Field Crops Research 187 (2016) 113–126

Contents lists available at ScienceDirect

Field Crops Research

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

Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali

Gatien N. Falconnier[a,b,*], Katrien Descheemaeker[b], Thomas A.Van Mourik[c], Ken E. Giller[b]

[a] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), BP 320 Bamako, Mali
[b] Plant Production Systems, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands
[c] Helen Keller International, Africa Regional Office, PO Box 29.898, Yoff, Toundoup Rya Lot 122, Route de l'aeroport, Dakar, Senegal

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
19 December 2015
Accepted 20 December 2015
Available online 6 January 2016

Keywords:
Intercropping
Cereals
Legumes
Soil type
Rotation

ABSTRACT

Options that contribute to sustainable intensification offer an avenue to improve crop yields and farmers' livelihoods. However, insufficient knowledge on the performance of various options in the context of smallholder farm systems impedes local adaptation and adoption. Therefore, together with farmers in southern Mali we tested a range of options for sustainable intensification including intensification of cereal (maize and sorghum) and legume (groundnut, soyabean and cowpea) sole crops and cereal-legume intercropping during three years on on-farm trials. There was huge variability among fields in crop yields of unamended control plots: maize yielded from 0.20 to 5.24 t ha^{-1}, sorghum from 0 to 3.53 t ha^{-1}, groundnut from 0.10 to 1.16 t ha^{-1}, soyabean from 0 to 2.48 t ha^{-1} and cowpea from 0 to 1.02 t ha^{-1}. This variability was partly explained by (i) soil type and water holding capacity, (ii) previous crop, its management and the nutrient carry-over and (iii) inter-annual weather variability. Farmers recognized three soil types: gravelly soils, sandy soils and black soils. Yields were very poor on gravelly soils and two to three times greater (depending on the crop) on black soils. Yields were also poor at the end of the typical crop rotation, i.e., after sorghum and millet, and 1.3–1.7 times greater (depending on the crop) after the fertilized crops maize and cotton. We diagnosed a number of cases of technology failure where no improvement in yield was observed with hybrid varieties of maize and sorghum and rhizobial inoculation of soyabean. Regardless of soil type and previous crop, mineral fertilizer improved yields by 34–126% depending on the crop. Targeting options to a given soil type and/or place in the rotation enhanced their agronomic performance: (i) the biomass production of the cowpea fodder variety was doubled on black soils compared with gravelly soils, (ii) the additive maize/cowpea intercropping option after cotton or maize resulted in an average overall LER of 1.47, no maize grain penalty, and 1.38 t ha^{-1} more cowpea fodder production compared with sole maize. Soil type and position in the rotation, two indicators easy to assess by farmers and extension workers, allowed the identification of specific niches for enhanced agronomic performance of legume sole cropping and/or intercropping.

1. Introduction

Farmers in Southern Mali grow cotton for income generation, cereals for food self-sufficiency and keep livestock for a wide variety of reasons, including draught power, manure, meat, milk and buffer against risk (Falconnier et al., 2015b; Kanté, 2001). Due to market uncertainty and increasing land pressure, agriculture needs to adapt to the decline in cotton profitability (Coulibaly et al., 2015) and reduced availability of fodder for livestock (Breman, 1992; De Ridder et al., 2004; Leloup, 1994). Sustainable intensification offers an avenue to improve farmers' livelihood and is based on three principles (Vanlauwe et al., 2014): (i) production of more food, feed and/or fuel from the same amount of land, labour and/or capital (ii) maintenance of healthy soils and reduction of negative environmental impacts and (iii) resilience to climate shocks and stresses. Two strategies are often mentioned to contribute to

* Corresponding author at: Plant Production Systems, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands.
E-mail addresses: falconniergatien@yahoo.fr, gatien.falconnier@wur.nl (G.N. Falconnier).

http://dx.doi.org/10.1016/j.fcr.2015.12.015
0378-4290/

sustainable intensification. Firstly, Integrated Soil Fertility Management (ISFM), which assembles locally-adapted practices based on the use of improved crop varieties together with combined fertilizer, organic resource management and other soil amendments (e.g., lime) can enhance crop productivity and contribute to maintenance of healthy soils (Vanlauwe et al., 2015). Secondly, crop diversification through cereal-legume rotations or cereal-legume intercropping can reduce yield variability and improve overall farm productivity (Franke et al., 2014; Snapp et al., 2010). The options we tested all fall under one of these two strategies and can thus contribute to sustainable intensification. Although many studies report increased crop productivity in trials with such practices (Kaizzi et al., 2012; Otinga et al., 2013; Pitan and Odebiyi, 2001; Rurinda et al., 2013), local adaptation to diverse smallholder farm systems and conditions has received less attention. Indeed smallholder farming in SSA exhibits wide variability in household resource endowment and in soil fertility (Giller et al., 2011), resulting in huge ranges in yields within the same agro-ecological zone or even within individual farms (Baudron et al., 2012; Ronner et al., 2015; Zingore et al., 2007). Large numbers of on-farm trials are required to unravel the relationships between the farmers' socio-ecological context and the performance of interventions. For example, 63 on-farm trials in semi-arid Zimbabwe showed that no tillage and insufficient mulch favoured crusting of sandy soils, thereby reducing water infiltration and decreasing cotton yields compared with ploughing (Baudron et al., 2012). Ojiem et al. (2007) used 27 trials to demonstrate that soil fertility status impacted the contribution of forage and grain legumes species to soil fertility improvement through biological nitrogen fixation.

In southern Mali, past research has identified a range of options for sustainable intensification including (i) maize-legume intercropping in which leguminous fodder is produced without penalizing maize grain yields (Bengaly, 1998), (ii) hybrid sorghum varieties that yield more than local landraces under fertilized conditions (Rattunde et al., 2013) and (iii) improved varieties of cowpea that allow grain production whilst also providing good quality fodder (Dugje et al., 2009). Yet little is known of the agronomic performance of these different options across the wide array of soil types, rotations and seasons that are encountered in the prevailing crop-livestock farming system. Hence, for better advice to farmers, information is needed on the niches where these options perform best. Such information needs to be easy to use and to assess by local farmers and farm advisors. Furthermore, numerous papers report on specific crop (maize, cowpea, soyabean) experiments, but very few studies encompass the complete set of farmers' crops in multi-year on-farm trials. However, such experimental setup is required to produce relevant information for farmer decision-making, which takes into account the management of the entire cropping system and the risk and trade-offs associated with certain decisions. Together with local farmers we therefore experimented with five crops (maize, sorghum, soyabean, cowpea and groundnut), two intercrops (maize/cowpea and sorghum/cowpea) and a whole range of options including hybrid varieties, combined additions of mineral fertilizer and manure, rhizobial inoculation of soyabean, improved varieties of cowpea and groundnut and intercropping patterns. After a series of participatory rural appraisals to understand and define farmers' constraints and opportunities, experiments to test these options were co-designed by researchers and farmers. Farmers tested the options in their fields over three consecutive seasons. The on-farm trials formed part of a larger participatory farming system re-design process (Falconnier et al., 2015a), which for example accommodated for annual adjustments in the set of trials.

In this paper we (i) assess the agronomic performance of a range of intensification options across a range of farmers' fields; (ii) explore the causes of the variability in farmers' yields and in the effects of the options on productivity; and (iii) define simple rules on where and when the intensification options perform best. In doing this, we explored the hypotheses that (i) soil type and characteristics, previous crop and its management, and seasonal rainfall variability explain the variability in farmers' yields and treatment effects; and (ii) better matching of intensification options with the environment (previous crop, soil type) increases the likelihood of increased crop yield.

2. Material and methods

2.1. Study area

The study area is located in Koutiala district in the cotton zone of Southern Mali, between the 800 mm and 1000 mm isohyets. The region is characterised by a uni-modal rainy season that starts in May and ends in October, with total rainfall fluctuating from 600 to 1400 mm. The population is relatively dense compared with the rest of the country, reaching 70 people km^{-2} (Soumaré et al., 2008). Farmers distinguish three main soil types with a vernacular name related to landscape position and texture (Blanchard, 2010; Kanté, 2001): "gravelly soils" at higher elevation, "sandy soils" in the middle and "black soils" in the lowest part of the catena. All soils are classified as Lixisols (FAO, 2006). Dominant crops are cotton, maize, sorghum, millet and groundnut. Farmers rely largely on cotton, maize and livestock for income and on maize, sorghum and millet as staple foods. The most common rotations are: (i) cotton and maize rotations, (ii) cotton and maize followed by sorghum and/or millet and (iii) sorghum and millet rotations. In all cases, organic and mineral fertilizers are applied solely on cotton and maize (Blanchard, 2010). The major livestock are cattle, sheep and goats. On average, farmers own 10 Tropical Livestock Units (TLU) of 250 kg with a wide range from 0 to 54 TLU (Falconnier et al., 2015b). Besides milk and meat, animals provide draught power for timely farming operations to cope with the erratic distribution of rainfall, while application of livestock manure in the fields has positive feedbacks on crop productivity (Kanté, 2001).

