Field Crops Research 186 (2016) 133–145

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria

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ARTICLE INFO

Article history:
Received 6 August 2015
Received in revised form 28 October 2015
Accepted 29 October 2015
Available online 16 November 2015

Keywords:
Bradyrhizobium
Smallholder farmers
Sustainable intensification
West Africa

ABSTRACT

Soybean yields could benefit from the use of improved varieties, phosphate-fertilizer and rhizobium inoculants. In this study, we evaluated the results of widespread testing of promiscuous soybean varieties with four treatments: no inputs (control); SSP fertilizer (P); inoculants (I) and SSP plus inoculants (P+I) among smallholder farmers in northern Nigeria in 2011 and 2012. We observed a strong response to both P and I, which significantly increased grain yields by 452 and 447 kg ha^{-1} respectively. The additive effect of P+I (777 kg ha^{-1}) resulted in the best average yields. Variability in yield among farms was large, which had implications for the benefits for individual farmers. Moreover, although the yield response to P and I was similar, I was more profitable due to its low cost. Only 16% of the variability in control yields could be explained by plant establishment, days to first weeding, percentage sand and soil exchangeable magnesium. Between 42% and 61% of variability in response to P and/or I could be explained by variables including year, farm size, plant establishment, total rainfall and pH. The predictive value of these variables was limited, however, with cross-validation R^2 decreasing to about 15% for the prediction between Local Government Areas and 10% between years. Implications for future research include our conclusion that averages of performance of technologies tell little about the adoption potential for individual farmers. We also conclude that a strong agronomic and economic case exists for the use of inoculants with promiscuous soybean, requiring efforts to improve the availability of good quality inoculants in Africa.

1. Introduction

The population of sub-Saharan Africa is projected to double in the next 40 years (Cleland, 2013) and increases in food production are much needed (FAO, 2014b; World Bank, 2014). As the potential to expand agricultural land is limited in many areas with high population densities, sustainable intensification of agricultural production is crucial (Pretty et al., 2011; Garnett et al., 2013; Vanlauwe et al., 2014a). A potential pathway for sustainable intensification is the integration of grain legumes in farming systems (Giller and Cadisch, 1995; Peoples et al., 1995). Legumes have the capacity to fix nitrogen from the air in symbiosis with *Rhizobium* bacteria. Legumes can therefore contribute to improved soil fertility in cereal-dominated cropping systems in Africa, including the savannahs of West Africa (Osunde et al., 2003a; Sanginga, 2003; Franke et al., 2008). Legumes can be grown in rotation with other crops, with the additional advantage of reducing the need for N fertilizer for subsequent cereals in the context of Integrated Soil Fertility Management (ISFM) (Vanlauwe et al., 2010). In addition legume rotations assist in reducing pest and disease incidence (Sanginga, 2003; Yusuf et al., 2009), or are grown as inter- or relay crops, often without compromising the yield of the main crop (Baldé et al., 2011). Grain legumes also have important nutritional value in terms of protein, amino acids and micro-nutrients (Gibson and Ferguson, 2008). The short growing period of some legumes ensures availability of food during the hunger period in the middle of the cropping season (Franke et al., 2004; Rubyogo et al., 2010).

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http://dx.doi.org/10.1016/j.fcr.2015.10.023

Legume yields in African smallholder farming systems are often far below their potential. Numerous studies have shown that legume yields can be enhanced with the use of improved legume varieties (Okogun et al., 2005; Buruchara et al., 2011), phosphate (P) based fertilizers (Weber, 1996; Kamara et al., 2007; Kolawole, 2012), rhizobial inoculants (Sanginga et al., 2000; Osunde et al., 2003b; Thuita et al., 2012), or their combination (Snapp et al., 1998; Ndakidemi et al., 2006). Despite increases in the use of inputs among African smallholders on specific crops in some regions (Sheahan and Barrett, 2014), the use of inputs with legumes remains limited (Chianu et al., 2011; Franke and De Wolf, 2011). Moreover, many African countries lack the facilities to produce, store and distribute high quality inoculants (Pulver et al., 1982; Bala et al., 2011).

Since the early 1980s, research has focused on breeding soybean (*Glycine max* (L.) Merrill) varieties that can nodulate with rhizobia indigenous to African soils—so-called 'promiscuous' varieties (Sanginga et al., 2000; Giller, 2001). A breeding programme was initiated at the International Institute for Tropical Agriculture (IITA) in Nigeria to cross promiscuous soybean varieties of Asian origin with varieties from the USA with greater yield potential and better disease resistance (Kueneman et al., 1984; Pulver et al., 1985). The developed varieties had a greater ability to nodulate without inoculation (Sanginga et al., 2000) and they have been widely adopted in West Africa (Sanginga et al., 2003). Despite this success, more recent studies report yield responses to inoculants in these promiscuous varieties (Osunde et al., 2003b; Thuita et al., 2012). Hence, the need to inoculate promiscuous soybean varieties is still under discussion (Thuita et al., 2012), even more so because previous studies did not involve large scale testing of these varieties with and without inoculation under farmers' management.

Nigeria is the largest producer and consumer of soybean in sub-Saharan Africa. Demand continues to grow both as source of feed for the poultry industry and for human consumption. Production is mainly done by smallholders on farms of less than five ha (ACET, 2013). Average soybean productivity in Nigeria is around 1 t ha^{-1} (three-year average 2011–2013 (FAO, 2014a)), way below the yields of around 3 t ha^{-1} achieved on research stations in Nigeria (Tefera, 2011). Soybean production is mainly constrained by poor soil phosphorus availability (Kamara et al., 2007; Kolawole, 2012), diseases such as soybean rust (Twizeyimana et al., 2008) and moisture stress (Tefera, 2011). Other constraints are the high costs or limited availability of good quality inputs (fertilizer, inoculants, herbicides and pesticides (ACET, 2013)). Although many farmers in Nigeria use fertilizers, most is applied to maize and at rates well below what is recommended (Manyong et al., 2001; Sheahan and Barrett, 2014).

Legume yields are determined by the effects of legume genotype (G_L), the rhizobium strain(s) nodulating the legume (G_R), the biophysical environment (E), agronomic management (M) and their interactions, as expressed by the relation (Giller et al., 2013):

$$(G_L \times G_R) \times E \times M$$

Understanding the relation between these variables to enhance legume yields requires analysis of the performance of legume/rhizobium combinations under a wide range of environments and management decisions.

In this paper, we describe the results of the widespread testing of phosphate-based fertilizer (P-fertilizer) and rhizobial inoculants in soybean on farmers' fields in northern Nigeria, with the aim to understand the effects of the different variables in the $(G_L \times G_R) \times E \times M$ relationship on soybean yields and response to input application. We also evaluate the consequences of variability in yield for the distribution of the (economic) benefits of input application. Finally, we explore the ability to predict soybean yields and response to inputs for targeting of technologies based on relevant environmental and management factors.

