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Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya

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ABSTRACT

Agricultural intensification of farming systems in sub-Saharan Africa is a prerequisite to alleviate rural poverty and improve livelihoods. Legumes have shown great potential to enhance system productivity. On-farm experiments were conducted in different agro-ecological zones (AEZ) in Western Kenya to assess the agronomic and economic benefits of promising legumes. In each zone, trials were established in fields of high, medium and low fertility to assess the effect of soil fertility heterogeneity on legume productivity and subsequent maize yield. Common bean, soybean, groundnut, lima bean, lablab, velvet bean, crotalaria, and jackbean were grown in the short rains season, followed by maize in the long rains season. Alongside, continuous maize treatments fertilised at different rates were established. AEZs and soil fertility gradients within these zones greatly affected crop productivity, returns to land and labour of rotations, as well as the relative performance of rotations. Poorer soil fertility and AEZs with lower rainfall gave smaller legume and maize yields and consequently, smaller returns to land and labour. The cultivation of legumes increased maize yields in the subsequent long rains season compared with continuous maize receiving fertiliser at a similar rate, while the increase of maize after green manure legumes was stronger than that after grain legumes. Maize yield responded strongly to increasing amounts of N applied as legume residues with diminishing returns to legume-N application rates above 100 kg N ha^{-1}. In the low potential zones, factors other than improved N availability likely also stimulated maize yield. Rotations with grain legumes generally provided better returns than those with green manures. Intercropping bean with maize in the long rains season provided an additional bean yield that did not come at the expense of maize yield and improved returns to land and labour, but more so in the high potential zones. The results demonstrate the strong impact of biophysical diversity on the productivity of the legumes and suggest the need for careful targeting of legume technologies to the different biophysical conditions.

1. Introduction

Poor soil fertility is a key constraint to the productivity of smallholder farmers in sub-Saharan Africa. In the East African highlands, high population growth and a shortage of employment opportunities outside the agricultural sector has led to small landholdings and a high pressure on the available land through continuous cultivation with little use of mineral fertilizers. This has likely led to resource-based poverty traps for certain groups of farmers in western Kenya (Stephens et al., 2012). Western Kenya with its high population densities and intense mixed crop-livestock smallholder systems is typical of the East African highlands' smallholder sector. Nitrogen (N) and phosphorus (P) are the major nutrients limiting crop production in western Kenya and elsewhere in the region (e.g. Bünemann et al., 2004; Jama and Kiwia, 2009; Kihara et al., 2010). Increased N and P inputs are therefore necessary for improved productivity of the farms. However, the use of mineral fertilizers supplying these nutrients is constrained by a number of factors, such as unreliable returns, inappropriate production packages, unreliable markets for produce (Hassan et al., 1998), and lack of access to capital (Hoekstra and Corbett, 1995). Legumes can fix N_2 and can meet part of the N demand of smallholder cropping systems (Giller, 2001). The inclusion of appropriate legumes in cereal-based cropping systems provides additional non-N benefits to cereal crops. Legumes are often considered a key component

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of integrated soil fertility management (ISFM) strategies for smallholders in sub-Saharan Africa (Vanlauwe et al., 2010) and provide opportunities for sustainable intensification of farming systems (Pretty et al., 2011).

Legume technology options with different characteristics and possible niches are available to farmers (Schulz et al., 2001). Green manure and fodder legumes, such as *Mucuna pruriens*, *Crotalaria* spp. or *Stylosanthes* spp., have primarily been selected for their ability to contribute large quantities of residual biomass and nitrogen (N) to the soil and/or to livestock as feed. The adoption of green manure and forage legume technologies by farmers in sub-Saharan Africa has remained limited, despite evidence of their beneficial effects on soil fertility and cereal yields (Sumberg, 2002; Bünemann et al., 2004; Nyambati et al., 2006; Njarui and Mureithi, 2010). There is a general reluctance among farmers to invest land, labour and seed in a technology that does not provide a quick economic return on investments. Leguminous trees and shrubs, such as *Calliandra calothyrsus* and *Gliricidia sepium*, have been promoted to provide livestock fodder while simultaneously contributing to soil fertility. Trees and shrubs fulfil different roles than green manures. For instance, because of their deep root system, trees and shrubs can produce well into the dry season (Paterson et al., 1998). However, the labour associated with cutting and application of prunings to the soil impedes the adoption of these technologies (e.g. Rao and Mathuva, 2000). Short-duration grain legumes are bred to produce high yields of edible grains rather than a high N_2 fixation or leafy biomass production. Therefore, their benefits in terms of soil fertility are generally less than those of green manure or forage legumes (e.g. Franke et al., 2008a). Nevertheless, roots, rhizodeposits and aboveground residues left after harvest contribute to soil organic C and N reserves (e.g. Laberge et al., 2009). More indeterminate, leafy grain legumes combine the production of leafy material, which can be used as animal feed, with the production of edible grains. Their harvest index is generally lower than that of grain legume varieties and they require more time to mature. Grain legumes have the advantage above green manure and forage legumes of giving a rapid return to investments in the form of edible grains (Schulz et al., 2001). The use of legumes residues as livestock feed, as is often the case in sub-Saharan Africa, impacts the residual effects of legumes. It often leads to reduced inputs from legumes to the soil, but the actual carry-over rates of carbon and nutrients strongly depend on residue and manure management (Lekasi et al., 2003; Rufino et al., 2006). Grain legumes such as common bean and groundnut are commonly cultivated by farmers in western Kenya, where crop production is often integrated with livestock husbandry.