2.2. On-farm trials

We carried out on-farm trials during three consecutive cropping seasons (2012–2014). Participating farmers originated from nine neighbouring villages of the Koutiala district: M'Peresso, Nitabougouro, Nampossela, Finkoloni, Try, Koumbri, Kaniko and Kani. A total of 372 trials were planted by 12, 111 and 132 farmers in 2012, 2013 and 2014 respectively. Trials were not repeated in the same location. The first season was an inception year with only 12 participating farmers, while in the second and third season the network of participating farmers expanded. Seven different trials on options with sole crops and intercrops were co-designed by researchers and farmers to explore the opportunities discussed in participatory rural appraisals. Treatments included: (i) a maize and (ii) a sorghum hybrid and local variety, with and without combined mineral fertilizer and manure application (iii) soyabean without any amendments, with rhizobial inoculation and/or P fertilizer with manure, (iv) a grain variety and a fodder variety of cowpea with and without P fertilizer (v) an improved and a local groundnut variety, (vi) the cowpea grain and fodder varieties intercropped with maize or (vii) sorghum, with an additive and a substitutive intercropping pattern. Farmers indicated which improved varieties for maize and sorghum they were interested in for testing. As farmers were eager to test groundnut options, the groundnut trial was added in the third year.

Each sole crop trial was comprised of four plots of 6×8 m each: a control plot, two plots to test the effect of the first and second factor and a plot to test the combination of the two factors (Table 3). The control was the current farmer practice for maize, sorghum and groundnut, i.e. the local variety of the crop without fertilizer for sorghum and groundnut and with the mineral fertilizer dose recommended by the Compagnie Malienne pour le Développement du Textile (CMDT) for maize (as farmers do not grow maize without fertilizer), i.e. 80, 7, 12 kg ha^{-1} for N, P and K respectively. For soyabean and cowpea, the control was an improved variety (as cowpea is grown by only 16% of farmers and soyabean is seldom grown) with no fertilizer inputs. Seed of the local varieties was purchased from one resource farmer and used in all the trials. Manure was bought at the abattoir in Koutiala and was a mix of cattle droppings and sand from the pen. This manure was similar to that which farmers commonly collect in their cattle pen (Blanchard, 2010). Manure analysis at ICRISAT Sadore lab (Niger) indicated a nutrient content of 0.88% N, 0.28% P, 0.65% K, 16% organic carbon (OC) and 72% ash in 2013 and 1.19% N, 0.33% P, 0.49% K, 15% OC and 69% ash in 2014. The rate of manure application used in the trials (9 t ha^{-1}) was in the range of the reported application rates by farmers (7–18 t ha^{-1}) (Blanchard et al., 2013).

Sun-dried manure (86% DM) was broadcasted before ploughing in plots established with a manure treatment. Farmers ploughed the fields and farmers and technicians planted the trials together. Seed was sown at a spacing of 75 cm between rows for maize, sorghum, cowpea and soyabean and 60 cm for groundnut. Within row spacing was 40 cm for maize, sorghum and cowpea, 30 cm for groundnut and 5 cm for soyabean, with one seed per station for soyabean, two for groundnut, three for maize and cowpea, and four for sorghum. Crops were thinned at 15 days after planting: one plant per station for groundnut and two plants per station for maize, cowpea, and sorghum were retained. Sorghum, cowpea and soyabean were weeded 15 days after sowing and ridged 45 days after sowing. Maize was weeded twice (15 days and 30 days after sowing) and ridged 45 days after sowing. Cowpea was sprayed with neem oil (from the tree *Azadirachta indica* A. Juss.) every two weeks after the first weeding and every week during flowering and pod filling.

For the intercropping trials, farmer chose cowpea as the companion crop for maize and sorghum. The intercropping arrangement proposed by farmers was an additive pattern where the cereal (maize or sorghum) was sown with the same density as the sole crop (67 000 plants ha^{-1}) and cowpea was added every other row between cereal planting stations two weeks after the cereal (giving a cowpea density of 33 500 plants ha^{-1}). The substitutive pattern designed by researchers was a substitutive pattern where one out of three rows of the cereal was replaced by cowpea, leading to a pattern of two rows of the cereal and one row of cowpea (giving a density of 45 000 and 22 000 plants ha^{-1} for maize and cowpea respectively). In the substitutive pattern, both the cereal and cowpea were sown the same day. The intercropping trials consisted of four intercropping plots for the cowpea variety and pattern combinations, and three additional plots for the sole cereal (maize or sorghum), the sole cowpea fodder variety and the sole cowpea grain variety.

Participating farmers managed the trials with the help of technicians to ensure that operations were conducted in a timely manner. Each farmer hosted one single, non-replicated trial with the four treatments, each trial forming a replicate. Further details of treatments are given in Table 3. In 2012, only the maize/cowpea intercropping trials were conducted.

2.3. Surveys and measurements

A number of factors were recorded at the plot or farm level to help understand the reasons for differences in crop yields. The factors recorded were (i) soil type as defined by farmers (three levels: gravelly soil; sandy soil; black soil); (ii) previous crop in the field

Table 1
Characteristics of the three farmer-defined soil types for different previous crops, derived from topsoil (0–15 cm) samples from the on-farm trials in 2012, 2013 and 2014 (SOC: soil organic carbon; N: total nitrogen; P: available phosphorus, K: exchangeable potassium, Mg: exchangeable magnesium, Ca: exchangeable calcium, SE = standarderror of the mean). Carbon, nutrient and clay + siltcontent were expressed per total weight (fine earth and gravel).

Farmer-defined soil type	Previous crop	*n*	pH		SOC (g/kg)		N (g/kg)		P (mg/kg)		Ca (cmol(+)/kg)		Mg (cmol(+)/kg)		K (cmol(+)/kg)		Clay + silt(g/kg)		Gravel (g/kg)	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Gravelly soils	Cotton/maize	26	5.3	0.49	3.4	0.27	0.28	0.019	4.7	0.85	0.86	0.128	0.33	0.038	0.16	0.017	162	16.2	432	37.7
	Sorghum/millet	28	4.9	0.25	3.1	0.28	0.25	0.018	3.4	0.30	0.96	0.126	0.32	0.027	0.12	0.013	156	7.8	416	44.4
	Legume	6	5.1	0.32	2.6	0.22	0.20	0.023	2.8	0.38	0.76	0.166	0.35	0.029	0.11	0.008	175	23.5	323	61.8
Sandy soils	Cotton/maize	65	5.0	0.38	2.8	0.11	0.24	0.008	5.7	0.22	1.43	0.112	0.47	0.034	0.23	0.010	192	10.7	45	5.1
	Sorghum/millet	131	5.0	0.24	2.7	0.11	0.23	0.007	4.3	0.17	1.43	0.072	0.54	0.023	0.20	0.006	177	5.8	58	4.4
	Legume	21	5.1	0.42	2.4	0.17	0.21	0.015	5.3	0.41	1.13	0.165	0.48	0.058	0.19	0.011	168	13.7	46	17.7
Black soils	Cotton/maize	60	5.2	0.54	3.8	0.18	0.30	0.013	5.5	0.30	1.41	0.119	0.54	0.031	0.22	0.010	255	9.7	62	7.7
	Sorghum/millet	77	5.3	0.52	3.2	0.16	0.26	0.012	4.5	0.19	1.19	0.094	0.49	0.030	0.21	0.008	243	10.9	68	11.8
	Legume	13	5.2	0.60	4.0	0.40	0.33	0.034	5.4	0.31	1.38	0.204	0.62	0.090	0.29	0.049	288	32.7	40	7.7
F-test probabilities																				
	Soil type		**0.0023**		**0.0000**		**0.0000**		**0.0044**		**0.0003**		**0.0000**		**0.0000**		**0.0000**		**0.0000**	
	Previous crop		0.9660		**0.0306**		**0.018**		**0.0000**		0.521		0.626		**0.0477**		0.1690		0.4570	
	Soil type x previous crop		0.1540		0.1331		**0.0295**		0.5854		0.4552		0.2230		**0.0082**		0.4430		0.6700	

Significant effects ($P < 0.05$) are highlighted in bold.

Table 2
Chemical and physical characteristics of three soil profile pits in each farmer-defined soil type in the Koutiala region.