2. Materials and methods

2.1. Study area

The study was carried out in two states: Kaduna and Kano in northern Nigeria, located between 6°50 and 9°15 East and 9°00 and 12°30 North. Kaduna State was split into two regions (North and South, with the latitude of Kaduna City as the border between North and South) to reflect the high diversity in agroecological conditions and agricultural intensification within the state. Rainfall falls in a single season between May and October. Kano State is the northernmost region with the driest climate (about 800 mm annual rainfall) and the shortest growing season (Table 1) and is more densely-settled than Kaduna State. Kaduna South receives about 1400 mm annual rainfall and has the longest growing season, but soils are highly variable and farming tends to be less intensive (e.g. in terms of fertilizer use and use of animal draught power). Erratic rainfall, poor soil fertility and weed infestation generally limit agricultural production in northern Nigeria (Manyong et al., 2001; Sanginga, 2003). Major crops in all three regions are cereals (maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and millet (*Pennisetum glaucum* (L.) R. Br.)). Yam (*Dioscorea* spp.) and ginger (*Zingiber officinale* Roscoe) are important next to cereals in Kaduna South (Franke and De Wolf, 2011). Soybean is an emerging crop in northern Nigeria, with about 30% of the households in Kano State to 50% in Kaduna State cultivating soybean in 2010 (Franke and De Wolf, 2011).

2.2. On-farm try-outs of improved soybean technologies

Around 6,000 households in 2011 and 13,800 households in 2012 participated in a dissemination campaign of improved soybean technologies in Kano, Kaduna North and Kaduna South. In each of these regions, Local Government Areas (LGAs) were selected (Fig. 1) based on their potential for soybean cultivation and in consultation with local partners. An LGA typically covered several villages that were managed by one extension agent. Within each village, participating farmers were selected by extension agents based on the farmer's interest in soybean cultivation and the accessibility of the farm (for visibility of the plot and possibility for other farmers to visit the plots, as the try-outs also served as demonstrations).

Farmers were organized in groups of 20–25 people, consisting of one lead farmer (trained directly by the project) and 19–24 satellite farmers (trained by the lead farmer). Each farmer received a package with seed of an improved soybean variety, single super phosphate (SSP) fertilizer and rhizobial inoculant. Farmers tested the package on their own field in a simple, non-replicated try-out whereby each farm formed a replicate. Lead farmers had try-outs measuring 20 × 30 m, with four treatments on sub-plots of 10 × 15 m; satellite farmers had try-outs of 20 × 20 m with four sub-plots of 10 × 10 m. The four treatments were: no inputs (control); SSP only (P); inoculants only (I) and a combination of SSP and inoculants (P + I). Soybean varieties used came from the IITA soybean breeding programme. All were promiscuously-nodulating varieties but they differed in maturity period, potential grain yield and harvest index (Table 2). Varieties were targeted to particular regions; hence not all varieties were assessed in all regions.

SSP (18% P_2O_5) was applied at a rate of 20 kg P ha^{-1} at planting. Recommendations were to band the fertilizer 10 cm away from the planting line in a 2–5 cm deep trench, covered after application. Actual application methods may have varied but were not

Table 1
Agro-ecological characteristics of study regions Kano, Kaduna North and Kaduna South in northern Nigeria.

	Kano	Kaduna North	Kaduna South
Agro-ecological zone	Northern Guinea/Sudan savannah	Northern Guinea savannah	Southern Guinea savannah
Dominant soil types	Luvisols	Luvisols	Luvisols
Annual rainfall (mm)	700–850	1100–1150	1400–1450
Mean temperature during growing season (°C)	22	22	22
Length of growing season (d)	135	165	195
Main crops	Rice, maize, sorghum, millet, cowpea, groundnut, vegetables	Soybean, cowpea, maize, sorghum, millet	Sorghum, maize, yam, ginger, sesame, soybean

Source: Franke et al. (2011).

Table 2
Soybean varieties and their maturity time and group used in try-outs in northern Nigeria in 2011 and 2012.

Breeding line	Maturity time (days)	Maturity group	Potential grain yield (t ha^{-1})	On-farm grain yield (t ha^{-1})[c]	Target region
TGx 1835-10E	89–92	Early	2.0[a]	1.8	Kano
TGx 1987-10F	94	Early	2.2[b]	1.7	Kano, Kaduna South
TGx 1935-3F	79–105	Early	1.0–3.1[a]	1.6	Kano, Kaduna North, Kaduna South
TGx 1987-62F	100–110	Medium	2.2[b]	2.1	Kano
TGx 1951-3F	105–110	Medium	1.7–2.4[a]	1.6	Kano, Kaduna North, Kaduna South
TGx 1955-4F	105–110	Medium	1.4–2.6[a]	1.6	Kaduna South
TGx 1904-6F	104–114	Medium	2.5–2.7[a]	1.9	Kano, Kaduna North, Kaduna South
TGx 1945-1F	105–115	Medium	1.2–2.6[a]	2.0	Kano
TGx 1448-2E	115–117	Late	2.4–2.5[a]	2.1	Kano, Kaduna North, Kaduna South

Source: Tefera (2011); Tefera et al. (2009a).

[a] Grain yields with 100 kg ha^{-1} of NPK (15:15:15) and 50 kg ha^{-1} of triple super phosphate, no rhizobial inoculants.

[b] Grain yields with 100 kg ha^{-1} of NPK (15:15:15), no rhizobial inoculants.

[c] Grain yields with 20 kg P ha^{-1} applied as SSP fertilizer and inoculated with *Bradyrhizobium japonicum*, as measured in on-farm try-outs in this study.

recorded. The inoculant (LEGUMEFiX) contained 10^{10} cells g^{-1} of *Bradyrhizobium japonicum* strain USDA 532c together with a polymer sticker allowing dry inoculation (www.legumetechnology.co.uk). Try-outs were planted by satellite farmers with the help of lead farmers. Lead farmers assisted with the application of inoculants: each farmer group received one sachet of inoculants, which was mixed on-site with the seed at a rate of 4 g kg^{-1}. The seed was sown by individual farmers immediately afterwards. Recommendations included to plant soybean on top of ridges at a spacing of 75 cm between rows and 10 cm between plants with 3 seeds per hill (Kamara et al., 2014). However, reported densities varied from 75 to 90 cm between rows and 5–25 cm between plants. Try-outs were planted between mid-June and early August depending on location. Management of the try-outs during the season was done by farmers so timing and number of weedings varied.

2.3. Data collection and analysis

A sub-set of the soybean try-outs was monitored during the growing season (143 try-outs in 2011 and 191 in 2012). This sub-set was based on stratification by LGA, gender and type of farmer (lead or satellite farmer) and further selection by extension agents (avoiding fields with major problems such as destruction by livestock or flooding). Information on planting, weeding and harvest dates; conditions of the field (perceived soil fertility, drainage) and cropping history of the field was gathered in a ‘field book’. The field book also contained questions on socio-economic characteristics of the household and an evaluation of the different treatments in the try-out by the farmer. Farmers filled in the field book with the help of extension agents. At the end of the season, farmers harvested the plots separately and the grain was kept until weighed and recorded