Incorporation of legumes into smallholder systems is impeded by the high degree of biophysical and socio-economic heterogeneity inherent to them (Franke et al., 2014). Also smallholders in Western Kenya operate under diverse agro-ecological conditions with strong rainfall and altitude gradients over relatively small distances. Moreover, soil fertility gradients between farms and fields within farms are common and farmers need to adapt their resource management strategies to deal with this variability (Tittonell et al., 2005a,b; Vanlauwe et al., 2006). The socio-economic and biophysical diversity provide specific socio-economic and ecological opportunities (or socio-ecological niches) for the incorporation of legumes in the systems (Ojiem et al., 2006; Giller et al., 2011). The choice of appropriate legumes that result in sustainable improvements in crop productivity in such systems is complex since the species must fit into the available socio-ecological niches. In doing so, the species and varieties must not only match farmers' preferences and production objectives, but should also be well adapted to the prevailing biophysical constraints.

This paper addresses the biophysical and economic dimensions of the socio-ecological niche by investigating the agronomic and economic performance of various legume–maize rotations. The nitrogen economy of the different legumes in the experiment, including N_2 fixation rates and partial field N balances, has been published already (Ojiem et al., 2007). The objectives of the current paper are: (1) to evaluate the effect of grain and green manure legume species on the yield of the subsequent maize crop; (2) to assess the influence of agro-ecological zones (AEZs) and soil fertility variations on the productivity of grain and green manure legume–maize and continuous maize rotations; and (3) to determine the economic benefits of these rotations.

2. Materials and methods

The experiment was conducted at three agro-ecologically distinct sites in Western Kenya: Museno (high rainfall, AEZ1), situated at 00° 14′ N and 34° 44′ E at an altitude of 1570 m above sea level (masl). Mean 30-year annual rainfall (Jaetzold and Schmidt, 1983) and temperature are 2000 mm and 18 °C; Majengo (medium rainfall, AEZ2), situated at 00° 00′ N and 34° 41′, 1385 masl. Mean annual rainfall and temperature are 1600 mm and 19 °C; and Ndori (low rainfall, AEZ3), situated at 00° 02′ S and 34° 20′ E, 1170 masl. Mean annual rainfall and temperature are 1200 mm and 22 °C. All three sites have bimodal rainfall, with the long rains season extending from March to August, and the short rains season from September to January. In each AEZ, fields were classified by farmers into three fertility classes (high, medium and low), based on farmers' knowledge of local soil fertility gradients. The differences were verified by soil chemical analysis. Three experimental fields were identified in each soil fertility class per AEZ.

The experiment was installed and managed by researchers from Kenya Agricultural Research Institute. It was laid out in a randomised complete block design (RCBD), replicated twice in each field. Plots were 4.5 m wide and 5.0 m long. Rotation treatments consisted of different grain and green manures legumes rotated with maize, and continuous maize receiving different rates of mineral fertiliser (Table 1). Legumes were planted at the beginning of the short rains season in September 2003 (SR2003 season) with most plantings done in the second half of September. The grain legumes assessed were common bean (*Phaseolus vulgaris* L.) variety KK8, soybean (*Glycine max* (L.) Merr.) variety TGx 1448-2E (long duration, promiscuously nodulating), groundnut (*Arachis hypogaea* L.) variety CG7 (long duration), Lima bean (*Phaseolus lunatus* L.) – local landrace, and lablab (*Lablab purpureus* (L.) Sweet), variety Rongai; the green manure legumes were velvet bean (*Mucuna pruriens* (L.) Walp), crotalaria (*Crotalaria ochroleuca* G. Don), and jackbean (*Canavalia ensiformis* (L.) DC.). Legume seeds were not inoculated with rhizobium prior to planting, as inoculants were not available. P was applied as triple superphosphate (TSP) at planting to all plots at a rate of 30 kg P ha^{-1}.

Three continuous maize plots were planted in the SR2003 season receiving different rates of mineral fertilizer: (i) no fertilizer, (ii) 50 kg P ha^{-1} but no N, and (iii) 50 kg N ha^{-1} and 50 kg P ha^{-1}. P was applied as TSP at planting, while urea-N was top-dressed in two split applications: at 26 days after planting (DAP) at first weeding, and at second weeding 56 DAP. The trial plots in AEZ1 and AEZ2 were planted with hybrid maize (H614 D), while the trial plots in AEZ3 were planted with an open-pollinated maize variety resistant to the herbicide Imazapyr (variety WS 303). Coating the seeds of this maize variety with this systemic herbicide controls *Striga* spp. (Kanampiu et al., 2003). AEZ3 had a high incidence of *Striga hermonthica* (DEL.) Benth. Maize was spaced at 0.75 m inter-row and 0.30 m intra-row with one plant per stand. Insecticides were applied to maize during the growing season to control stalk borer.