Pit No	Farmer-defined soil type	Soil classification (FAO)	Horizon	Depth (cm)	Abundance of roots[a]	Sand (%)	Clay (%)	Gravel (%)	Organic matter[b] (%)	Plant available water (mm)[c]
1	Gravelly soil	Lixisol	A	0–10	Many	66	14	52	1.53	5.5
			B1	10–30	Common	43	38	50	0.86	15.2
			B2	30–50	Common	41	39	64	0.80	12.1
2	Sandy soil	Lixisol	A	0–25	Many	57	12	2	0.81	26.1
			B1	25–50	Common	46	33	2	0.38	28.4
			B2	50–100	Few	36	44	7	0.27	59.5
			B3	100–150	None	36	43	25	0.17	52.5
3	Black soil	Lixisol	A	0–20	Many	67	8	3	0.52	16.8
			B1	20–50	Common	38	39	6	0.42	35.8
			B2	50–100	Few	36	42	1	0.22	61.9
			B3	100–160	Few	35	42	0	0.14	75.2

[a] Number of roots per square decimetre (FAO, 2006): None: 0; Very few: 1–20 (<2 mm) and 1–2 (>2 mm); Few: 20–50 (<2 mm) and 2–5 (>2 mm); Common: 50–200 (<2 mm) and 5–20 (>2 mm); Many: >200 (<2 mm) and >20 (>2 mm).
[b] In the fine earth fraction.
[c] Estimated using pedo-transfer functions (Saxton and Rawls, 2006); applies to the bulk soil (fine earth and gravels).

where the trial was implemented (three levels: cotton or maize; millet or sorghum; groundnut or cowpea further referred to as legume); and (iii) cropping season (three years: 2012, 2013 and 2014).

In each village, one farmer collected daily rainfall data with a manual rain gauge. We geo-referenced each trial and recorded the soil type as defined by the farmer. Farmers also described the field history based on the previous crops and the amount of mineral and organic fertilizer applied in the three years prior to the trial.

In May of 2012, 2013 and 2014, soil was sampled in each trial (a composite sample bulked from 9 cores at 0–15 cm depth following a W in the trial) before the start of the rainy season and before plots were established with different treatments. Samples were weighed, air-dried, ground and passed through a 2 mm sieve. Gravel was separated and weighed and fine earth was analysed for organic C, total N, extractable P, K, Ca and Mg and pH. Organic C and total N were determined with the Walkley-Black and Kjeldhal procedures respectively; total N, K Ca and Mg were determined from H_2SO_4 extracts; P was determined from $NaHCO_3$ extracts according to the Olsen method. Proportions of clay, silt and sand were determined through sedimentation. Carbon and nutrient content and% clay, silt and sand were expressed per total weight (fine earth and gravel).

Timing of the different operations (weeding, harvest) was recorded by field agents. At crop maturity, farmers and researchers jointly harvested the central area of the plot discarding two border rows. Mature sorghum and maize plants were harvested following the local practice of cutting the panicles and cobs. Legume pods were harvested when mature. Stover of all crops was weighed at the plot and a stover sub-sample was taken and weighed. Sorghum panicles, maize cobs and legume pods were dried on a clean floor at the homestead. Sorghum panicle and maize cobs were threshed and hand-winnowed and legume pods were shelled by hand. Grains were weighed and grain sub-samples were taken and weighed. All sub-samples (grain and stover) were oven-dried at the ICRISAT Research Station in Samanko, and re-weighed to determine dry weights. All grain and stover yields were expressed in t DM ha^{-1}.

After the 2014 harvest, a profile pit was dug in each major local soil unit within farmers' fields (one on a gravelly soil, one on a sandy soil and one on a black soil). Morphological characteristics were described using the FAO guidelines (FAO, 2006) and soil samples of each horizon were weighed, air-dried, ground and passed through a 2 mm sieve. The fine earth and gravels were weighed and fine earth was analysed for organic C, sand, silt and clay content. Plant available water in each horizon was estimated using pedo-transfer functions (Saxton and Rawls, 2006).

2.4. Statistical analysis

The two experimental units of our design were (i) the plot within a trial and (ii) the trial (blocking factor). Treatments were plot attributes, while covariates such as soil type, previous crop, season and soil characteristics were trial attributes. Linear mixed effects models (Coe, 2002; Parsad et al., 2009) were used to explain variability in sole crop yields and partial Land Equivalent Ratio (pLER) of intercrops (Willey, 1979). pLERs were calculated as follows:

$$\text{pLER} = \frac{I}{S} \quad (1)$$

where I is the intercrop yield, S is the sole crop yield. We considered fodder and grain yield for cowpea and grain yield for maize.

A trial was a given experimental unit on a particular soil type, with a particular previous crop, for a particular farm during a particular cropping season. Each trial was thus randomly chosen from a wider population of possible experimental units on the same soil type, and following the same previous crop. Therefore, the factor 'trial' was treated as a random effect in the models below (Allan and Rowlands, 2001). The attributes of the experimental units were fixed effects (Allan and Rowlands, 2001) and included (i) the experimental treatments, i.e., fertilization, pattern, variety or inoculation and (ii) covariates to explain the variability, i.e., soil type, cropping season, previous crop in the field where the trial was implemented and topsoil characteristics (i.e. pH, C, N, P, Mg, Ca, K and clay + silt).

Mixed linear models were constructed as follows:

(Model1) $Y_{il} = \alpha F_i + \varepsilon NT_l + R$

(Model2) $Y_{jl} = \beta V_j + \varepsilon NT_l + R$

(Model3) $Y_{ijl} = \alpha F_i + \beta V_j + \varepsilon NT_l + R$

(Model4) $Y_{ijl} = \alpha F_i + \beta V_j + \delta FV_{ij} + \varepsilon NT_l + R$

(Model5) $Y_{ijkl} = \alpha F_i + \beta V_j + \gamma C_k + \varepsilon NT_l + R$

(Model6) $Y_{ijkl} = \alpha F_i + \beta V_j + \gamma C_k + \delta FC_{ik} + \varepsilon NT_l + R$

(Model7) $Y_{ijkl} = \alpha F_i + \beta V_j + \gamma C_k + \delta VC_{jk} + \varepsilon NT_l + R$

where Y_{ijkl} represents the square-root transformed yields for sole crops and pLER for intercrops, F_i is the i^{th} level of the fertilization treatment (or pattern in the intercropping trials), V_j is the j^{th} level of the variety treatment (or inoculum in the soyabean trial), C_k is the k^{th} level of the covariate (soil type, previous crop, season and continuous topsoil characteristics for which levels are irrelevant and k can be ignored), $FV_{ij,}$ FC_{ik} and VC_{jk} are the interactions between F_i and V_j, F_i and C_k, and V_j an C_k respectively, NT_l the l^{th} trial and R is the residual, and α, β, γ, δ, ε represent fixed and random effects coefficients.

Visual inspection of plots of residuals did not reveal heteroscedasticity or deviations from normality. P-values to test the significance of effects were obtained by likelihood ratio tests of the full model with the effect tested against the model without the effect. Concretely this was done for treatments effects by testing model 3 against model 1 or 2, for covariates effect by testing Model 5 against Model 3, for interaction effects between treatments by testing Model 4 against Model 3 and for interaction effects of treatments with covariates by testing model 6 or 7 against Model 5. Trials that suffered crop damage by animals (roaming cattle, rabbits) were excluded from the analysis (2, 4, 16, 6, and 2 trials for maize, sorghum, soyabean, cowpea and maize/cowpea respectively). The analysis was done using R (R Development Core Team, 2005; http://www.R-project.org, last accessed 13/07/2014) and the linear mixed-effect model was developed and tested with the R package *lme4* (http://cran.r-project.org/web/packages/lme4/index.html, last accessed 13/07/2015). We performed the likelihood ratio test using the *anova* function.

The coefficients of determination (R^2) of final models (containing all significant treatments and covariates) were calculated as the squared Pearson correlation between predicted and observed values. Predicted values were calculated using the estimated fixed effects coefficients for treatments and covariates.

3. Results

3.1. Season and soil characteristics

The seasons started earlier and received more total rainfall in 2012 and 2014 compared with 2013 (Fig. 1). 2013 was a "bad" season with an average of 723 mm across all villages, i.e. a value below the first quartile of rainfall in Koutiala for the period 1980–2010 (data not shown). On the contrary, 2012 and 2014 were "good" seasons with average annual rainfall of 1023 and 883 mm respectively, i.e., values above the third quartile and above the median rainfall in Koutiala for the period 1980–2010, respectively.

Gravel content and texture differed among the farmer-defined soil types. Gravelly soils contained more gravel than black and sandy soils, while black soils had higher silt + clay content compared with the other soils (Table 1). Gravelly and sandy soils had a loamy sand texture, while the texture of black soil was sandy loam. Soil organic carbon (SOC) and nutrient content (N, P, K, Ca, Mg) also differed among the soil types (Table 1). Black soils had larger SOC and nutrient content than the other soil types. Cotton and maize received more manure and mineral fertilizer than other crops, regardless of the soil type (Table S1). SOC and nutrient (N, P and K) content was larger after cotton and maize compared with after sorghum and millet (Table 1). SOC and nutrient (N, P, Ca, K) content was smaller after legumes compared with after cotton and maize on gravelly and sandy soils, but larger on black soils (Table 1).

Roots were observed up to 160, 100 and 50 cm in the soil pits in black soil, sandy soil and gravelly soil respectively (Table 2). We could not sample deeper than 50 cm in the gravelly soil pit due to the presence of concretions. The estimated cumulative plant available water (in the zone where roots were observed) was greater in black soils (189 mm) compared with sandy soils (166 mm) and gravelly soils (33 mm) (Table 2).

