supporting the statement in literature that the adaptive capacity of a farm affects the variability in yield.

Differences in managemental practices on a farm may also explain part of the yield variability. Callo-Concha, Gaiser & Ewert (2012) discuss the importance of managemental practices on soil quality and yield. They also state that the management of a cropping system is determined by labour and capital, rainfall variability and nutrient deficiency, and emphasize the importance of effective managemental practices for grain yield. However, the N2Africa trial data does not provide sufficient data to conclude that there is indeed an effect of managemental practices on grain yield.

Ultimately, there are large differences in crop responses within the N2Africa trial which could be caused by numerous factors. In many cases, the data does not provide satisfactory answers about the effect of many biophysical and socioeconomic factors on grain yield. It is beyond the scope of this study to elaborate further on the complexity of these factors and the possible cohesion between them.

6.4. Cost and benefit analysis.

It was hypothesized that the benefits due to increase in crop yield using the new technologies outweigh the direct costs of the new technologies. For the analysis of the costs and benefits, there is focussed on the mean response to the new technologies. As variability has proven to be high, it should be stated that the results of the analysis may not apply to all farmers in northern Ghana. When looking at the absolute numbers, the new technologies turn out to be profitable for most of the farmers in the trial, despite the variability in response and the additional costs. However, the relative benefits (i.e. the expected benefits per USD invested in inputs) of the new technologies seem to be lower than the relative benefits of the conventional technologies.

The profit is based on the estimated farmgate prices in the year of this study. However, farmgate prices may be highly variable between districts, urban or rural areas, and years or seasons. Furthermore, it is assumed that the farmers sell 100% of the grain yield, although it might very well be possible that farmers use part of the grain yield for their own consumption. The costs are based on the estimated input prices for the seeds (local and improved varieties), TSP fertilizes, and Rhizobium inoculants. Again, the input prices may be highly variable between the districts, urban or rural areas, and years or seasons.

Furthermore, the cost-benefit analysis only includes the direct input and output costs of the conventional and new technologies. Little is known about the additional costs for labor and transportation, or other costs that might be involved with the implementation of the new technologies. The high uncertainty and variability regarding the costs and benefits of both conventional and new technologies make it impossible to draw actual conclusions on the cost-effectiveness of the new technologies. A more elaborate study is necessary to gain understanding of the costs and benefits involved in the implementation of the new technologies.

6.5. Recommendations and closing remarks

In summary, average crop yields using the new technologies promoted by the N2Africa project do exceed average crop yields under conventional technologies in the northern regions of Ghana. The average crop responses to the promoted technologies are consistent with the expected responses, but the variability amongst farmers is high. Variability in crop responses can partly be explained by the variability in soil properties, climatic conditions and adaptive capacity. However, within the N2Africa trial data there is not always found a causal relationship between these factors and crop response. Further research is necessary to gain more insight in the causes of the high variability in crop response to the promoted technologies. More focal farmers should be included in the trial, and several years should be taken into consideration.

From the cost-benefit analysis can be concluded that for most farmers in northern Ghana, the benefits of the crop responses outweigh the direct costs. However, a more elaborate analysis of crop responses and costs and benefits is required to gain better insight in the profitability of the promoted technologies.

7. Resources

Akpalu, M. M., Siewobr, H., Oppong-Sekyere, D., & Akpalu, S. E. (2014). Phosphorus application and Rhizobia inoculation on growth and yield of soybean (Glycine max L. Merrill). *American Journal of Experimental Agriculture, 4(6),* 674.

Ampadu-Boakye, T., Stadler, M., Kanampiu, F. (2017). N2Africa Annual Report 2016, www.N2Africa.org, 89pp.

Anderson, G. D. (1970). Fertility studies on a sandy loam in semi-arid Tanzania: II. Effects of phosphorus, potassium and lime on yields of groundnuts. *Experimental Agriculture, 6(3),* 213-222.

Antwi-Agyei, P., Fraser, E. D., Dougill, A. J., Stringer, L. C., & Simelton, E. (2012). Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield and socioeconomic data. *Applied Geography*, 32(2), 324-334.

Antwi-Agyei, P., Stringer, L. C., & Dougill, A. J. (2014). Livelihood adaptations to climate variability: insights from farming households in Ghana. *Regional environmental change*, *14*(4), 1615-1626.

Bravo, S.P. (2017). Analysis and revision of the N2Africa focal adaptation trial survey, a tool for monitoring technology performance and untangling yield variability. N2Africa.

Breisinger, C., Diao, X., Thurlow, J., & Hassan, R. M. A. (2011). Potential impacts of a green revolution in Africa—the case of Ghana. Journal of international development, 23(1), 82-102.