The green manure plots were cut between flowering and early pod filling in January 2004 and the total biomass was weighed in the field. A fresh biomass sample was taken for each plot by harvesting three randomly chosen 0.5 m by 0.5 m quadrats. The

Table 1
Overview of treatments in the experiment. Treatments were similar across AEZs.

Abbreviation	Crop	Short rains 2003 season		Long rains 2004 season	
		Spacing (m)	Fertiliser rate (N/P in kg ha^{-1})	Crop	Fertiliser rate (N/P in kg ha^{-1})
Grain legumes					
1. Sb-Mz	Soybean	0.5 × 0.05	0/30	Maize	0/50
2. Sb-Mz/Bean	Soybean	0.5 × 0.05	0/30	Maize[a]	0/50
3. Gnut-Mz	Groundnut	0.5 × 0.10	0/30	Maize	0/50
4. Bean-Mz	Bean	0.5 × 0.10	0/30	Maize	0/50
5. Lima-Mz	Lima bean	0.25 × 0.15	0/30	Maize	0/50
6. Lablab-Mz	Lablab	0.60 × 0.30	0/30	Maize	0/50
Green manures					
7. Crot-Mz	Crotalaria	0.3 × drill	0/30	Maize	0/50
8. Velvet-Mz	Velvet bean	0.3 × drill	0/30	Maize	0/50
9. Jack-Mz	Jackbean	0.6 × 0.30	0/30	Maize	0/50
Cont. maize					
10. Mz-Mz (0/0)	Maize	0.75 × 0.30	0/0	Maize	0/0
11. Mz-Mz (0/50)	Maize	0.75 × 0.30	0/50	Maize	0/50
12. Mz-Mz (50/50)	Maize	0.75 × 0.30	50/50	Maize	50/50

[a] Intercropped with bean.

sample was dried in an oven at 60–65 °C to constant weight to determine dry matter concentration. All remaining biomass was incorporated into the soil to a depth of about 15 cm. The maize and grain legume species matured at different times and were harvested between January and February 2004, leaving out the outer rows at each side as well as the first and last plant in the row. Grain was threshed and total fresh grain and residues were weighed. A sample of fresh legume and maize grain and of legume residues was taken to determine dry matter concentration as described above. The grain legume and maize residues were returned to the respective plots and incorporated into the soil to a depth of about 15 cm.

At the beginning of the long rains season in mid March 2004 (LR2004 season), all plots were manually tilled and planted with maize, using the same varieties and plant spacing as in the continuous maize treatments in the first season (described above). Planting took place 35–45 days after incorporation of grain legume or green manure residues. The continuous maize treatments received the same fertilizer rates as the season before. Maize following legumes was fertilised at planting with 50 kg P ha^{-1} using TSP, but no mineral N fertilizer was applied. Plots were weeded twice at all sites and insecticides were applied to control stalk borers. Maize grain yield was determined at the end of the season in August 2004 by harvesting the plot leaving out the two outer rows and the first and last plant of each row. A sample of fresh grain was used to determine dry matter concentration as described above.

Soils of all experimental fields were sampled prior to sowing in the SR2003 season. In each field (having two replicates), nine samples were taken at 0–20 cm depth and combined to a composite sample for laboratory analysis. Samples were air dried, crushed and sieved through a 2-mm sieve, and subsequently analysed for pH (H_2O), texture, extractable P (Olsen), total N, total organic C, and exchangeable calcium, magnesium and potassium, following procedures as described by Anderson and Ingram (1993). Soils of plots containing legumes in the SR2003 season were sampled once more 45 days after legume residue incorporation, around maize planting. The samples were taken at 0–15 cm depth at three points in each plot and bulked, and subsequently analysed for total mineral N. Soil was weighed and wet extracted with KCl, followed by filtration of the extract and colorimetric analysis. Nitrate and ammonium concentrations were converted to kg ha^{-1} based on bulk density of the soil. Soils from AEZ3 and plots with crotalaria or jackbean were removed from the analyses due to coding errors. Rainfall data were obtained from the nearest weather recording stations, situated not more than 5 km from the experimental fields in each AEZ.

Labour work rates were observed on the trial fields during planting, weeding, legume biomass cutting and incorporation into the soil, grain harvesting, threshing and shelling. A village-based field assistant recorded work rates through observations in the trial and conducted interviews with trial and neighbouring farmers to cross check the observations with farmers' estimates of labour requirements in their own fields. Seed and fertilizer prices were obtained from the nearest local input dealers; output prices (maize and legume grain) by conducting price surveys at local markets (Table 2). Since prices fluctuate, these were monitored monthly for one year. Costs of transporting produce to the nearest local market were included. All monetary values were converted to US$ at the 2004 exchange rate of US$ 1.0 = KSh 78.0. Labour was valued at US$ 1.30 per day and a day was assumed to contain eight working hours. Net present values (NPV) were calculated, using output prices averaged over twelve months, for evaluating land, labour and cash productivity, following Rao and Mathuva (2000) and Degrande (2001). Returns to land and labour were calculated for the different rotation treatments, and discounted at 15% (for 6 months), half the local interest rate of 30% per annum. Returns to land were calculated as the difference between discounted gross returns and discounted costs (including labour), while returns to labour were calculated as the difference between discounted gross returns and discounted non-labour costs divided by the number of labour days. Sensitivity analyses were conducted to assess the effects of seasonal fluctuations in output prices on returns to land and labour using maximum and minimum output prices recorded in a 12-month period (Table 2).