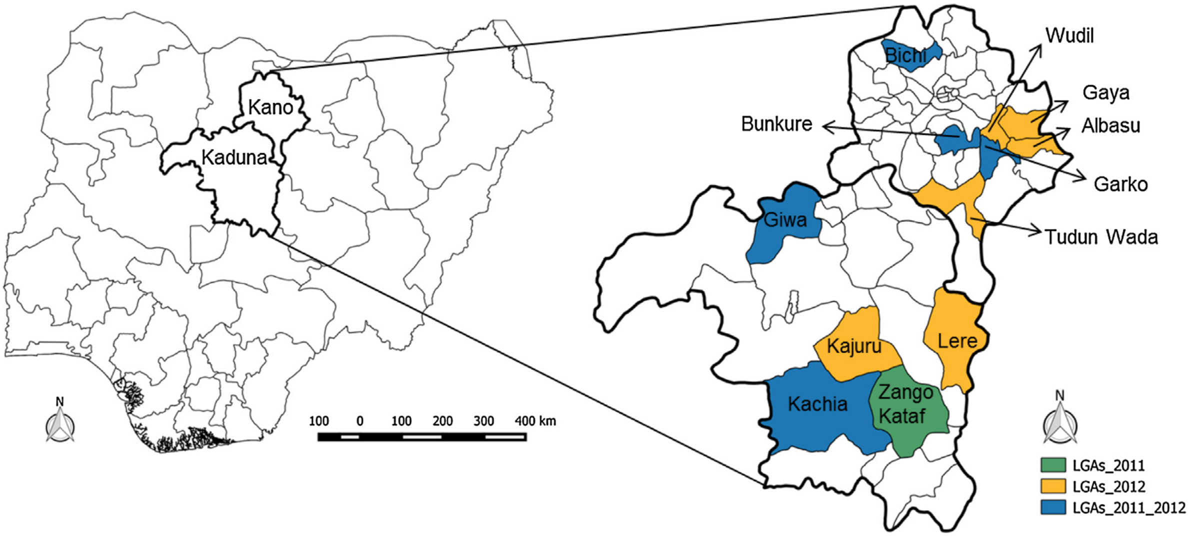

Fig. 1. LGAs with try-outs in 2011 and 2012 in northern Nigeria. Different colours represent the year of study.

by extension agents. Soil samples (0–15 cm depth) were taken at the establishment of the try-outs at a sub-sample of farms and LGAs (58 farms in 2011 and 43 farms in 2012).

The data set was cleaned to include only try-outs where grain yields of all four treatments were reported. From this dataset some try-outs were discarded due to irregularities in data collection (e.g. unclear treatment codes, unclear conversion of units). This resulted in a cleaned set of 63 try-outs in 2011 and 93 in 2012 (44% and 48% of the total try-outs monitored). Soybean grain yields were reported as shelled yields, with the exception of three try-outs. The unshelled yields of these three try-outs were converted to shelled yields through a conversion factor of 0.7 (Van den Brand, 2011), to allow direct comparison with shelled yields. Grain yields represent air-dry weight (11–14% moisture). Soils were analysed for pH (H2O, 1:1 soil to H2O ratio), organic C (Walkley–Black), total N (Kjeldahl), P Olsen (2011) and P Mehlich (2012), and exchangeable K, Ca and Mg (IITA, 1982). P was only assessed as P Olsen by specific request in 2011, while assessment in 2012 was done according to the standard laboratory procedure (P Mehlich). A few farmers applied organic fertilizer across all plots (type of organic fertilizer indicated, quantities not measured). For other farmers the distinction between 'not applied' and 'missing data' could not be made. As there was no significant difference in yield between farmers who did and did not record organic fertilizer application, nor an interaction with the response to treatments, this variable was excluded from further analyses. Daily rainfall data was obtained from NASA's Tropical Rainfall Measuring Mission (TRMM). Estimates were obtained for 150 days from June 16th in 2011 and 2012. Days with less than 0.5 mm of rain were designated as dry days. A drought period was defined as 7 or more consecutive dry days. An indicator variable was created for the occurrence of one or more drought periods.

An economic analysis of the profitability of an investment in SSP and/or inoculants was carried out by deducting the costs of SSP fertilizer and inoculants from the additional yield obtained with these inputs compared with the control yield. Prices of SSP and soybean were obtained from a market survey carried out in the study area in 2013 and were set at 0.60 US$ kg^{-1} for soybean and 126 US$ ha^{-1} for SSP (20 kg P ha^{-1}). Inoculants were not available on the market at the time of the study and were estimated to cost 5 US$ ha^{-1}. Labour requirements for the application of SSP were based on Van Heemst et al. (1981) and set at 35 h ha^{-1}. Casual labour in the area cost 300–400 Naira at the time of study, or about 2.25 US$ (1 US$ is 155 Naira). With a working day of 8 h labour costs for application of SSP were 10 US$ ha^{-1}. Additional labour for the application of inoculants was considered negligible and excluded. The benefit cost ratio for the investment in SSP and/or inoculants was calculated as the difference in grain yield between the control and P and/or I yield, multiplied by the price of soybean and divided by the costs of inputs and additional labour. A sensitivity analysis was carried out whereby input and output prices were varied by 50%, reflecting variations in market prices found in northern Nigeria (Berkhout, 2009; Franke et al., 2010).

2.4. Statistical analyses

Statistical analyses were performed in R version 3.1.2 (R Core Team 2014). The effects of year, region, variety maturity group, P, I and their interactions on yield were estimated with a linear mixed model, taking each farm as a random block term. Yield was square root transformed to ensure homoscedasticity of residuals. Farms with plot-level residuals larger than three standard deviations (2 farms in 2011 and 9 in 2012) were excluded.

Mean yields and input responses per farm were estimated by fitting a linear model with a farm main effect and interaction between farm and P and I, ignoring any interaction between P and I. The use of model-based means instead of observed plot values was deemed preferable for subsequent analysis of variability since it accounts for some of the variation due to experimental error.

We studied the relation between treatment yields and different environmental and management variables measured in the field books. For this analysis, we only included try-outs for which soil data was present (85 farms). In addition, try-outs with missing values for any of the other relevant variables (Table 3) had to be left out. Finally, try-outs with outliers of more than four standard deviations from the mean for any of the variables were also removed. This resulted in a total of 57 try-outs (37% of the try-outs with four treatments), distributed over 6 LGAs, for which data on all relevant variables were available. A mixed model was used to test for potential bias caused by this selection. No significant difference in yield or response to P between selected and non-selected farms was found, but there was a moderate effect of I (140 kg, $P = 0.025$). A linear mixed model with LGA as random factor was used to model control yield, response to P, response to I and response to P + I as a function of the parameters listed in Table 3. Soil P could not be included as variable in the analyses due to the different methods used to determine P in 2011 and 2012. We also explored the relation between the, partially correlated, explanatory parameters and yield and input response by redundancy analysis of the residual from the above model with year as the only fixed effect.

A final statistical model was obtained by backward selection of variables using the function *step* in the R package *lmerTest*. The R^2 of this model was defined as the squared correlation between the predicted and observed values and significance, although of limited meaning in a model resulting from variable selection, was calculated by simple linear regression. The predictive value of the model was evaluated by cross validation by dividing the data equally between training and validation sets at the farm or LGA level. The training set was used to obtain parameter estimates for all variables in the final model, which were then used to predict yields in the validation sets. Cross validation R^2 was calculated as the squared average Pearson correlation (R) between predicted and observed values over 1000 random subsets. Significance of R was determined based on the 5% lower tail of the generated distribution. The ability to predict across years was also evaluated, where R^2 was calculated as the squared average R for prediction of 2012 data from 2011 and vice versa. Prediction was deemed significant if the lowest value of P for the two tests of positive correlation was 0.025 (i.e. Bonferroni correction for two tests at $\alpha = 0.05$).