Callo-Concha, D., Gaiser, T., & Ewert, F. (2012). Farming and cropping systems in the West African Sudanian Savanna. WASCAL research area: Northern Ghana, Southwest Burkina Faso and Northern Benin (No. 100). ZEF Working Paper Series.

Dessalegn, T. Y. (2006). Modeling Farm Irrigation Decisions Under Rainfall Risk in the White-Volta Basin of Ghana: A Tool for Policy Analysis at the Farm-household Level. Cuvillier-Verlag.

Dorward, A., & Kydd, J. (2005). Making agricultural market systems work for the poor: Promoting effective, efficient and accessible coordination and exchange. *Imperial College London*.

Ehui, S., & Pender, J. (2005). Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. *Agricultural Economics*, *32*(s1), 225-242.

Farrow, A., Wolde-Meskel, E., Adjei-Nsiah, S., Sangodele, E., Kamara, A., Kamai, N., ... & Ebanyat, P. (2015). *N2Africa Action Areas in Ethiopia, Ghana, Nigeria, Tanzania and Uganda in the N2Africa Project* (Vol. 77). N2Africa project.

Farrow, A., Ronner, E., van den Brand, G. J., Boahen, S. K., Leonardo, W., Wolde-Meskel, E., ... & Sangodele, E. A. (2016). From best fit technologies to best fit scaling: incorporating and evaluating factors affecting the adoption of grain legumes in Sub-Saharan Africa. *Experimental Agriculture*, 1-26.

Fatima, Z., Zia, M., & Chaudhary, M. F. (2007). Interactive effect of Rhizobium strains and P on soybean yield, nitrogen fixation and soil fertility. *Pakistan Journal of Botany*, *39*(1), 255.

Franke, A. C., Rufino, M. C., & Farrow, A. (2011). Characterisation of the impact zones and mandate areas in the N2Africa project. *Milestone reference*, (1.4), 1.

Franke, A. C., van den Brand, G. J., & Giller, K. E. (2014). Which farmers benefit most from sustainable intensification? An ex-ante impact assessment of expanding grain legume production in Malawi. *European Journal of Agronomy*, *58*, 28-38.

Ikeogu, U. N., & Nwofia, G. E. (2013). Yield parameters and stabilty of soybean [Glycine max.(L.) merril] as influenced by phosphorus fertilizer rates in two ultisols. *Journal of Plant Breeding and Crop Science, 5(4),* 54-63.

Jama, B., & Pizarro, G. (2008). Agriculture in Africa: Strategies to improve and sustain smallholder production systems. *Annals of the New York Academy of Sciences*, *1136*(1), 218-232.

Janssen, B. H., Guiking, F. C. T., Van der Eijk, D., Smaling, E. M. A., Wolf, J., & Van Reuler, H. (1990). A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma*, *46*(4), 299-318.

Kaizzi, K. C., Byalebeka, J., Semalulu, O., Alou, I. N., Zimwanguyizza, W., Nansamba, A., ... & Kasharu, A. K. (2012). Optimizing smallholder returns to fertilizer use: Bean, soybean and groundnut. *Field Crops Research, 127,* 109-119.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1-26.

Luo, D., Ganesh, S., Koolaard, J., & Luo, M. D. (2014). Package 'predictmeans'.

N2Africa (2017). Vision of success. Retrieved from http://www.n2africa.org/content/vision-success

Naab, J. B., Seini, S. S., Gyasi, K. O., Mahama, G. Y., Prasad, P. V. V., Boote, K. J., & Jones, J. W. (2009). Groundnut yield response and economic benefits of fungicide and phosphorus application in farmer-managed trials in Northern Ghana. *Experimental agriculture, 45(4),* 385-399.

Ncube, B., Twomlow, S. J., Van Wijk, M. T., Dimes, J. P., & Giller, K. E. (2007). Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. *Plant and Soil*, *299*(1-2), 1-15.

Ndakidemi, P. A., Dakora, F. D., Nkonya, E. M., Ringo, D., & Mansoor, H. (2006). Yield and economic benefits of common bean (Phaseolus vulgaris) and soybean (Glycine max) inoculation in northern Tanzania. *Australian Journal of Experimental Agriculture, 46(4),* 571-577.

Opala, P. A., Okalebo, J. R., & Othieno, C. O. (2012). Effects of organic and inorganic materials on soil acidity and phosphorus availability in a soil incubation study. *ISRN Agronomy*, *2012*.