Differences in soil parameters were tested with a linear mixed model (REML) with AEZ and soil fertility as explanatory factors. As soil fertility gradients differed between AEZs (e.g. soil characteristics of fields classified as fertile in AEZ1 and AEZ2 were different from those in AEZ3), soil fertility was nested within AEZ. Differences in maize yields in the LR2004 season were also tested using REML with AEZ, soil fertility status and rotation as fixed factors, and 'field' (having two replications) as random factor. Again, soil fertility was nested within AEZ. The model was run once again using 'rotation type' (continuous maize, grain legume–maize, or green manure legume–maize) instead of 'rotation' as a factor in the fixed model. With a similar statistical model, differences in returns to land and labour for the two-year rotations were assessed, as well as differences in grain legume yield in the SR2003 season. To quantify the relation between N applied through legume residues and maize grain yield in the subsequent season, negative exponential

Table 2
Farm-gate prices used in the economic analyses (USD kg^{-1}). Between brackets minimum and maximum grain prices over a 12-month period are given.

	Seed input all AEZs	Grain output (min–max price)		
		AEZ1	AEZ2	AEZ3
Maize	1.6	0.24 (0.16–0.29)	0.23 (0.21–0.30)	0.24 (0.19–0.28)
Bean	3.0	0.41 (0.22–0.51)	0.60 (0.45–0.87)	0.35 (0.26–0.45)
Soybean	1.6	0.66 (0.45–0.83)	1.02 (0.83–1.15)	0.65 (0.51–0.78)
Groundnut	2.7	0.75 (0.58–0.83)	1.05 (0.78–1.17)	0.92 (0.78–1.22)
Lima	1.3	0.41 (0.22–0.51)	0.60 (0.45–0.87)	0.35 (0.26–0.45)
Lablab	1.3	0.41 (0.22–0.51)	0.60 (0.45–0.87)	0.35 (0.26–0.45)
	Fertiliser input			
TSP	0.57			
CAN	0.65			

curves were fitted in regression analyses. Statistical analyses were done with the software package Genstat vs. 15.1.0. Grain yields are presented at 12% moisture; legume residue yield at 0% moisture. Data on the nitrogen economy of the legumes in this trial were published by Ojiem et al. (2007). The only overlap with the current paper is the soil characteristics at the start of the experiment, legume grain yields in the SR2003 season, and the summary of N content of the legume biomass.

3. Results

Chemical analyses of soils sampled at the start of the trial confirmed farmers' fertility classification (Table 3). Significant differences between fertility classes were observed in pH, total C, available P, exchangeable Ca and Mg and soil texture. Soil C values were highest in AEZ1, while available P levels were highest in AEZ2. AEZ3 had lower values of total C and especially available P, but higher values of exchangeable Ca and Mg compared to AEZ1 and AEZ2. Soil exchangeable cations were generally high and unlikely to limit crop growth in most fields. Differences between soil fertility classes were relatively large within AEZ2 and small within AEZ3. The difference in precipitation between AEZs in the SR2003 and LR2004 seasons was atypical (Fig. 1), as AEZ2 received about 30% more rain than AEZ1. AEZ1 received only slightly more rain than AEZ3 in the 2003SR season, but the rains were more equally distributed in AEZ1. Crops in the SR2003 season in AEZ1 suffered from a brief drought spell directly after planting in the middle of September.

Legume grain yields differed significantly among AEZs (average SED = 0.04), fertility status nested in AEZ (SED = 0.06) and rotations (SED = 0.05) ($P < 0.001$) with a significant interaction between grain legume and AEZ ($P < 0.001$) (SED = 0.09), and between grain legume and soil fertility nested in AEZ ($P = 0.030$) (SED = 0.15) (Table 4). AEZ3 had considerably lower legume yields than AEZ1 and AEZ2, while AEZ2 had slightly higher yields than AEZ1, reflecting differences in amount and distribution of rainfall. Yields at low fertility sites were significantly lower than at medium and high soil fertility sites. Soybean yield for instance varied from 0.30 t ha^{-1} (AEZ3, low soil fertility) to 1.40 t ha^{-1} (AEZ2, high soil fertility). There were large differences in grain yield between legume species within AEZs and soil fertility status, but these differences were not consistent across sites and soil fertility status. Lablab for instance gave yields comparable with those of other grain legumes in AEZ1 and AEZ2, but performed poorly relative to other legumes in AEZ3 where the crop did not mature properly before the rains stopped. Groundnut yields were small in AEZ1 with poor establishment due to drought, while it was among the highest yielding grain legumes in AEZ2. Under low fertility conditions and in AEZ3, the differences in yield between legumes (in absolute terms) were less pronounced (i.e. all yields were small) than under high fertility and high rainfall conditions (AEZ1 and AEZ2).