3.2. Effect of treatments on grain and fodder yields

We observed a huge variability of yield in the control plots: maize yield in the control plot varied from 0.20 to 5.24 t ha^{-1}, sorghum yield from 0 to 3.53 t ha^{-1} and soyabean yield from 0 to 2.48 t ha^{-1} (Fig. 2a–c). Maize grain pLER ranged from 0.32 to 1.97 (Fig. 3a). We also found a large variability in response to the treatments (Figs. 2 and 3).

There were no significant differences in grain yield between the hybrid varieties and the local varieties of maize and sorghum (Fig. 2a and b and Table 4). Inoculation did not result in an increase in soyabean grain yield (Fig. 2c and Table 4). The fodder variety of cowpea yielded no grain (Fig. 2d). Improved groundnut yielded significantly more grain compared with the local variety ($P < 0.001$) (Table 4). Use of fertilizer significantly increased maize, sorghum, soyabean and cowpea grain yield ($P < 0.01$) (Fig. 2a–d and Table 4). The fodder variety of cowpea yielded significantly ($P < 0.0001$) more fodder compared with the grain variety (Table 4). There were no significant interactions (i.e., fertilizer × variety or fertilizer x inoculation) for any of the sole crops.

For the maize/cowpea intercropping, the cowpea fodder variety resulted in a significantly smaller ($P < 0.001$) pLER of maize grain and a significantly greater ($P < 0.001$) pLER of cowpea fodder compared with the cowpea grain variety (Fig. 3a and c and Table 4). This was true for both the additive and the substitutive pattern. The substitutive pattern significantly increased ($P < 0.01$) the pLER of cowpea fodder while significantly ($P < 0.01$) decreasing the pLER of maize grain when compared with the additive pattern (Fig. 3a and c and Table 4) for both the grain and the fodder variety of cowpea. No significant effect of the intercropping pattern on pLER of cowpea grain was found (Fig. 3b and Table 4). As in the sole crop, the fodder variety yielded no grain in the intercrop. For the sorghum/cowpea intercropping, the pattern had no effect on sorghum and cowpea pLERs. Pattern x variety interaction significantly ($P < 0.05$) affected sorghum pLER (Fig. 3d): the cowpea fodder variety grown in the substitutive pattern resulted in the smaller sorghum pLER.

Table 3
Options tested with farmers for sole crops and intercrops. ap = additive pattern, sp = substitutive pattern.

		Number of trials			Treatment	Variety			Fertilizer		Pattern	Inoculation
Type of trial	Crop	First year (2012)	Second year (2013)	Third year (2014)		Local name	Type	Cultivar name	Mineral fertilizer N;P;K ($kg\,ha^{-1}$)	Manure ($t\,ha^{-1}$)		
Cereals	Maize	0	45	41	Control	Dembanyuma[1]	Local variety	–	80;7;12[2]	0	–	–
					Variety	Bondofa	Hybrid	EV8444 SR x SR22[a]	80;7;12[2]	0	–	–
					Fertilizer	Dembanyuma[1]	Local variety	–	80;7;12	9	–	–
					Variety + Fertilizer	Bondofa	Hybrid	EV8444 SR x SR22[a]	80;7;12	9	–	–
	Sorghum	0	23	26	Control	Segetana	Local variety	–	0	0	–	–
					Variety	Pablo	Hybrid	FambeA x Lata[b,e]	0	0	–	–
					Fertilizer	Segetana	Local variety	–	14;15;0	9	–	–
					Variety + Fertilizer	Pablo	Hybrid	FambeA x Lata[b,e]	14;15;0	9	–	–
Legumes	Soyabean	0	39	25	Control	Houla1	Landrace	–	0	0	–	No
					Inoculum	Houla1	Landrace	–	0	0	–	Yes
					Fertilizer	Houla1	Landrace	–	0;20;0	4	–	No
					Fertilizer + Inoculum	Houla1	Landrace	–	0;20;0	4	–	Yes
	Cowpea	0	39	39	Grain variety	Wulibali	Pure line	IT 90 K 372-1-2[e]	0	0	–	–
					Fodder variety	Dounanfana	Pure line	PBL 112[e]	0	0	–	–
					Grain variety + Fertilizer	Wulibali	Pure line	IT 90 K 372-1-2[e]	0;20;0	0	–	–
					Fodder variety + Fertilizer	Dounanfana	Pure line	PBL 112[e]	0;20;0	0	–	–
	Groundnut	0	0	24	Control	Kampiani	Local variety	–	0	0	–	–
					Variety	–	Pure line	ICGV 86124[b]	0	0	–	–
Intercropping	Maize/ cowpea[3]	12	31	19	Grain variety, ap	Wulibali	Pure line	IT 90 K 372-1-2[d]	80;7;12	0	ap	–
					Fodder variety, ap	Dounanfana	Pure line	PBL 112[e]	80;7;12	0	ap	–
					Grain variety, sp	Wulibali	Pure line	IT 90 K 372-1-2[d]	80;7;12	0	sp	–
					Fodder variety, sp	Dounanfana	Pure line	PBL 112[e]	80;7;12	0	sp	–
	Sorghum/ cowpea[3]	0	5	4	Grain variety, ap	Wulibali	Pure line	IT 90 K 372-1-2[d]	0	0	ap	–
					Fodder variety, ap	Dounanfana	Pure line	PBL 112[e]	0	0	ap	–
					Grain variety, sp	Wulibali	Pure line	IT 90 K 372-1-2[d]	0	0	sp	–
					Fodder variety, sp	Dounanfana	Pure line	PBL 112[e]	0	0	sp	–

Institute that released the variety: [a] INERA; [b] ICRISAT; [c] IRAD; [d] IITA; [e] IER.
[1] Farmers use the same name as the improved variety bred by CIMMYT/CRI.
[2] No mineral fertilizer in 2013.
[3] Intercropping trials also contain a sole maize, a sole grain cowpea and a sole fodder cowpea plot. In the intercropping trials, the maize and sorghum varieties are “Dembanyuma” and “Segetana” respectively.

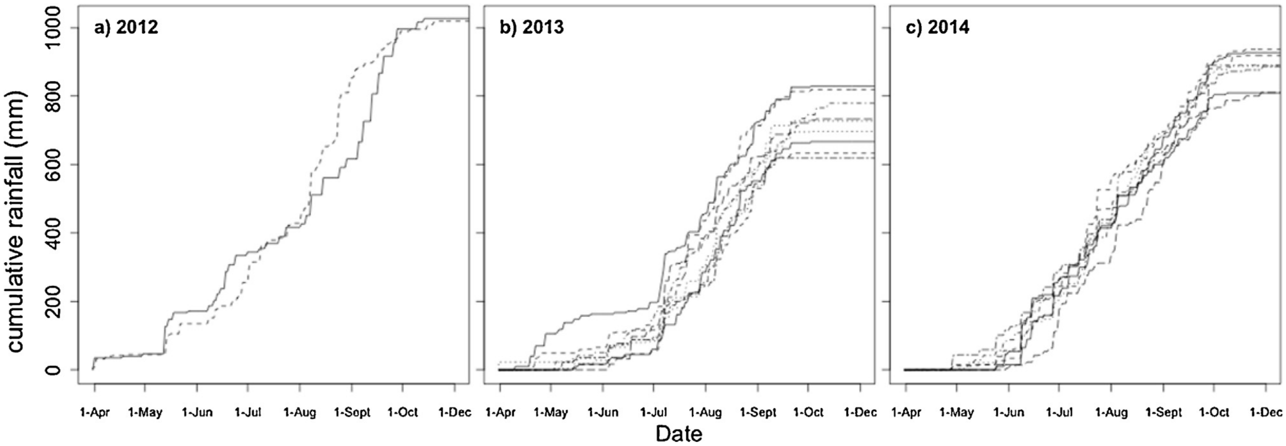

Fig. 1. Cumulative rainfall during the 2012 (a), 2013 (b) and 2014 (c) seasons measured in 2, 9 and 8 villages in the Koutiala district (represented by the different line types) respectively. Total rainfall ranged from 1019 to 1026 mm in 2012, from 619 to 829 mm in 2013, and from 809 to 927 mm in 2014.