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

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

Rademacher-Schulz, C., Schraven, B., & Mahama, E. S. (2014). Time matters: shifting seasonal migration in Northern Ghana in response to rainfall variability and food insecurity. Climate and Development, 6(1), 46-52.

Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature communications*, *3*, 1293.

Reeves, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research*, *43*(1-2), 131-167.

Savini, I., Kihara, J., Koala, S., Mukalama, J., Waswa, B., & Bationo, A. (2016). Long-term effects of TSP and Minjingu phosphate rock applications on yield response of maize and soybean in a humid tropical maize–legume cropping system. *Nutrient cycling in agroecosystems, 104(1),* 79-91.

Schindler, J. (2009). Ecology and Development Series No. 68, 2009.

Stacey, G., & Upchurch, R. G. (1984). Rhizobium inoculation of legumes. *Trends in biotechnology*, *2*(3), 65-70.

Stadler, M., van den Brand, G. J., & Adjei-Nsiah, S. (2016). *N2Africa Early Impact Survey Ghana* (No. 91). N2Africa.

Tairo, E. V., & Ndakidemi, P. A. (2013). Yields and economic benefits of soybean (Glycine max L.) as affected by Bradyrhizobium japonicum inoculation and phosphorus supplementation. *American Journal of Research Communication, 1(11),* 159-172.

Tharanathan, R. N., & Mahadevamma, S. (2003). Grain legumes—a boon to human nutrition. *Trends in Food Science & Technology*, *14*(12), 507-518.

Verde, B. S., Danga, B. O., & Mugwe, J. N. (2013). Effects of manure, lime and mineral P fertilizer on soybean yields and soil fertility in a humic nitisol in the Central Highlands of Kenya. *International journal of Agricultural science research, 2(9),* 283-291.

Wani, S. P., Rupela, O. P., & Lee, K. K. (1995). Sustainable agriculture in the semi-arid tropics through *biological nitrogen fixation in grain legumes. In Management of Biological Nitrogen Fixation for the Development of More Productive and Sustainable Agricultural Systems* (pp. 29-49). Springer, Dordrecht.

Young, C. C., Juang, T. C., & Chao, C. C. (1988). Effects of Rhizobium and vesicular-arbuscular mycorrhiza inoculations on nodulation, symbiotic nitrogen fixation and soybean yield in subtropical-tropical fields. *Biology and fertility of soils*, *6*(2), 165-169.

8. Appendix

8.1. Literature review: Groundnut

Country	P source	Amount of P (kg/ha)	Yield with application of P (kg/ha)	Yield control (kg/ha)	Absolute difference (P treatment-control)	NUE (Yield difference per kg P)	Cultivar	Additional	Source
Tanzania	Double Superphosphate	46	117,25	1153,08	20,17	0,44	Natal Common groundnut		Anderson, 1970
Tanzania	Double Superphosphate	46	1164,56	1133,18	31,38	0,68	Dodoma Bold groundnut		Anderson, 1970
Tanzania	Double Superphosphate	47	1908,81	1714,9	193,91	4,13	Dodoma Bold groundnut		Anderson, 1970
Tanzania	Double Superphosphate	11,49	1221,73	1194,83	26,9	2,34	Natal Common groundnut		Anderson, 1970
Tanzania	Double Superphosphate	22,98	1299,07	1194,83	104,24	4,54	Natal Common groundnut		Anderson, 1970
Tanzania	Tororo Single Superphosphate	11,49	1241,9	1194,83	47,07	4,10	Natal Common groundnut		Anderson, 1970
Tanzania	Tororo Single Superphosphate	22,98	1429,09	1194,83	234,26	10,19	Natal Common groundnut		Anderson, 1970
Tanzania	ground Minjingu phosphate	11,49	1260,96	1194,83	66,13	5,76	Natal Common groundnut		Anderson, 1970
Tanzania	ground Minjingu phosphate	22,98	1308,03	1194,83	113,2	4,93	Natal Common groundnut		Anderson, 1970
Ghana	Single Superphosphate	26	1037	895	142	5,46	Chinese (Spanish type)	Fungicide	Naab et al., 2009
Ghana	Single Superphosphate	26	1029	895	134	5,15	Chinese (Spanish type)	Fungicide	Naab et al., 2009
Ghana	Single Superphosphate	26	1061	895	166	6,38	Chinese (Spanish type)	Fungicide, high planting density	Naab et al., 2009
Ghana	Single Superphosphate	26	1029	895	134	5,15	Manipinter (Virginia type)	Fungicide	Naab et al., 2009
Uganda	Triple Superphosphate (TSP)	15	1630	850	780	52,00	Red Beauty, Serenut2/3/4		Kaizzi et al., 2012
Uganda	Triple Superphosphate (TSP)	30	1720	850	870	29,00	Red Beauty, Serenut2/3/5		Kaizzi et al., 2012
Uganda	Triple Superphosphate (TSP)	45	1820	850	970	21,56	Red Beauty, Serenut2/3/6		Kaizzi et al., 2012
	means	**27,3**	**1333,3**	**1081,3**	**252,1**	**10,1**			
	SD	**9,7**	**230,2**	**179,9**	**233,0**	**9,0**			