N and P fertiliser improved grain yield in continuous maize rotations in both seasons (Table 4). Maize yield was greater in the LR2004 season than in the SR2003 season in all AEZs because of better rainfall. Maize grain yields in the LR2004 season (all rotations) were significantly different between AEZs (SED = 0.09), soil fertility status (SED = 0.15) and rotation (SED = 0.18) ($P < 0.001$) with a significant interaction between AEZ and rotation (SED = 0.31; $P < 0.001$) (Table 4). Differences in maize yields in the LR2004 season between AEZs were significant, with the lowest yield in AEZ3 and the best in AEZ2. Fields in the low soil fertility class yielded significantly less maize than fields in medium or high fertility classes. The absolute response of maize to fertiliser applications (compare Treatments 10–12) was less in low rainfall zones. Thus, maize responded more strongly to fertiliser in high potential areas.

Maize yields after green manures were significantly larger (on average 36%) than after grain legumes across AEZs and soil fertility classes (Table 4). The average yield of maize after grain or green manure legumes was considerably larger than that of continuous maize receiving a similar fertilizer rate (0N/50P) across AEZs and fertility classes, though this was not true for all individual legume treatments. Maize after bean even gave a smaller yield than Mz-Mz (0N/50P) in a few instances. Overall, green manures increased maize yield by 112%, grain legumes by 56%, relative to continuous maize (0N/50P). The highest relative increase was observed in AEZ3 where green manures increased maize yields by 149% and grain legumes by 74%. The average yield of maize after green manures was also consistently higher (on average 54% higher) than that of continuous maize receiving both N and P fertilizer (50N/50P). The yield of maize after grain legumes was often comparable with or slightly higher than that of Mz-Mz (50N/50P). Bean intercropped with maize in the LR2004 season provided an additional bean grain yield of 0.32–0.63 t ha^{-1} without any significant effect on maize yield (compare maize yields in 1. Sb-Mz vs. 2. Sb-Mz/Bean).

The amount of N in legume residues incorporated into the soil was strongly affected by AEZ and soil fertility status (Ojiem et al., 2007; summary of the data given in Table 5). As expected, green manures on average provided more legume-N to the soil than grain legumes. Among the grain legumes, lablab provided most legume-N to the soil, often followed by groundnut. Bean turned out to be a poor provider of N in residues in all AEZs. The amounts applied through grain legumes did not necessarily reflect differences in legume grain yield. In some cases, e.g. with groundnut in AEZ1 and lablab in AEZ3, low grain yields were associated with high amounts of residual legume N, because grain production was hampered due to drought and most plant N remained in the residues. Mineral N available at maize sowing following the incorporation of the legume residues (only measured for a selection of legumes in AEZ1 and AEZ2) was highest for velvet bean, intermediate for lablab, groundnut, soybean, and lowest for bean (Table 5). Maize grain yield reflected differences in mineral N values at sowing with maize after velvet bean giving the largest yield and maize after

Table 3
Average soil fertility characteristics of the three soil fertility categories of fields identified by farmers in three AEZs in western Kenya, and results from the statistical analyses of soil data.

AEZ/Fertility category	pH (H_2O)	Total C (g/kg)	Total N (g/kg)	C:N ratio	P (ppm)	Exch. cations ($cmol_+ kg^{-1}$)			Particle size (%)		
						K	Ca	Mg	Clay	Sand	Silt
AEZ1											
High	6.0	16.4	1.7	9.6	8.8	0.40	6.30	1.48	24	35	45
Medium	5.9	16.3	1.6	10.2	4.3	0.35	6.35	1.73	22	43	38
Low	6.2	14.8	1.3	11.4	3.4	0.23	5.43	1.93	21	38	41
AEZ2											
High	5.9	15.0	1.9	7.9	15.4	0.36	6.96	2.10	22	33	48
Medium	5.4	14.6	1.7	8.6	8.0	0.43	5.82	1.65	16	36	46
Low	5.6	12.8	1.4	9.1	3.5	0.17	5.90	1.75	29	36	35
AEZ3											
High	5.8	15.2	1.7	8.9	2.5	0.39	6.40	2.30	37	28	30
Medium	6.2	12.3	1.6	7.7	1.2	0.36	6.45	3.28	35	28	40
Low	5.7	13.2	1.6	8.3	1.2	0.30	6.40	2.55	25	45	30
Significance (AEZ)	***	***	n.s.	**	***	n.s.	**	***	***	***	***
Significance (AEZ × Fertility)	**	**	n.s.	n.s.	***	***	***	***	***	***	***
SED (AEZ × Fertility)	0.17	0.74	0.17	1.27	0.25	0.027	0.182	0.095	1.8	1.6	1.5

n.s., not significant.
** Fpr < 0.01.
*** Fpr < 0.001.