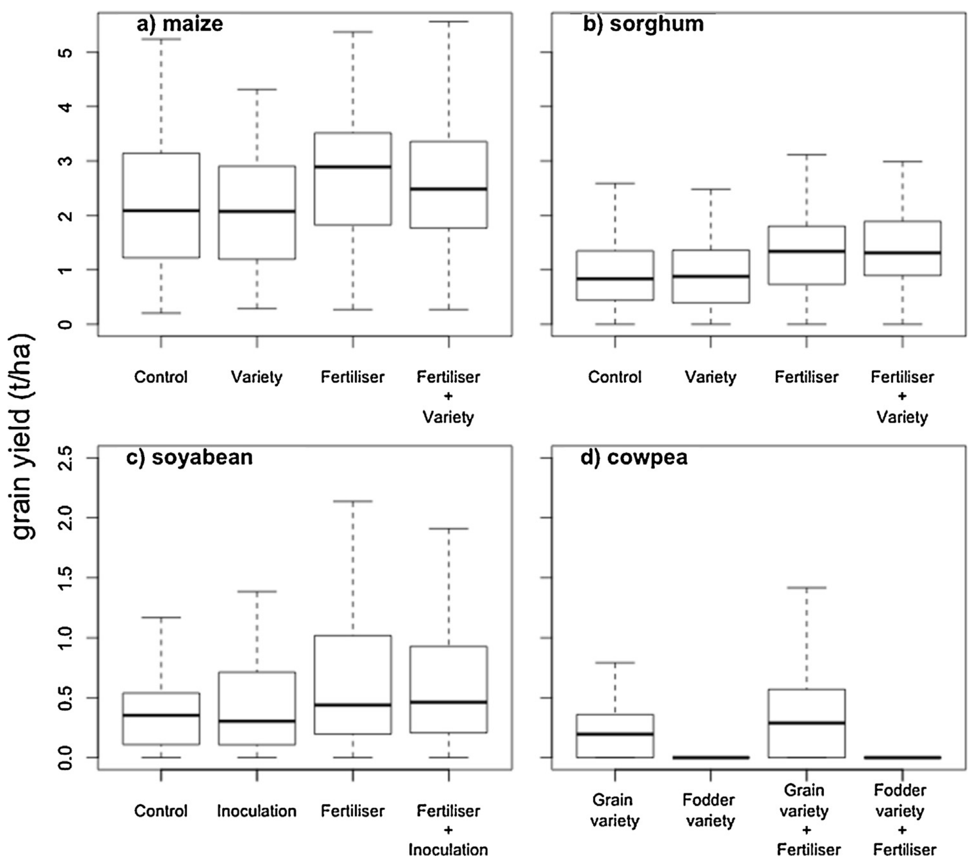

Fig. 2. Grain yield for the four treatments of the maize trial (a), the sorghum trial (b), the soyabean trial (c) and the cowpea trial (d) over the two years of the trials (2013–2014). A detailed description of the treatments is given in Table 3. The horizontal line in the box indicates the median. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box.

3.3. *Effect of topsoil characteristics, soil type, previous crop and season on yields*

Yield of maize, soyabean and cowpea increased significantly ($P < 0.05$) with soil P content. Soyabean and groundnut yield increased significantly ($P < 0.05$) with soil K concentration, and groundnut yield increased significantly ($P < 0.05$) with pH, Ca and Mg. Sorghum grain yield was larger ($P < 0.05$) on soils with more gravel.

There was significant ($P < 0.01$) variation among farmer-defined soil types in grain yield of sorghum, with greater yields on black soils than on sandy and gravelly soils (Fig. 4a). We found no significant relationships between soil type and grain yield of the other crops nor on pLERs in the intercropping trials. The effect of fertilizer on grain yield was not altered by soil type as illustrated by the lack of any interactions between soil type and fertilizer for sorghum (Fig. 4a). The variety x soil type interaction was significant ($P < 0.0001$) for cowpea fodder yield and the effect of variety on fodder yield was stronger on black soils than on sandy and gravelly soils (Fig. 4b).

The previous crop in the field where the trial was planted had a significant effect ($P < 0.05$) on grain yield of maize and

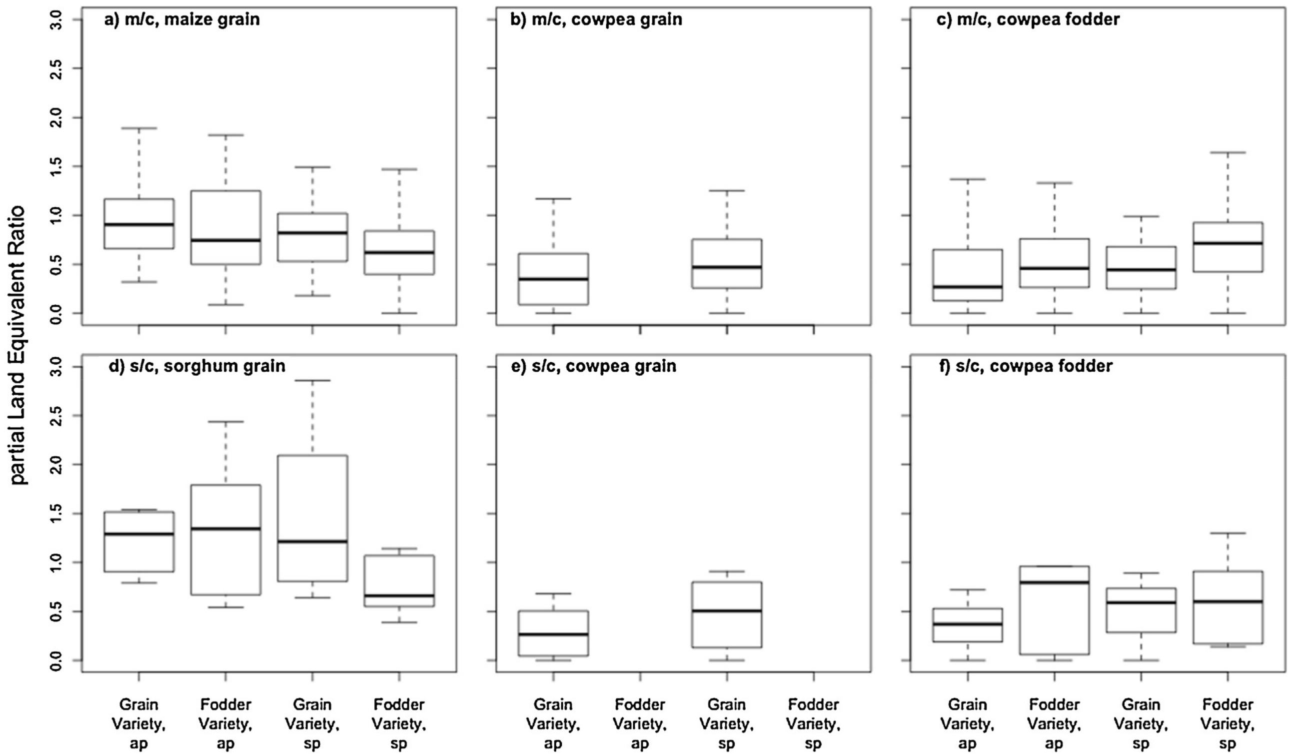

Fig. 3. Partial Land Equivalent Ratio (pLER) for maize grain, cowpea grain and cowpea fodder in the maize/cowpea intercropping trial (m/c) and in the sorghum/cowpea intercropping trial (s/c) over the three years of the trials (2012–2014). ap = additivepattern, sp = substitutivepattern. A detailed description of the treatments is given in Table 3. The horizontal line in the box indicates the median. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box.

Table 4
Average yields (t ha^{-1}) for sole crops and pLER for intercrops for the different treatments (square-root transformed values between brackets).

		Sole crops					
Treatment	Level	Maize grain	Sorghum grain	Soyabean grain	Cowpea grain	Cowpea fodder	Groundnut grain
Fertilizer	No	1.6 (1.26)	0.86 (0.93)	0.33 (0.58)	0.15 (0.37)	1.29 (1.14)	–
	Yes	2.02 (1.42)	1.22 (1.11)	0.55 (0.74)	0.21 (0.46)	1.67 (1.29)	–
	Max LSD	(0.03)	(0.06)	(0.04)	(0.06)	(0.13)	–
	P-value	**0.0000**	**0.0000**	**0.0000**	**0.0039**	**0.0213**	–
Variety/Inoculation[a]	Local/no	1.96 (1.40)	1.02 (1.01)	0.41 (0.64)	–	0.71 (0.84)	0.48 (0.69)
	Improved/yes	1.87 (1.37)	1.05 (1.02)	0.46 (0.68)	–	2.49 (1.59)	0.57 (0.75)
	Max LSD	(0.05)	(0.03)	(0.05)	–	(0.09)	(0.03)
	P-value	0.2010	0.642	0.1762	–	**0.0000**	**0.0001**

		Maize/cowpea			Sorghum/cowpea		
Treatment	Level	pLER maize	pLER cowpea grain	pLER cowpea fodder	pLER sorghum	pLER cowpea grain	pLER cowpea fodder
Pattern	Additive pattern	0.84 (0.92)	0.29 (0.54)	0.42 (0.65)	1.36 (1.16)	0.22 (0.46)	0.42 (0.64)
	Substitutive pattern	0.69 (0.83)	0.49 (0.7)	0.54 (0.74)	1.17 (1.08)	0.44 (0.67)	0.43 (0.66)
	Max LSD	(0.05)	(0.21)	(0.06)	(0.15)	(0.28)	(0.3)
	P-value	**0.0014**	0.1256	**0.0050**	0.1455	0.2909	0.7798
Variety	Cowpea grain variety	0.85 (0.92)	–	0.4 (0.64)	1.41 (1.19)	–	0.31 (0.56)
	Cowpea fodder variety	0.69 (0.83)	–	0.56 (0.75)	1.12 (1.06)	–	0.55 (0.74)
	Max LSD	(0.05)	–	(0.06)	(0.15)	–	(0.3)
	P-value	**0.0002**	–	**0.0002**	**0.0187**	–	0.2455

Significant effects ($P < 0.05$) are shown in bold. Maximum Least Significant Differences (Max LSDs, values between brackets) were calculated based on the transformed yield and pLER data.
[a] Variety for maize, sorghum, cowpea and groundnut, Inoculation for soyabean.

groundnut, on pLER of maize grain and cowpea fodder in the maize/cowpea intercropping trial and on pLER of sorghum grain in the sorghum/cowpea intercropping trial. We found no effect of previous crop on cowpea grain and fodder yield. Maize and groundnut grain yields in the control were larger when the previous crop was cotton or maize compared with sorghum and millet as previous crop (Fig. 5a and b). There was no significant interaction between fertilizer and previous crop for maize and between variety and previous crop for groundnut (Fig. 5a and b). When the previous crop was cotton or maize, maize grain pLER was larger and cowpea fodder pLER was smaller, while it was the opposite when sorghum or millet was the previous crop (Fig. 5c).