3. Results

3.1. Soil properties

Soils of Kano State contained a larger percentage of sand than those of Kaduna State, and contained smaller percentages of organic C and N (Table 4). In all three regions, average concentrations of available P, as well as effective cation exchange capacity were low to very low (Hazelton and Murphy, 2007; Mallarino et al., 2013). Exchangeable K was optimal in most sites, and low in Garko and Kajuru (Mallarino et al., 2013). Most soils had a pH around 6; only the soils in Kajuru in Kaduna State were strongly acidic (pH 4.8).

3.2. Soybean grain yields

Both P and I had a strong and highly significant ($P < 1e\text{-}5$) effect on grain yield, increasing yield by 452 and 447 kg ha^{-1} respectively (Table 5). The interaction between the response to P and I was slightly negative (122 kg ha^{-1}, $P = 0.026$). Variety maturity group had no significant effect on yield and no interaction with either P or I. Yield was 25 kg ha^{-1} more in 2012 ($P = 0.015$) while response to I was 53 kg ha^{-1} less in 2012 than in 2011, causing a significant

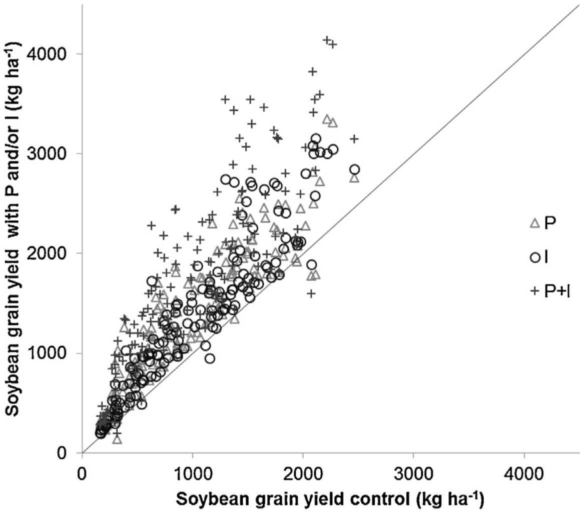

Fig. 2. Soybean grain yields control (kg ha^{-1}) and response to P, I and P + I for individual farms in northern Nigeria (2011 and 2012). P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*.

interaction between year and I application ($P < 0.001$). The highly significant response to inoculant is remarkable considering that all varieties used in the try-outs were bred for promiscuity.

Yields differed per region ($P = 0.015$): average yields were larger in Kaduna North than in Kano State and Kaduna South (Table 5). There were no interactions between region and variety or input application. The lack of interaction between region and input application is explained by the large variation within regions, and interactions between LGA and input application were significant (data not presented). In Kano State, for instance, Bichi and Bunkure LGA had relatively small, and Gaya and Wudil had relatively large yields. Differences within Kaduna South were even larger: yields in Kachia LGA were overall about four to five times smaller than in Kajuru and Zango Kataf.

3.3. Variability in yields and response to SSP and inoculants

While the best average yields were achieved with the combination of P + I, the variability in yields between individual farms was large (Fig. 2). Yields in the control plots ranged from 250 kg ha^{-1} to 2500 kg ha^{-1}. On almost all farms, yields increased with P and/or I; only a few farms had yields with P and/or I below the 1:1 line. The response to these inputs varied widely, however, with yields of P+ I for example ranging from 250 kg ha^{-1} to more than 4000 kg ha^{-1}. Yields on farms with the smallest grain yields of around 250 kg ha^{-1} did not respond well to the application of P and/or I. All these farms, in the bottom left-hand corner of Fig. 2, were located in Kachia LGA.

Small absolute responses to P and/or I were most frequently found on farms with control yields between 250 kg ha^{-1} and 500 kg ha^{-1} (Fig. 3A). Farms with control yields between 500 kg ha^{-1} and 1500 kg ha^{-1} had the largest response. For each level of control yield, however, there were also farms with a minimal response. The differences in response were again related to location: LGAs with better control yields had better responses, and LGAs with small control yields (e.g. Kachia) had only minor responses to treatments. Responses varied less between farms within each LGA. The relative response to treatments (Fig. 3B) showed the same pattern of farms with control yields of less than 500 kg ha^{-1} having the largest relative increase in yield with P and/or I. As the control yield increased, the relative response diminished. Although some of the farms with a control yield of less than 250 kg ha^{-1} gave double the grain yield with the application of P + I, the absolute increase remained small.

3.4. Distribution of responses to SSP and inoculants

Not all farmers benefitted to the same extent from the application of P and/or I (Figs. 2 and 3). Investing in fertilizer or inoculants comes with a risk, and farmers will be reluctant to apply inputs if there is a considerable chance of a weak response. We considered this risk and expressed it as the probability of achieving a certain absolute or relative response to P and/or I compared with the control yield.

In absolute terms, more than 95% of the farmers saw a positive response to the application of P and/or I compared with the control. Half of the farmers increased their grain yield by about 318 kg ha^{-1} or more with P, by 280 kg ha^{-1} or more with I and by 690 kg ha^{-1} or more with P + I (Fig. 4A). Gains of 1000 kg ha^{-1} or more were achieved by only 3% of the farmers with P, by 6% with I and by 26% with P + I. To judge if a technology works, farmers need to see a substantial increase in yield in the field. An increase in grain yield of at least 10% would be needed for the effect of a given treatment to be visible for farmers. A 10% increase occurred on a large majority of farms: about 88% achieved an increase of >10% with P or I and 94% with P + I (Fig. 4B). Half of the farms had an increase in yield of about 37% with P or I, and of 79% with P + I. About 10% of the farmers doubled their grain yield with the application of P, 3% doubled their yield with I and 37% with P + I. As indicated in Fig. 3B, farmers with smaller control yields had the largest relative increases, although their absolute increases were small.

The use of inputs is only attractive to farmers when the benefits in yield outweigh the additional input and labour costs. Risk can

Table 3
Variables included in redundancy analysis (RDA) and mixed model, and abbreviations used in the RDA.

Variable and description	Acronym in RDA	Variable and description	Acronym in RDA
Estimated control yield (kg ha^{-1})	Cont_yield	% organic matter	OC
Estimated response to P (kg ha^{-1})	P_res	% N	N
Estimated response to I (kg ha^{-1})	I_res	K (cmol + kg^{-1})	K
Response to P + I (kg ha^{-1})	P + I_res	Ca (cmol + kg^{-1})	Ca
Planting day	Planting_day	Mg (cmol + kg^{-1})	Mg
Number of weedings	No_weedings	ECEC (cmol + kg^{-1})	ECEC
Number of days between planting and first weeding	Weeding_day	Percentage sand	Sand
Number of days between planting and harvest	Harvest_day	Percentage clay	Clay
Plant establishment (%)	Plant_estab	Farm size (ha)	Farm_size
Plant density	Plant_density	Household hired labour: yes (1) or no (0)	Hired_labour
Cumulative rainfall from 150 days after June 16th (first planting date) in 2011 and 2012 (mm)	Tot_rain	Household members worked on other people's fields: yes (1) or no (0)	Sold_labour
Number of drought days (<0.5 mm rainfall)	Drought_days	Gender of farmer: male (1) or female (0)	Gender
Drought period (7 or more days without rainfall)	Drought	Age of farmer	Age
pH (H_2O)	pH		

Table 4
Average soil properties of fields with try-outs in Local Government Areas (LGA) of Kano, Kaduna North and Kaduna South.