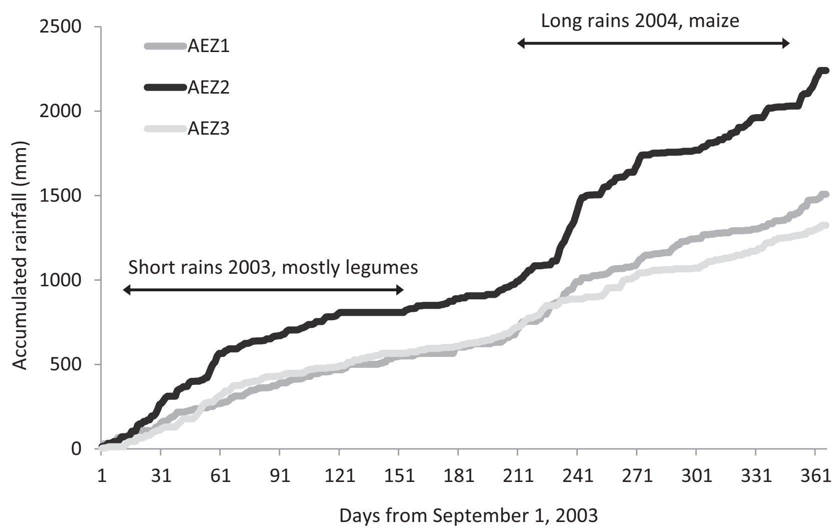

Fig. 1. Rainfall recorded at: (a) Museno (AEZ 1); (b) Majengo (AEZ 2); (c) Ndori (AEZ 3) in western Kenya during the field experiment.

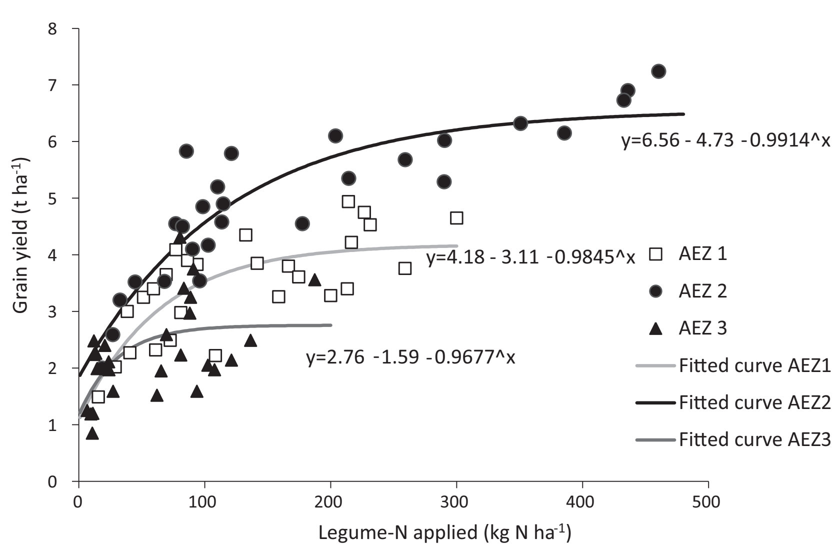

Fig. 2. Relationship between legume-N applied and maize grain yield in three AEZs in western Kenya. R^2 value of the combined regression analysis was 81.4%.

Table 4
Legume and maize grain yields in different treatments for different soil fertility status for different AEZs in western Kenya (t ha^{-1}).

Site/rotation	High fertility		Medium fertility		Low fertility	
	SR2003	LR2004	SR2003	LR2004	SR2003	LR2004
AEZ1						
1. Sb-Mz	1.20	3.66	0.74	3.25	0.68	2.27
2. Sb-Mz/Bean	1.13	3.90/0.63 [a]	0.72	3.40/0.60 [a]	0.61	2.32/0.35 [a]
3. Gnut-Mz	0.71	3.80	0.56	3.85	0.43	3.22
4. Bean-Mz	1.26	3.00	0.83	2.02	0.37	1.49
5. Lima-Mz	0.76	3.83	0.70	2.98	0.53	2.49
6. Lablab-Mz	0.84	4.75	1.10	3.40	0.77	3.27
Mean	**0.98**	**3.82**	**0.77**	**3.15**	**0.57**	**2.51**
7. Crot-Mz	–	4.65	–	4.22	–	3.28
8. Velvet-Mz	–	4.95	–	3.96	–	3.77
9. Jack-Mz	–	4.35	–	4.09	–	3.62
Mean		**4.65**	–	**4.09**	–	**3.55**
10. Mz-Mz (0/0)	1.27	2.15	1.13	1.76	0.89	1.05
11. Mz-Mz (0/50)	1.46	2.77	1.37	2.29	1.01	1.35
12. Mz-Mz (50/50)	1.96	4.11	1.72	3.43	1.36	2.25
AEZ2						
1. Sb-Mz	1.40	4.50	0.94	4.10	0.79	3.53
2. Sb-Mz/Bean	1.22	4.90/0.63 [a]	0.86	4.58/0.38 [a]	0.69	3.54/0.35 [a]
3. Gnut-Mz	1.25	5.17	1.12	5.15	0.80	4.17
4. Bean-Mz	0.94	3.20	0.70	2.59	0.49	3.23
5. Lima-Mz	0.50	4.85	0.53	4.55	0.41	3.52
6. Lablab-Mz	1.40	6.90	0.96	6.02	0.78	4.54
Mean	**1.12**	**4.92**	**0.85**	**4.51**	**0.66**	**3.76**
7. Crot-Mz	–	6.32	–	6.15	–	5.29
8. Velvet-Mz	–	7.24	–	6.73	–	5.68
9. Jack-Mz	–	6.11	–	5.80	–	5.35
Mean		**6.55**		**6.22**		**5.44**
10. Mz-Mz (0/0)	1.91	2.06	1.45	1.90	1.33	1.23
11. Mz-Mz (0/50)	2.04	3.42	1.53	2.81	1.42	2.38
12. Mz-Mz (50/50)	2.49	4.09	1.96	3.60	1.93	3.18
AEZ3						
1. Sb-Mz	0.53	2.49	0.42	2.26	0.34	1.25
2. Sb-Mz/Bean	0.59	1.89/0.39 [a]	0.40	2.24/0.33 [a]	0.30	1.20/0.32 [a]
3. Gnut-Mz	0.34	2.59	0.30	1.95	0.31	1.52
4. Bean-Mz	0.39	1.99	0.29	1.29	0.30	0.85
5. Lima-Mz	0.50	2.11	0.45	1.97	0.33	1.60
6. Lablab-Mz	0.05	3.41	0.05	2.97	0.06	1.79
Mean	**0.40**	**2.50**	**0.33**	**2.10**	**0.27**	**1.37**
7. Crot-Mz	–	3.56	–	2.49	–	1.94
8. Velvet-Mz	–	4.31	–	3.25	–	1.79
9. Jack-Mz	–	3.75	–	2.23	–	2.05
Mean		**3.87**		**2.66**		**1.93**
10. Mz-Mz (0/0)	0.44	1.11	0.30	0.86	0.25	0.49
11. Mz-Mz (0/50)	0.49	1.36	0.49	1.23	0.46	0.78
12. Mz-Mz (50/50)	0.78	1.65	0.78	1.56	0.67	1.45
SED (AEZ × Rotation × Fertility)	0.15	0.31	0.15	0.31	0.15	0.31