Maize and cowpea grain yields and also cowpea fodder yields differed significantly ($P < 0.01$) between the two years of experi-

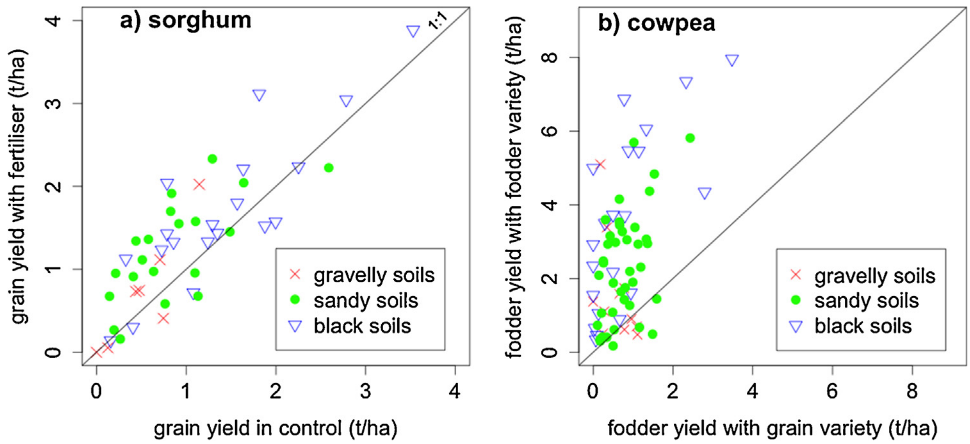

Fig. 4. Treatment (fertilizer or variety) effect for different soil types in the sorghum (a) and cowpea (b) trials over the two years of the trials (2013–2014). A detailed description of the treatments is given in Table 3.

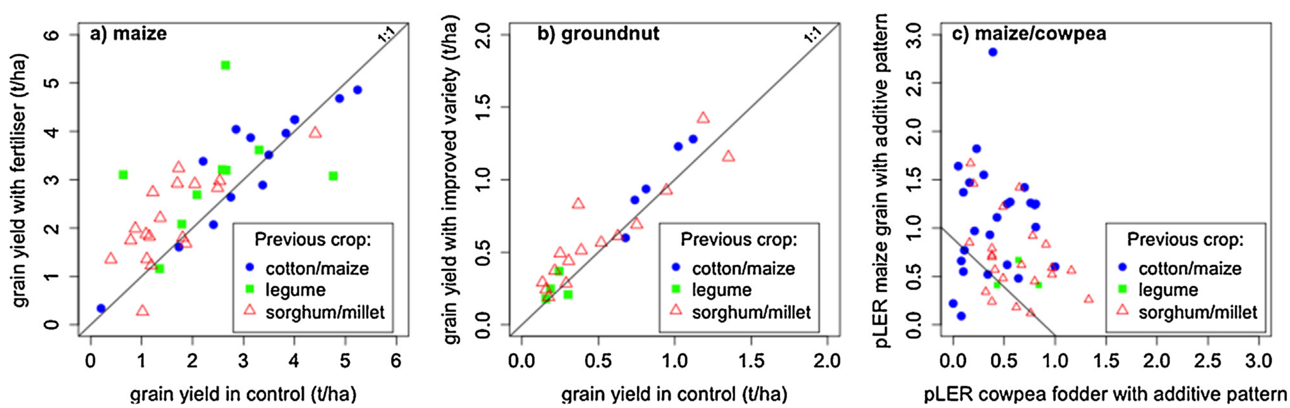

Fig. 5. Fertilizer and variety effect for different previous crops in the maize (a) and groundnut (b) trials over 2013–2014; maize and cowpea pLER for different previous crop in the maize/cowpea intercropping (c) trials over the three years of the trials (2012–2014). A detailed description of the treatments is given in Table 3. The black line in c) indicates an overall LER of one.

mentation. The average grain yield of local maize with mineral fertilizer and manure was smaller in the relatively dry 2013 season (1.86 t ha^{-1}) than in the wetter 2014 season (2.75 t ha^{-1}). By contrast, mean cowpea grain yield in the control plot was larger in 2013 (0.34 t ha^{-1}) than in 2014 (0.13 t ha^{-1}). Sorghum and soyabean grain yields and maize and cowpea pLER did not differ significantly between seasons. The fertilizer × season interaction was significant ($P < 0.001$) for cowpea fodder yield, with a stronger effect of fertilizer in 2014 (Fig. 6).

When averaged per significant covariate, (i) control yields varied by a factor two to four depending on conditions of previous crop,

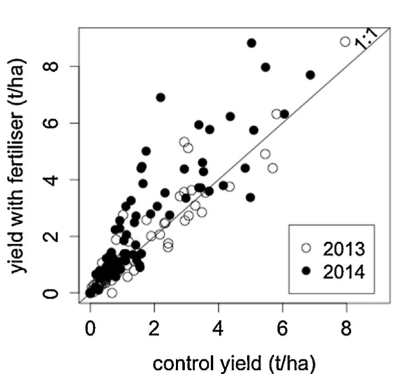

Fig. 6. Effect of P fertilizer on cowpea (grain and fodder variety) fodder yield for the two years of the trials (2013, 2014).

soil type and/or season (Table 5), (ii) the tested options resulted in a yield increase ranging from 34 to 413% depending on the crop and the covariate (Table 5), and (iii) maize/cowpea intercropping LER was always above one and high maize grain pLER was associated with low cowpea fodder pLER (Fig. 7).

In the final statistical model which contained all significant treatments and covariates, soil type and/or previous crop explained between 9 and 44% of yield variability. Taking into account covariate information helps to define niches with greater probability of an increase in yield. For example, the cowpea fodder variety resulted in at least a 3.7 relative increase in fodder yield compared with the cowpea grain variety for half of the farmers on black soils and for only 30% of farmers on other soil types (Fig. 8a). After cotton and maize, a maize grain pLER of at least one was achieved by half of the farmers and by only 22% of farmers after other crops (Fig. 8b). A soyabean yield of at least 0.6 t ha^{-1} was achieved by half of the farmers on black soils after cotton or maize and by only 13% of farmers with other soil type or previous crop conditions (Fig. 8c). 37% of the farmers cultivating soyabean on black soils after cotton or maize produced at least 1 t ha^{-1}, whereas only 2% reached a similar yield in other conditions (Fig. 8c).

4. Discussion

4.1. Variability in control yields and responses to treatments

We found a wide variability in control yields and responses to treatments for all crops, which is a common feature of on-farm tri-

Table 5
Sole crop control yields and relative increase in yield due to fertilizer or variety/inoculation as affected by soil type or previous crop. Control yields and relative increase in yield due to treatment were averaged per level of covariate when there was a significant interaction between treatment and covariate or averaged across levels of the covariate when there was no significant interaction (see Table 4 and Table S2).

			Average control yield ($t\,ha^{-1}$)		Average increase in yield due to fertilizer		Average increase in yield due to variety/inoculation[a]	
Crop	Covariate that significantly affected yield	Levels of the covariate	Wetter years	Drier years	Wetter years	Drier years	Wetter years	Drier years
Maize	Previous crop	Cotton/maize	3.15	–	40%	Not tested	No significant effect	
		Sorghum/millet	1.6	–				
		Legume	2.42	–				
Sorghum	Soil type	Gravelly soil	0.52		56%		No significant effect	
		Sandy soil	0.85					
		Black soil	1.39					
Soyabean	None	–	0.41		126%		No significant effect	
Cowpea grain	None	–	0.34	0.13	49%		No yield with fodder variety	
Cowpea fodder	Soil type	Gravelly soil	0.55	0.66	60%	34%	185%	
		Sandy soil	0.8	0.75			243%	
		Black soil	1.08	0.88			413%	
Groundnut	Previous crop	Cotton/maize	0.87	–	Not tested		28%	Not tested
		Sorghum/millet	0.51	–				
		Legume	0.22	–				

[a] Variety for cereals, cowpea and groundnut, Inoculation for soyabean.