Region LGA	*n*	pH (H_2O)	OC (g kg^{-1})	Total N (g kg^{-1})	P Olsen (mg kg^{-1}), 2011[a]	P Mehlich (mg kg^{-1}), 2012[a]	Exchangeable K (cmol + kg^{-1})	Exchangeable Ca (cmol + kg^{-1})	Exchangeable Mg (cmol + kg^{-1})	ECEC (cmol + kg^{-1})	% Sand	% Silt	% Clay
Kano	20	5.92	4.37	0.40	4.39	8.30	0.22	2.03	0.71	3.34	74	14	12
Bunkure	6	6.50	5.48	0.51	6.69	n.a.	0.28	2.30	0.85	3.56	69	18	13
Garko	14	5.66	3.90	0.36	2.42	8.30	0.19	1.91	0.66	3.24	76	12	12
Kaduna North	16	5.99	8.65	0.74	2.30	3.90	0.21	2.18	0.84	3.37	45	37	17
Giwa	16	5.99	8.65	0.74	2.30	3.90	0.21	2.18	0.84	3.37	45	37	17
Kaduna South	61	5.65	9.45	0.85	2.90	10.21	0.26	2.21	0.65	3.52	61	19	20
Kachia	18	5.52	9.59	1.00	3.10	15.71	0.23	1.76	0.55	2.83	66	14	20
Kajuru	12	4.79	n.a.	0.65	n.a.	4.87	0.17	2.21	0.74	4.09	52	28	20
Lere	16	6.30	10.79	0.84	n.a.	14.64	0.33	3.34	0.91	4.96	61	23	17
Zango Kataf	15	5.84	7.95	0.85	2.69	n.a.	0.28	1.63	0.43	2.46	57	19	23
Total/mean	97	5.76	8.09	0.74	3.12	9.17	0.24	2.17	0.69	3.46	61	21	18
Significance (*P*-values)													
Region		ns	<0.001	<0.001	ns	ns	ns	ns	ns	ns	<0.001	<0.001	<0.001
LGA		<0.001	<0.001	<0.001	ns	ns	ns	0.005	<0.001	0.001	<0.001	<0.001	<0.001

Note: OC = organic carbon, ECEC = effective cation exchange capacity, n.a. = not available.

[a] P analysed with Olsen in 2011 and Mehlich in 2012.

Table 5

Average soybean grain yields (kg ha^{-1}) for control (no inputs), P, I and P + I treatments in on farm try-outs in regions and LGAs of northern Nigeria, 2011 and 2012. P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*. LSDs were calculated based on the transformed yield data (values between brackets).

	n	Control	P	I	P + I
Total	145	968 (31.1)	1420 (37.7)	1415 (37.6)	1745 (41.8)
Max LSD			(1.0)		
Year					
2011	61	902 (30.0)	1406 (37.5)	1380 (37.2)	1833 (42.8)
2012	84	1035 (32.2)	1423 (37.7)	1460 (38.2)	1660 (40.7)
Max LSD year			(4.3)		
Region/LGA					
Kano State	64	782 (28.0)	1251 (35.4)	1104 (33.2)	1590 (39.9)
Albasu	1	2330	2697	2782	3024
Bichi	7	609	1164	9845	1356
Bunkure	20	586	1049	952	1467
Garko	16	808	1323	1181	1686
Gaya	3	1697	1623	1749	2017
Tudun Wada	8	956	1326	961	1498
Wudil	9	1119	1378	1376	1716
Kaduna North	17	1265 (35.6)	1755 (43.9)	1924 (41.9)	2108 (45.9)
Giwa	17	1357	1890	2085	2444
Kaduna South	64	887 (29.8)	1279 (35.8)	1278 (35.7)	1565 (39.6)
Kachia	20	325	500	472	643
Kajuru	14	1373	2106	1982	2428
Lere	15	822	973	969	1248
Zango Kataf	15	1602	2411	2603	2917
Max LSD region			(6.0)		

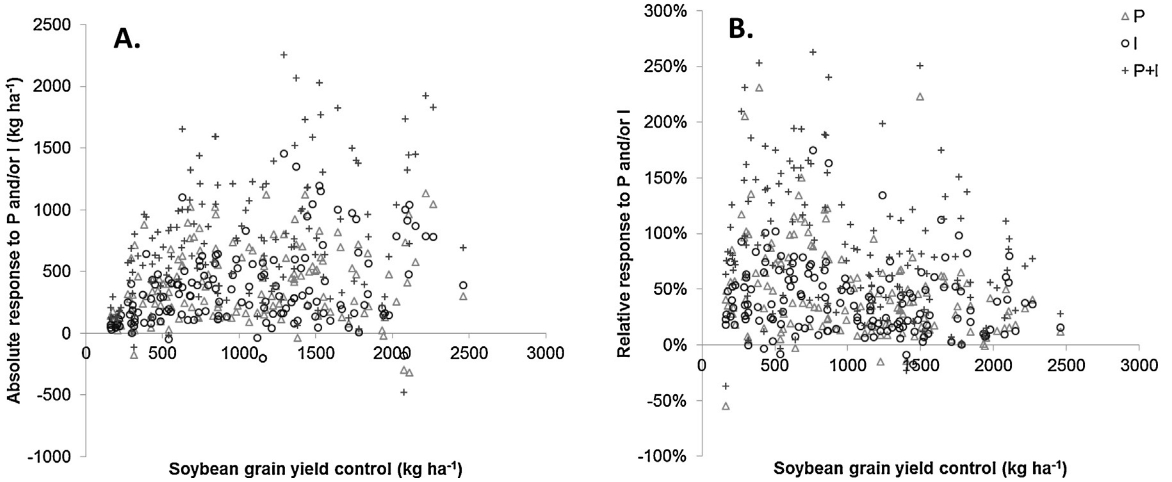

Fig. 3. Estimated soybean grain yields of control (no inputs) (kg ha^{-1}) and response to P, I and P + I for individual farms in northern Nigeria (2011 and 2012) as absolute response (kg ha^{-1}; yield of P and/or I minus control yield) (A); and relative response (%; yield of P and/or I minus control yield, divided by control yield) (B). P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*.

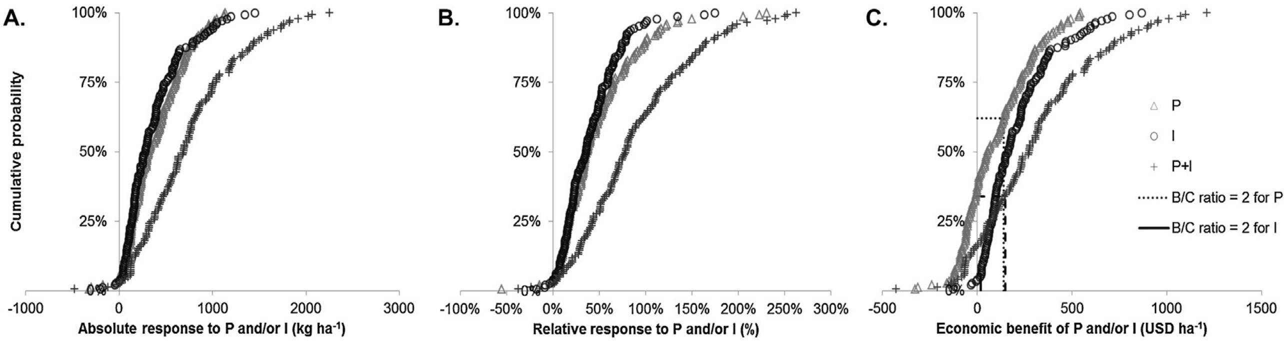

Fig. 4. Cumulative probability of estimated absolute response (kg ha^{-1}) (A); relative response (%) (B) and economic benefits (additional yield minus relevant input costs, US$ ha^{-1}) (C) of P and/or I compared with control. Dashed lines in C represent a benefit/cost (B/C) ratio of 2 for the application of P and/or I. P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*.