[a] Yield of maize/bean.

Table 5
Amount of N applied through legume residues before maize planting and subsequent mineral N available at maize sowing (only given for a selective number of treatments in AEZ1 and 2) in legume–maize rotations, average of soil fertility levels (kg N ha^{-1}).

	AEZ1		AEZ2		AEZ3
	Legume-N applied	Mineral N at sowing	Legume-N applied	Mineral N at sowing	Legume-N applied
1. Sb-Mz	54	110	80	114	11
2. Sb-Mz/Bean	69		108		15
3. Gnut-Mz	139	114	100	116	66
4. Bean-Mz	28	57	26	60	12
5. Lima-Mz	83		74		25
6. Lablab-Mz	200	119	301	114	88
Mean	**95**		**115**		**36**
7. Crot-Mz	239		342		148
8. Velvet-Mz	235	155	384	161	92
9. Jack-Mz	128		180		92
Mean	**201**		**302**		**111**

common bean the smallest among the legume–maize rotations. The relationships between legume-N applied and maize grain yield were well described by a response curve with AEZ as a group factor with diminishing returns at greater N application rates (Fig. 2; $R^2 = 81\%$). A single response curve across AEZs explained 62% of the variation in maize yield, while adding fertility as a group factor to the regression analyses only marginally improved the percentage of variability explained ($R^2 = 69\%$). Regression analyses per AEZ explained 53%, 80% and 26% of the variation in the data from AEZ1, AEZ2 and AEZ3, respectively. Clearly, the response of maize to legume N was stronger and more consistent in the AEZs that received higher rainfall. A relatively poor fit was obtained for the data from AEZ3 where responses to legume N were poor, probably due to a moisture deficit during the growing season overriding effects of N availability on maize growth.

The maize and legume grain yields accumulated over the two seasons showed that rotations with grain or green manures provided more yield than continuous maize receiving P fertiliser only (Fig. 3). In comparison with continuous maize receiving both N and P fertiliser (Mz-Mz 50/50), accumulated yields of legume–maize rotations were generally lower in AEZ1 and comparable in AEZ2 and AEZ3, except for the high fertility site in AEZ3 where green manure legume–maize rotations gave considerable larger yields. Intercropping beans with maize increased accumulated yield, relative to grain legume–maize rotations without intercrop (Fig. 3). The accumulated grain yield of green manure–maize rotations was often comparable with or higher than that of grain legume–maize rotations, despite the fact that green manures themselves did not produce any edible yield.

Labour requirements for land cultivation and weeding were comparable between crops (Table 6). Planting of grain legumes required up to 24 more days of labour ha^{-1} than the planting of green manures or maize, with soybean requiring the most labour due to its dense plant spacing. Biomass cutting and incorporation into the soil represented a major additional labour activity for green manures (43–48 days t^{-1} biomass). Labour demands for harvesting a tonne of produce were relatively high for groundnut and soybean and least for maize. Post-harvest threshing and shelling is a laborious activity for groundnut (46 days t^{-1}).

Returns to land and labour were significantly affected by AEZ (SED = 0.07 and 0.02 for returns to land and labour, respectively), soil fertility nested in AEZ (SED = 0.12/0.04), and crop rotation (SED = 0.14/0.05), with significant interactions between rotation and AEZ (SED = 0.24/0.08), rotation and soil fertility class nested in AEZ (SED = 0.41/0.14) ($P < 0.001$ for all individual terms and interactions) (Table 7). Cropping in AEZ1 and AEZ2 provided significantly higher monetary returns to land and labour than in AEZ3. Furthermore, cropping at high soil fertility sites provided significantly higher returns to land and labour than at sites lower in fertility. Absolute differences in returns between rotations within a site/soil fertility level reduced with decreasing soil fertility and decreasing rainfall.