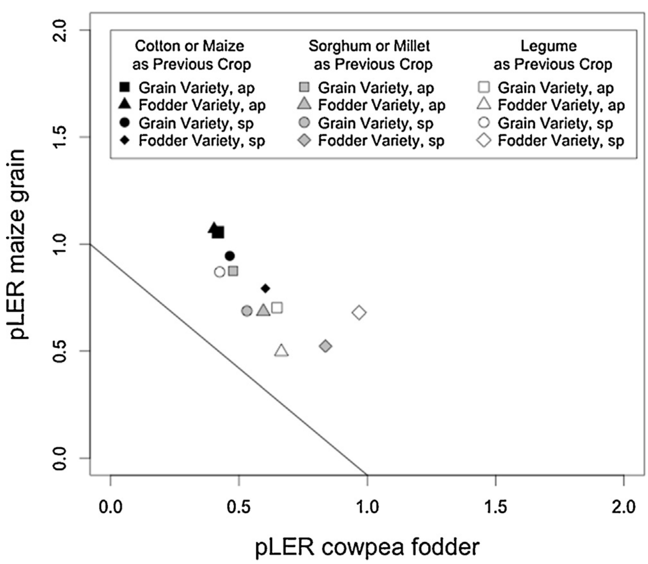

Fig. 7. Average Partial Land Equivalent Ratio (pLER) of maize grain and cowpea fodder for different intercropping patterns (ap, sp), cowpea varieties (grain or fodder) and previous crops. ap = additivepattern, sp = substitutivepattern. The black line indicates an overall LER of one.

als in the African smallholder context. For example, yields of maize ranged from 0.1 to 3.0 $t\,ha^{-1}$ in central Zimbabwe (Zingore et al., 2007) and yields of sorghum from 0.11 to 3.92 $t\,ha^{-1}$ in northern Zimbabwe (Baudron et al., 2012). With the location of our trials being left to the choice of the farmer, the resulting variability in soil types and management history created a patchwork of soil fertility status prior to trial implementation. Soil nutrients (e.g., P and K) and one other edaphic characteristic, i.e., gravel content, explained variability in yield for some crops. Soil nutrient content, texture and gravel content varied among soil type and previous crop, which were covariates determining the yield and yield response of several crops. By providing quantitative on-farm evidence of the effect of soil type and previous crop on crop yield in southern Mali, our study confirms trends that were observed on research stations (Ripoche et al., 2015) and farmers' estimates (Blanchard, 2010; Djouara et al., 2005; Dufumier and Bainville, 2006). Sorghum yields were decreased threefold on gravelly soils compared with black soils (Table 5). For soyabean, the effect of soil type was weaker and not significant, but grain yield followed a similar trend, with on gravelly soils half of those on black soils. Gravelly soils held two to three fold less water compared with sandy and black soils respectively (Table 2). It is possible that soil moisture depletion was accelerated in gravelly soils, creating stronger water stress during grain filling. Decreasing water availability alongside smaller yield of rainfed crops due to soil type and increasing gravel content was also reported in humid sub-tropical India (Grewal et al., 1984). By contrast, maize and groundnut grain yield were not affected by soil type. With shorter cycles and earlier sowing (as per farmer practice) compared with sorghum and soyabean, it is possible that these two crops escaped the water stress during grain filling on gravelly soils (in the 2014 trials, maize reached maturity on average 25 days before sorghum and groundnut 24 days before soyabean).

We found smaller SOC and nutrient content after legume crops on gravelly and sandy soils (Table 1). This indicates that farmers usually grow legume crops at the end of the cotton/maize rotation and/or in fields without cotton and maize and with little past investment in manure and mineral fertilizer. Similarly, Ebanyat et al. (2010) found that farmers target legumes (pigeon pea) to low fertility fields. We found a better soil fertility status (N, P, K) at the start of the season in fields previously grown with cotton or maize, compared with fields previously grown with sorghum or millet (Table 1). Cotton and maize are the crops that most often receive fertilizer and show positive N, P, and K partial budgets in southern Mali (Kanté, 2001; Ramisch, 1999). Other studies also reported better availability of mineral N and P for the subsequent crop in rotation with cotton and/or with the use of fertilizer and manure on the previous crop (Bado et al., 2012; Ripoche et al., 2015). The better SOC status we found at the start of the season in fields previously grown with cotton or maize was related to the previous manure inputs by farmers. Depending on soil type, the SOC difference between fields established after cotton or maize and fields established after sorghum or millet ranged from 0.1 to 0.6 $g\,kg^{-1}$. It is unlikely that a single manure application led to such a change in SOC. Farmers divide their cropped land into fields where only cotton and maize are grown (application of mineral fertilizer and/or manure every year), fields where cotton and maize are in rotation with sorghum and millet (more

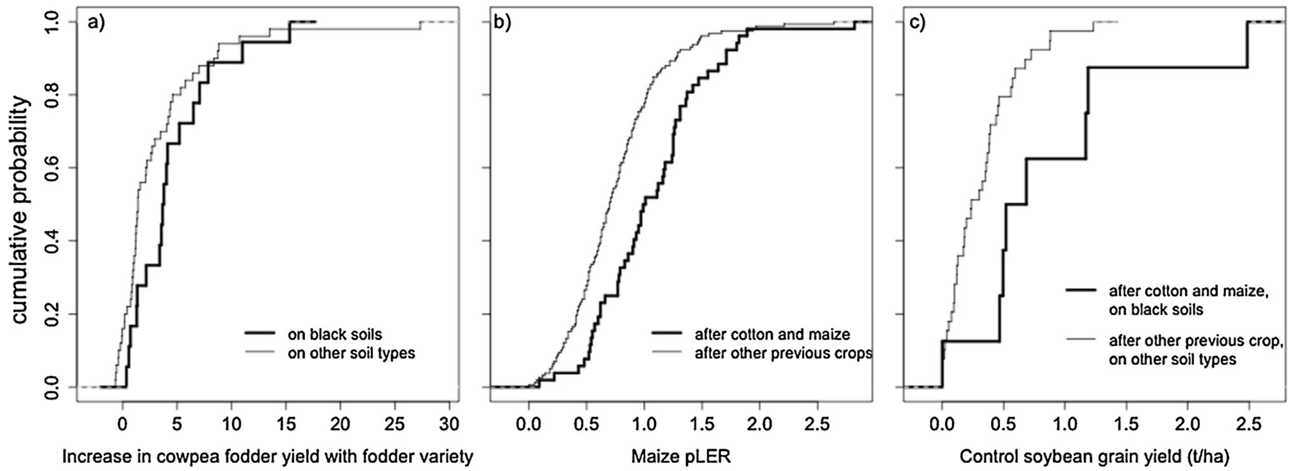

Fig. 8. Cumulative probability of observed (a) relative increase in cowpea fodder yield with the fodder variety compared with the grain variety (b) maize pLER and (c) control soyabean grain yield for different conditions of soil type and/or previous crop.

sporadic application of mineral fertilizer and manure) and fields where only sorghum/millet are grown (no application of mineral fertilizer and/or manure) (Blanchard, 2010). Therefore, fields previously established with cotton or maize likely had a greater past investment in manure and/or mineral fertilizer, compared to fields previously established with sorghum or millet. Small SOC improvements (as we observed due to previous crops) are unlikely to create a better moisture availability (De Ridder and van Keulen, 1990; Diels et al., 2001), but are related to better availability of additional plant nutrients (De Ridder and van Keulen, 1990). This "previous crop effect", i.e., nutrient carry-over from past fertilizer use and additional nutrient availability related to soil organic matter, explained that control grain yields for maize and groundnut were 1.3 and 1.7 times greater when cotton or maize was the previous crop compared with sorghum or millet as previous crops (Table 5). For sorghum and soyabean, the effect of previous crop was weaker and not significant, but grain yields followed a similar trend, with soyabean grain yield being 1.8 times greater after cotton or maize than after sorghum or millet. The previous crop had no observable effect on cowpea grain yield as pest pressure was overriding.

Cutting across soil type and previous crop, the type of rainy season also explained variability in the yield in the control plots. Yield of the local maize variety with fertilizer was 48% smaller in the drier 2013 season compared with the 2014 wetter season while sorghum yield was not affected by season. Sorghum has a stronger and deeper rooting system than maize (Frere, 1984), which suffered more from water deficit (Muchow, 1989; Traore et al., 2014). Cowpea grain yields followed an opposite trend compared with maize yields and were halved in the wetter season (Table 5) when the high relative humidity favoured infestation of pod borers (Oghiakhe et al., 1991).

Though soil type, previous crop and season explained part of the variability in control yield, these factors seldom explained the variability in response to the various intensification options. As an exception, the fodder yield increase obtained with the cowpea fodder variety (compared with the grain variety) was two times greater on black soils than on gravelly soils (Table 5). The cowpea fodder variety had a longer duration (110 days) compared with the grain variety (70 days), and was more susceptible to water stress on gravelly soils.