8.2. Literature review: Soybean

Country	P source	Inoculation with rhizobium	Amount of P (kg/ha)	Yield with application of fertiliser and/or inoculant (kg/ha)	Yield control (kg/ha)	Absolute difference (P treatment-control)	NUE (Yield difference per kg P)	Cultivar/variety	Additional	Source
Kenia	Triple Superphosphate (TSP)	no	60	1200	1140	60	1,00	Gazelle	Acidic soil	Verde, Danga & Mugwe, 2013
Tanzania	Triple Superphosphate (TSP)	no	26	1027	604	423	16,27	Bossier	Rombo district	Ndakidemi et al., 2006
Tanzania	Triple Superphosphate (TSP)	no	26	886	610	276	10,62	Bossier	Moshi district	Ndakidemi et al., 2006
Kenia	Triple Superphosphate (TSP)	no	50	1740	530	1210	24,20	SB20 and SB25		Savini et al., 2016
Kenia	Triple Superphosphate (TSP)	no	25	1470	530	940	37,60	SB20 and SB26		Savini et al., 2016
Kenia	Triple Superphosphate (TSP)	no	12,5	1070	530	540	43,20	SB20 and SB27		Savini et al., 2016
Nigeria	Triple Superphosphate (TSP)	no	10	793,78	636,65	157,13	15,71	TGX		Ikeogu & Nwofia, 2013
Nigeria	Triple Superphosphate (TSP)	no	20	751,11	636,65	114,46	5,72	TGX		Ikeogu & Nwofia, 2013
Nigeria	Triple Superphosphate (TSP)	no	30	703,72	636,65	67,07	2,24	TGX		Ikeogu & Nwofia, 2013
Nigeria	Triple Superphosphate (TSP)	no	40	784,23	636,65	147,58	3,69	TGX		Ikeogu & Nwofia, 2013
Ghana	Triple Superphosphate (TSP)	no	30	730	380	350	11,67	-	P amount is estimated	Akpalu et al., 2014
Uganda	Triple Superphosphate (TSP)	no	15	1750	830	920	61,33	Namsoy2 or Maksoy1N/2/4		Kaizzi et al., 2012
Uganda	Triple Superphosphate (TSP)	no	30	1870	830	1040	34,67	Namsoy2 or Maksoy1N/2/5		Kaizzi et al., 2012
Uganda	Triple Superphosphate (TSP)	no	45	1940	830	1110	24,67	Namsoy2 or Maksoy1N/2/6		Kaizzi et al., 2012
		means	**30,0**	**1194,0**	**668,6**	**525,4**	**20,9**			
		SD	**10,8**	**400,9**	**136,5**	**372,5**	**14,3**			
Tanzania	Triple Superphosphate (TSP)	yes	26	1854	604	1250	48,08	Bossier	Rombo district	Ndakidemi et al., 2006
Tanzania	Triple Superphosphate (TSP)	yes	26	2021	610	1411	54,27	Bossier	Moshi district	Ndakidemi et al., 2006
Tanzania	-	yes	0	1372	604	768	-	Bossier	Rombo district	Ndakidemi et al., 2006
Tanzania	-	yes	0	1456	610	846	-	Bossier	Moshi district	Ndakidemi et al., 2006
Ghana	Triple Superphosphate (TSP)	yes	30	761	380	381	12,70	-	P amount is estimated	Akpalu et al., 2014
Ghana	-	yes	0	441	380	61	-	-		Akpalu et al., 2014
Tanzania	Triple Superphosphate (TSP)	yes	20	837,5	745,7	91,8	4,59	Soya 2		Tairo & Ndakidemi, 2013
Tanzania	Triple Superphosphate (TSP)	yes	40	997,5	745,7	251,8	6,30	Soya 2		Tairo & Ndakidemi, 2013
Tanzania	Triple Superphosphate (TSP)	yes	80	1083,7	745,7	338	4,23	Soya 2		Tairo & Ndakidemi, 2013
		means	**24,7**	**1202,6**	**602,8**	**599,8**	**21,7**			
		SD	**17,5**	**420,5**	**99,0**	**416,8**	**19,7**			