therefore also be expressed as the probability of achieving a certain economic benefit from the application of P and/or I compared with the control yield (Fig. 4C). Looking at the economic benefits changes the picture: although over 95% of the farmers increased their yield with the application of P, only about 60% achieved an economic benefit (i.e. marginal values larger than marginal costs), as the cost of SSP fertilizer application including labour is large. Inoculant application is relatively cheap, and almost all farmers (about 95%) achieved an economic benefit from its application. Because yields for the combination of P + I were larger than for P or I only, this combination was also economically beneficial for 83% of the farmers.

For the adoption of technologies, however, the break-even point is often not sufficiently attractive. A benefit cost ratio (B/C) of 2:1 is generally considered necessary to lead to adoption. This ratio was still achieved by almost all farmers who applied inoculants (95%). For P, however, only about 40% of the farmers achieved a B/C ratio of 2, so again much less than the 60% of farmers who broke even. For P + I this ratio was achieved by about two-third of the farmers.

The distribution of economic benefits depends greatly on fluctuations in input and output prices, as assessed in a sensitivity analysis (Table 6). Fluctuations in the price of soybean grain or SSP fertilizer considerably affected the economic benefits achieved with P. With a 50% decrease in soybean grain price, the percentage of farmers breaking even decreased from about 60% to 40%, and only 6% of the farmers achieved a B/C ratio of 2. Also for P + I the percentage of farmers achieving a B/C ratio of 2 decreased to only one-third. Considering the need of many smallholders to sell their grain shortly after harvest in search for cash, this scenario again shows the financial risk associated with the application of fertilizer. On the other hand, with a 50% increase in soybean price, almost 90% of the farmers broke even with P + I, and almost 80% achieved a B/C ratio of 2. A 50% decrease in the price of SSP fertilizer also had a large effect: the percentage of farmers breaking even with the application of P increased to more than 80%, and almost 60% of the farmers had a B/C ratio of 2. For P + I, more than 90% would break even and more than 80% would have a B/C ratio of 2. The economic benefits achieved with the application of I were very stable under price fluctuations due to the small costs for inoculants. Fluctuations in labour prices only had a minor influence on profitability, as the additional labour costs for fertilizer application constitute a small part of the total costs.

3.5. Understanding variability in yield and response to SSP and inoculants

In the remainder of this study we explore the factors influencing the variability in yields to understand where the technologies work best, and to what extent we could use this information to target technologies to the farmers that will achieve the greatest benefits from them.

A redundancy analysis of the environmental and management factors, to identify the relation between these factors and control yield and response to P and/or I, showed that the responses to P and/or I were all related to the first redundancy axis (Fig. 5). Variables that were positively correlated with this axis were farm size (the larger the farm, the stronger the response), the number of weedings and households that sold labour (households with family members working on other people's fields had better yields). Variables negatively correlated with the response to P and/or I were pH, percentage OC and N. These soil fertility parameters were correlated with each other as well. Total rainfall, the number of drought days and planting day were also correlated, and negatively related with the responses. Control yields were related to the second axis and showed no relation with the response to P and/or I. The lack of relation between control yields and responses is in contrast to the relation observed in Fig. 3A, and is the result of the correction for location in the redundancy analysis: responses differed between LGAs, but not within LGAs. Control yields were related with plant establishment, and also with a number of soil fertility parameters (K, Mg and Ca) which were again related with each other. Harvest day had a negative relationship with control yields.

A mixed model tested which environmental and management factors had a significant effect on control yield and the response to P and/or I. Control yields were positively related with plant establishment, and this relationship was highly significant (Table 7). Control yields were also positively related to the number of days to first weeding, the percentage of sand and Mg.

Year, farm size, planting day, total rainfall and pH all had significant effects on the response to P and/or I. Year had a negative effect, with yields in 2012 smaller than in 2011. Larger farms had better responses to the treatments. Remarkably, total rainfall was negatively related with the response to P, and positively with P + I. Finally, pH had a negative, significant relation with the response to P and/or I.

The R^2 for the percentage variability in control yields and response to P and/or I explained by environmental and management factors ranged from 16% for the control yield to 61% for the response to P + I. Ideally, by understanding variability in yields, we would be able to predict the performance of P and I on new farms, and hence to target our technology interventions. We could use the relevant variables from the model to select farmers who would be expected to benefit most from the application of P and/or I. Cross-validation of the model outcomes showed, however, that the predictive value of these variables was much smaller than the percentage of variability that could be explained (to be compared with R^2 values of the training model) (Table 7). We first based the cross-validation on a random sub-set of farms from the dataset. This gave a reasonable prediction, meaning that if we would expand the work among a very similar group of farmers we could do a reasonable estimate of where the technologies would work best. However, when results of a sub-set of LGAs were used to predict yields in other LGAs, the cross-validation R^2 drastically decreased. The result was again worse for the prediction between years. LGA and year were partly confounded, however, as 2011 and 2012 included different LGAs and this could not be corrected for due to the limited overlap between LGAs in both years. Hence, even though the variability in yields and responses to P and/or I could be explained reasonably well with the variables included in the analysis, the predictive value of these variables across seasons and geographical areas (LGAs) was limited.

4. Discussion

4.1. Response to SSP fertilizer and inoculants

Soybean varieties included in this study were bred for promiscuity, yet we observed widespread yield responses to inoculation among all varieties. This is in contrast to previous studies in Nigeria which reported no significant increase in grain yields of these varieties with inoculation (Okogun and Sanginga, 2003; Osunde et al., 2003b; Okogun et al., 2005). Some authors reported a significant increase, however, in the number of nodules (Okogun and Sanginga, 2003; Osunde et al., 2003b) or biomass (Osunde et al., 2003b; Pule-Meulenberg et al., 2011; Thuita et al., 2012).

A large majority of farmers benefitted from the application of inoculants in soybean, in agronomic (Fig. 4A) as well as economic terms (Fig. 4C). Inoculation therefore is effective in increasing soybean yields with little financial risk, provided good quality inoculants are available to farmers. Availability of inoculants in rural areas remains a key constraint to the use of inoculants in

Table 6
Sensitivity analysis of the economic benefits of P and/or I under fluctuation of input and output prices as percentage of farmers breaking even or achieving benefit/cost (B/C) ratio of 2. P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*.

Variable	Fluctuation	% Of farmers breaking even			% Of farmers with B/C = 2		
		P	I	P + I	P	I	P + I
Average market prices		62	95	83	38	94	66
Soybean grain price	−50%	39	95	66	6	94	31
	+50%	73	96	88	51	95	78
SSP and inoculant price	−50%	82	96	92	58	95	82
	+50%	49	95	74	21	95	50
Labour price[a]	−50%	65	–	83	41	–	66
	+50%	61	–	83	36	–	64

[a] Additional labour for the application of inoculants was considered negligible and therefore not used in the calculation of economic benefits.