4.2. A disappointingly small response to the tested options

The hybrid maize variety "Bondofa" did not out-yield the farmers' local maize, regardless of the fertilizer treatment and the season (Table 4), although the two varieties had similar maturity (95–110 days). The "Bondofa" hybrid is intensively promoted in Mali and Burkina Faso on the basis that it can double farmers' yields yet we found no scientific evidence to support such claims. By contrast, in semi-arid Zimbabwe, maize hybrids yielded 18% more than the best open-pollinated varieties (Pixley and Bänziger, 2001), independent of the use of mineral fertilizer (Chiduza et al., 1994). In the Guinea savannah of Ghana, a newly released maize hybrid yielded better than the local variety in farmers' fields (Buah et al., 2013). The tall-statured sorghum hybrid "Pablo" chosen for testing by farmers, failed to increase yield compared with the farmers' local variety, regardless of the fertilizer treatment and the season (Table 4). Conversely, on-farm comparison of short-statured hybrids with another local variety called "Tieble" (CSM 335), using 40 kg N ha^{-1} and 20 kg P ha^{-1}, in three environments including the Koutiala district, indicated a 30% yield advantage of the hybrid (Rattunde et al., 2013). More intensive on-farm comparison of the wide array of available sorghum (i.e., short-statured and tall-statured) and maize hybrids is thus needed.

We observed no effect of inoculation on grain yield of the soyabean "Houla1" variety used in our trials. It is possible that this landrace from northern Cameroon collected and popularized by the parastatal cotton company (Leroy et al., 2011) nodulated with rhizobia present in the soil. Pule-Meulenberg et al. (2011) reported that soyabean nodulated well with indigenous rhizobia in the Guinea savannah of Ghana. Competition between introduced rhizobial strain and the native rhizobia population can also explain this lack of response to inoculation (Sanginga and Okogun, 2003).

The breeder's technical manual for the cowpea fodder variety indicates a potential grain yield of 1.5 t ha^{-1} (Dugje et al., 2009). Neem oil was ineffective in control of flower thrips and pod borers. As a result the cowpea fodder variety yielded no grain at all in our trials. The high sowing density (0.4 m within row) is known to favour pests as it eases host colonization and provides a better shelter against natural enemies and adverse weather conditions (Asiwe et al., 2005; Karungi et al., 2000). Less dense planting (>1 m within row) would reduce pest density (Asiwe et al., 2005) but at the same time would decrease fodder production.

4.3. Promising tailored options

A detailed characterization of 37 farms participating in the trials showed that only 14 and 16% of them grew cowpea in 2011 and 2012 and no farmers grew soyabean. Cowpea and soyabean present farmers with an opportunity to diversify their sources of income and diet. Without inputs soyabean yielded best after cotton and maize on black soils with 0.88 t ha^{-1}. Soyabean grain is the most expensive legume grain after groundnut in the Koutiala market. Women use it as a replacement for the seeds of neré (*Parkia biglobosa*) to prepare the local condiment "Sumbala". Similarly, without any fertilizer input (and thus at low cost for farmers), the cowpea grain variety produced at least some grain early in the season (0.34 t ha^{-1} in the drier year and 0.13 t ha^{-1} in the wetter year), together with an average of 777 kg ha^{-1} of fodder. With addition of 20 kg of P ha^{-1} in the wetter year and on black soils, the cowpea fodder variety yielded 6.7 t ha^{-1} fodder, i.e., twice the stover production of maize with fertilizer under the same conditions. As cowpea fodder is a high quality feed (Singh et al., 2003) this option provides an opportunity to alleviate fodder constraints in the dry season. These findings highlight the opportunity for future research on farm scale trade-offs between food and fodder production.

Average total LER in maize/cowpea intercropping was always greater than one, regardless of pattern, cowpea variety and previous crop (Fig. 7), indicating no detrimental competition between maize and cowpea. Cowpea creates a "live mulch" that lowers surface soil temperature and evaporation, thus improving water conservation compared with sole cropping (Lima Filho, 2000). Rusinamhodzi et al. (2012) also reported LER values ranging from 1 to 2.4 in additive and substitutive maize/cowpea intercropping in central Mozambique. However, this overall promising picture masked a trade-off for maize grain production (Fig. 7). In most treatment by previous crop combinations, the intercropping arrangement produced cowpea fodder but less maize yield compared with the sole crop (maize pLER <1). However, the additive pattern after cotton or maize proved to be a specific niche with great relevance for farmers as there was no penalty for maize grain (maize pLER >1) (Fig. 7) and a bonus production of cowpea fodder (0.29 and 1.38 t ha^{-1} on average for cowpea grain variety and cowpea fodder variety respectively). In this niche, nutrient reserves carried-over from the previous fertilization and the cowpea live mulch allowed a maize yield greater than the sole crop yield. Naudin et al. (2010) also reported a bonus of fodder biomass without penalty for the cereal in cereal/legume intercropping while other studies reported a penalty for maize grain (Pitan and Odebiyi, 2001; Rusinamhodzi et al., 2012). Though for the sole crops, maize grain and cowpea fodder yields were affected by the type of rainy season and the soil type respectively, season and soil type did not affect the performance of the maize/cowpea intercropping options, showing the low inter-annual risk for farmers and the suitability of the option on all soil types.

The R^2 values for relationships between crop yield and soil type and/or previous crop ranged from 9 to 44% depending on the crop. Bielders and Gérard (2015) found that management and environmental factors explained 20% of the variation in millet yield under similar conditions. In a widespread testing of soyabean varieties in Northern Nigeria, management and environmental factors explained 16–61% of the variation in soyabean yield (Ronner et al., 2015). In on-farm trial work, a large proportion of the variability tipically remains unexplained which could be due to factors that were not monitored. In our case, these could include incidence of *Striga* on cereals, other pests and diseases especially on cowpea grain and local drought stress. Yet we were able to link local knowledge (i.e., soil type as defined by farmers) and an easy-to-assess indicator of soil fertility (i.e., previous crop in the field) to specific niches with greater probability of an increase in yield (Fig. 8). Such contextual variables (soil type, previous crop) ensure that research results are relevant, appropriate and available to farmers and local development organizations who can follow up with a larger number of farmers (Hellin et al., 2008). Similarly, Snapp et al. (2002) showed that linking local knowledge and biological processes through farmer/researcher partnerships helped developing technologies with a wide relevance. The analyses of the trials led to a basket of options (as defined by Giller et al., 2011) that are promising in the farmer context and narrower than the initial wide range of options tested. For example the hybrid varieties and inoculation fell from the basket (Table 5), whereas intercropping options with both cowpea varieties and both patterns form part of the basket as all have LER > 1 (Fig. 7). Farmers may choose from this basket and further tailor the options to their own situations. With these easy to use niche indicators and the basket of options, we provide credible, legitimate and salient "boundary tools" (Clark et al., 2011), which will help communicating with a variety of stakeholders, thus linking research with local decision making.

5. Conclusion

Testing of options for sustainable intensification within the wide array of conditions found in farmers' fields provided important insights in variability of crop yields and yield responses. We tested different options on cereals (maize, sorghum), legumes (cowpea, groundnut, soyabean) and two intercropping combinations during contrasting seasons and in the wide variety of soil types and previous crops prevailing in the Koutiala district. Our study suggests that little improvement is to be expected from the recommended cereal hybrids we tested, even with combined application of mineral fertilizer and manure in amounts currently available to farmers. Rhizobial inoculation also failed to improve soyabean yields. Soyabean and cowpea, currently not commonly grown, offer opportunities to diversify income and diets and to produce high quality fodder. Our analysis showed that targeting either the best position in the rotation, i.e., after cotton or maize to benefit from nutrient carry over, or the best soil type, i.e., black soils with the greatest water holding capacity, can drastically improve grain and legume fodder yields in farmers' conditions, with and without further inputs. Maize/cowpea intercropping after cotton or maize can provide a bonus of fodder for crop-livestock farmers on all soil types, without penalty on the cereal grain production, regardless of the type of rainy season. Based on a large number of trials on different crops, we developed boundary tools consisting of (i) easy-to-use indicators related to soil type and previous crop for farmers and extension workers to predict the effect of intensification options, and (ii) a basket of options, which are promising in the farmer context. Based on similarities in farming systems, soil types, climate and market context these boundary tools can be scaled out within similar environments in West Africa. Our current work is focused on exploring these promising options at farm scale.

Acknowledgements

We thank the McKnight Foundation for funding through the project "Pathways to Agro-ecological Intensification of Sorghum and Millet Cropping Systems of Southern Mali" and also the CGIAR Research Program on Dryland Systems. We thank Joost van Heerwaarden for advice on statistical analysis and Alice Lame for her valuable contribution to data analysis. We are grateful to farmers of M'Peresso, Nampossela, Nitabougouro, N'Goukan, Finkoloni, Kani, Karangasso, Koumbri and Try for their availability and willingness to participate in the on-farm trials. We thank the Association Malienne d'Eveil au Développement Durable (AMEDD), Ousmane Dembele, Michel Sagara, Bakary Dao, Moumine Toure, Abdoulaye Dembele, Soungalo Bware and several trainees who assisted in data collection.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2015.12.015.

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