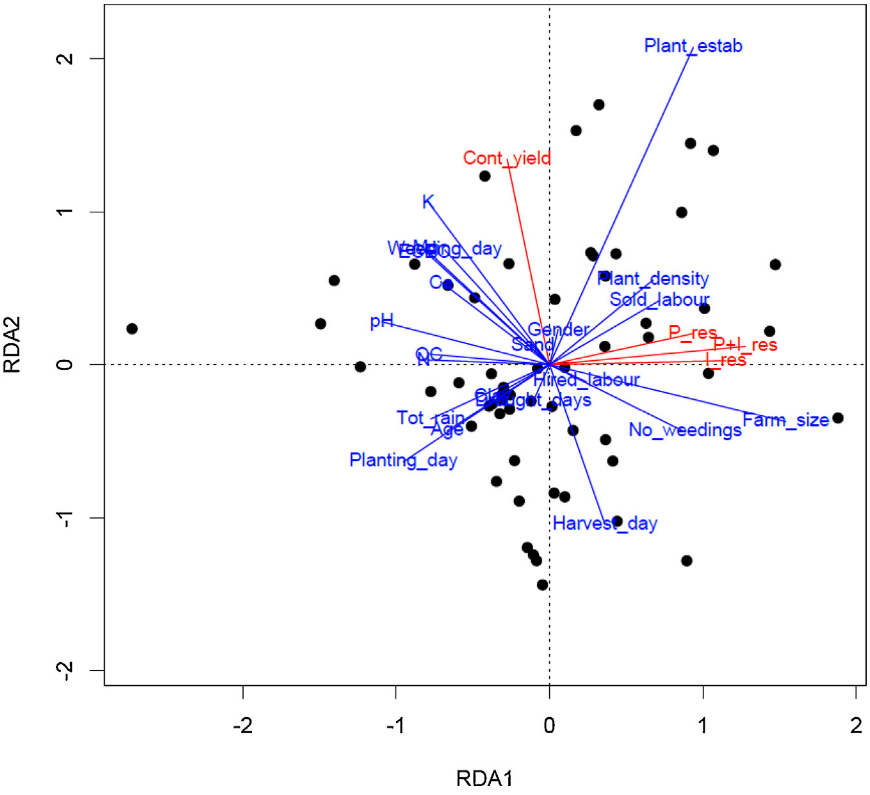

Fig. 5. Redundancy analysis (RDA) of control yield and response to P and/or I with location as random, and year as fixed effect. Abbreviations of explanatory variables are given in Table 3. P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*.

much of sub-Saharan Africa, although there is commercial production in Kenya and South Africa and semi-commercial production in Zimbabwe with extensive distribution to farmers in several countries.

The yield response to SSP was similar to the yield response to inoculation, but the use of inoculants was economically more attractive. SSP applied alone was barely profitable, and farmers would be better off applying SSP together with inoculants as the combination was profitable for a large majority of farmers (Fig. 4C). Advice to farmers could be to start with inoculants, and to add SSP when additional capital is available. A stepwise process for the introduction of new technologies has been suggested with increasing requirements in terms of capital, risk and complexity, but also with increasing productivity and profitability (Byerlee and Polanco, 1986; Aune and Bationo, 2008; Vanlauwe et al., 2010). Frequent cultivation of soybean without P-fertilizer, however, will exhaust soil P reserves, especially considering the already poor soil availability of P in northern Nigeria (Table 4) (Okogun et al., 2005; Kamara et al., 2007; Franke et al., 2010). Next to direct effects of P on soybean yield, subsequent crops may benefit from the residual effects of P (Janssen et al., 1987; Van der Eijk et al., 2006). With repeated applications, the need for P in subsequent crops will be reduced, enhancing the profitability of P-fertilizer. *Vice versa*, soybean would benefit from P applied on a previous crop. Soybean is often grown in rotation with maize to which farmers in Nigeria often apply fertilizer (Manyong et al., 2001). As farmers tend to believe legumes can grow well without fertilizer, they may prefer to use fertilizer on maize, although Zingore et al. (2008) found that in some cases application of P-fertilizer on soybean was more profitable than on maize. Such considerations emphasize the need to analyse cropping systems rather than single crops. Given the strong residual effects of soybean through provision of N and suppression of *Striga hermonthica*, often leading to large increases in yield of the subsequent cereal crop (Franke et al., 2006), the overall economic benefits to farmers are likely to be larger still.

Despite the highly significant response overall to SSP and inoculants, responses differed greatly among farms. Only 21 farms out of 145 (14%) had a response to P + I that was within 10% of the mean of 750 kg ha^{-1}. On 10% of the farms the response was (more than) double the mean, while 17% had responses of less than 250 kg ha^{-1}

Table 7

Explanatory variables for variability in control yield and response to P and/or I, R^2 of the model for the whole dataset (the value for the training model is given in brackets for direct comparison with the cross-validation R^2s) and results of cross-validation (CV) of the model between fields, LGAs and years (* indicates values significantly different from 0). P = 20 kg P ha^{-1} applied as SSP fertilizer; I = seed inoculated with *Bradyrhizobium japonicum*.

Treatment (yield)/explanatory variables	Effect pos (+) or neg (−)	*P*-value	R^2	CV1 (fields)	CV2 (LGA)	CV3 (year)
Control (1030 kg ha^{-1})						
Plant establishment	+	8.09e-05	0.16* (0.80*)	0.13*	0.12	0.24*
Weeding day	+	0.03766				
% Sand	+	0.01562				
Mg	+	0.00227				
Response P (382 kg ha^{-1})						
Year	−	0.00019	0.45* (0.56*)	0. 25*	0.02	0.05*
Farm size	+	0.00773				
Planting day	+	0.03529				
Total rainfall	−	0.00015				
Plant density	−	0.03957				
pH	−	0.03405				
Response I (432 kg ha^{-1})						
Year	−	0.037854	0.42* (0.58*)	0.11*	0.11*	0.08*
Farm size	+	0.009007				
Plant establishment	+	0.025225				
Number of weedings	+	0.029292				
pH	−	0.015017				
Response P + I (815 kg ha^{-1})						
Year	−	0.000592	0.61* (0.70*)	0. 47*	0.06	0.01
Farm size	+	0.000056				
Plant establishment	+	0.015277				
Planting day	−	0.036012				
Total rainfall	+	0.017109				
pH	−	0.002006				

and 2% had a negative response. The presentation of mean yields therefore gives misleading expectations about the adoption potential of technologies, as mean yields hide the risks for individual farmers (Sileshi et al., 2010; Bielders and Gérard, 2014). In addition, the economic analysis revealed that the use of SSP was unattractive for a relatively large proportion of farmers, despite substantial yield responses. Analysing variability in yield, in responses and in the associated economic risk therefore gives a more complete impression of the attractiveness of these technologies.

4.2. *Explaining variability*

With the variables we measured we could explain a reasonable part (16–61%) of the variability, comparable with the results of Bielders and Gérard (2014) who found that environmental and management factors explained 20% of variability in millet yields under similar experimental conditions. The largest differences were found between locations. Try-outs in Kachia clearly had the smallest yields and response to treatments caused by a combination of factors such as late planting and shallow, rocky soils. On these soils, multiple nutrient deficiencies may have caused the soil to be non-responsive (Foli, 2012; Vanlauwe et al., 2014b). In other cases it appears that excessive rainfall is likely to have caused periodic waterlogging. Better control yields were associated with, among other variables, larger soil Mg contents. As concluded from Fig. 5, this could indicate better overall soil fertility considering the correlation with other soil fertility parameters. Hence better control yields were found on more fertile soils. In contrast, the response to treatments was negatively related with the combination of pH, OC and N, which could indicate that fields with better soil fertility had smaller responses to the treatments. The negative relationship between pH and response to treatments seems counterintuitive. Closer analysis showed that soils with a pH of between 5 and 6.5 had better responses than soils with higher or lower pH (data not presented). The positive relation between control yields and percentage sand is also counterintuitive, and may have been the result of confounding other variables. Total rainfall had a positive effect on response to P + I, but was negatively associated with the response to P. This is mainly explained by results in Kachia LGA, where yields were smallest but cumulative rainfall largest in both years. Yields in 2012 were smaller than in 2011, perhaps due to less rainfall in 2012 (data not presented).

4.3. *Methodological considerations*

While we could explain variability reasonably well, a considerable proportion remained unaccounted for. Would we be able to explain a larger part of the variability if we would have collected more detailed data? We take some examples from Western Europe, where detailed data are available. Bakker et al. (2005) found an R^2 of about 0.90 for the relationship between yield data (10 year average of regions in Europe) and soil, climate and economic variables. Variables in their study were all measured at a high aggregation level, not at farm level, and trends in yields over multiple years also poorly correlated with the explanatory variables (R^2 of 0.17–0.43). Landau et al. (2000) found an R^2 (adjusted) of 0.26 for the relation between detailed climatic data and yields of wheat trials in the UK, similar to our results. A detailed study on yield differences between farms in a very homogenous environment in the Netherlands explained 80–90% of variability, largely based on management factors (Zachariasse, 1974). The latter suggests that a more detailed approach in a limited number of sites in a more homogenous environment, together with accurate measurements of potential explanatory variables, could give better results. However, during the first rounds of analyses we also found that many of the observed significant relationships between yield and explanatory factors were based on one or two outliers in these explanatory variables which strongly dominated the outcomes. These outliers were subsequently removed in a systematic way (>4 SD from the mean). A systematic and transparent approach of checking the relevance of these observed significant relations and being open about uncertainties rather than stressing the robustness of the outcomes is a necessity to achieve useful results.

Through cross-validation of our model we showed that the predictive value of the variables we measured was limited for targeting of technologies among farmers in new areas or in subsequent seasons. The prediction for a random sub-set of farmers was reasonable, but probably the result of overfitting of the model rather than actual predictive power. If we would be able to improve this power by better understanding the observed variability, farmers could benefit from targeting technologies: the 50% best performing farmers in Fig. 4C achieved an average economic benefit of about 550 US\$ ha^{-1} with P + I application, while the bottom half gained only 70 US\$ ha^{-1}. What could be done to better understand variability and improve the predictive power of future studies? First, many of the explanatory variables were confounded, which may lead to misidentification of the true explanatory factors (Bakker et al., 2005). For instance, varieties were confounded with location: varieties were targeted to LGAs where they were expected to perform well, and not all varieties were grown in all LGAs. This made it hard to find differences in performance between varieties, in contrast to e.g. Tefera et al. (2009b). Planting dates were also confounded with location, making it difficult to establish whether late planting reduced yield or if this was just related to, for instance, a later onset of the rains in that location. Second, we could have missed important variables; as reflected on by Bielders and Gérard (2014). Our study could have benefitted from better rainfall data (measured at plot level instead of averages per LGA), soil data (collected on all farms, with standard procedures for analysis across years), and more detailed information on pests, diseases and ‘external events’ such as destruction of crops by livestock, storms, floods or drought.

A better understanding of which variables determine soybean yields would not necessarily allow better targeting. Taking soil samples on all sites and analysing them before the try-outs are sown would be practically impossible. Rainfall cannot be predicted for the next season, so what works in one season may not work in the next. What would be feasible for targeting? Targeting can be thought of at different geographical scales. At higher levels we could make use of agro-ecological zones, and predict areas in which a technology is expected to perform better based on temperature, length of growing season, soils, etc. with the help of remote sensing, GIS and soil maps. This is was the approach taken to target soybean, amongst other legumes, to farmers in northern Nigeria in this study (Franke et al., 2011), and requires relatively little local prior information. As this study shows, however, there is also considerable variability within agro-ecological zones, e.g. related to differences in resource endowment and gender of the farmer (Franke et al., forthcoming), or soil fertility and management history (Tittonell et al., 2005; Zingore et al., 2011). We measured a number of agronomic parameters (planting and weeding dates, number of weedings) to explain this variability, but the difficulty with such parameters is that they cannot be predicted among new groups of farmers. To improve the predictive value of the dataset, we could therefore look for proxies for these parameters: delays in planting and weeding are often related to labour or cash constraints, and hence to resource endowment (Tittonell et al., 2007; Pircher et al., 2013). In addition, we found that larger, and presumably wealthier, farms had better responses to treatments, suggesting better crop management by wealthier farmers. Socio-economic profiles of farmers could therefore help in targeting. Collecting such information would be data intensive, but could work well in countries where such profiles are already available (e.g. Rwanda).

Although our results could have benefitted from a more detailed and complete dataset, it should be kept in mind that our study was undertaken in the context of a legume dissemination campaign, with development rather than research as primary aim. Development partners were responsible for much of the sampling strategy and data collection, which inevitably resulted in greater variability in implementation than trials conducted by researchers. The power of this type of work therefore lies in the large number of observations and the realistic context of farming, which helps to understand the variability in performance, economic benefits and related adoption potential of improved soybean technologies.

5. Conclusion

We observed a widespread response to inoculation in soybean varieties that had been bred for promiscuity. Rhizobial inoculation proved to be a cheap way to increase soybean yields with low financial risks. In addition, inoculation made the application of P-fertilizer economically attractive for a large proportion of farmers, unlike the use of P alone. Despite the strong agronomic and economic case for the use of inoculants, the local availability of good quality inoculants in Africa is problematic at present.

The observed variability in yield and responses to technologies, as well as the associated variability in economic benefits, implies that averages of on-farm performance of technologies are of little value to estimate the adoption potential of a technology for individual farmers. Understanding the causes of variability helps to target technologies to groups of farmers who are expected to benefit most. While we could explain a reasonable percentage of the variability in yields observed in our dataset, the potential to use this information to predict the performance of technologies or to target technologies to a new group of farmers remains limited. Spatial models (GIS, remote sensing) and farm typologies may help to improve such targeting.

Acknowledgements

We thank the Bill & Melinda Gates Foundation for funding this research through N2Africa: Putting Nitrogen fixation to work for smallholder farmers in Africa (www.N2Africa.org); a grant to Wageningen University implemented in 11 countries in sub-Saharan Africa. We also thank the farmers, extension officers and dissemination partners (Sasakawa Global 2000, Kaduna State Agricultural Development Project (KADP), Kano Agricultural and Rural Development Authority (KNARDA) and Federal University of Technology, Minna) in northern Nigeria for their cooperation in data collection.

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