When comparing the continuous maize treatments without and with fertiliser, it is clear that investments in N and P fertiliser were profitable in all AEZs across soil fertility zones. However, the profitability of these investments was greater in the high rainfall sites AEZ1 and AEZ2 and at high fertility sites. Grain legume–maize rotations generally gave higher returns to land than continuous maize, but this was not significant for all legume maize rotations and some grain legume–maize rotations (e.g. 4. Bean-Mz and 5. Lima-Mz) often gave lower returns than continuous maize with fertiliser (50/50). This is also true for returns to labour, with a main difference that returns from green manure-maize rotations were not very different from continuous-maize rotations in AEZ1 and AEZ2.

Rotations with grain legumes generally gave higher returns to land and labour than with green manures, with the exception of the high fertility site at AEZ3 (Table 7). Returns to land were negative in all green manure–maize rotations in AEZ3 at the low fertility site. The inclusion of bean as an intercrop in maize during the LR2004 season usually resulted in higher returns than the same rotation without the intercrop (2. Sb-Mz/Bean vs. 1. Sb-Mz). Rotations with common bean as a monocrop or Lima bean gave lower returns in most cases than rotations with soybean, groundnut or lablab. The different rotations with green manures did not show any consistent differences in returns to land or labour. Seasonal variation in output prices (Table 2) had an impact on the returns to land and labour (Table 7). Selling at maximum prices often doubled or tripled the returns to land compared to selling at minimum prices. However, these fluctuations did not greatly affect the relative performance of the different rotations or AEZs. For instance, if farmers in AEZ3 would sell produce at maximum prices, their returns to land and labour would still be less than those of farmers in AEZ1 and AEZ2 selling at average prices.

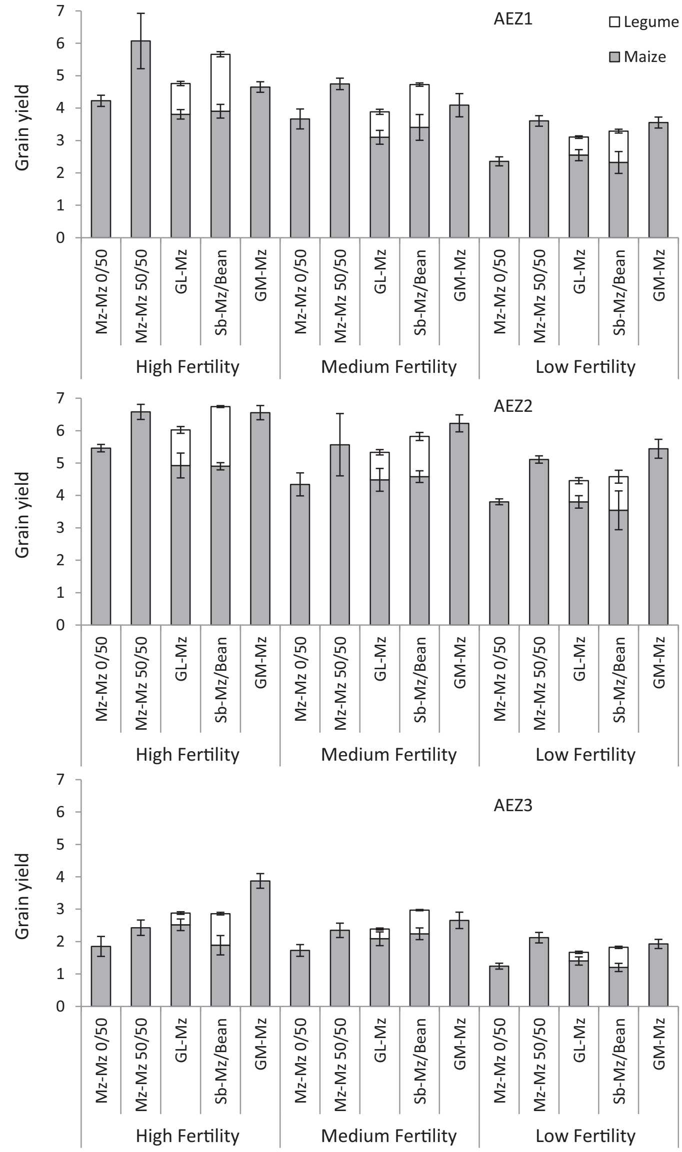

Fig. 3. Accumulated legume and maize grain production ($t\,ha^{-1}$) in selected rotations in the SR2003 and LR2004 season in three AEZs in western Kenya. Green manure (GM)-Mz and grain legume (GL)-Mz represent the average yields in green manure and grain legume legume–maize rotations, excluding the Sb-Mz/Bean rotation. Error bars represent standard errors of means.

Table 6
Estimated labour requirements for different operations in maize and legume production in western Kenya.

Crop	Land cultivation (days ha^{-1})	Planting [a] (days ha^{-1})	Weeding (days ha^{-1})			Biomass cutting and incorporation (days t^{-1})	Harvesting (days t^{-1})	Treshing [c] (days t^{-1})
			First [b]	Second	Third			
Soybean	54	43	43	37	16	–	22	25
Groundnut	50	30	42	36	16	–	26	46
Bean	50	30	42	36	16	–	14	17
Lima	50	40	43	37	16	–	14	25
Lablab	50	24	39	33	15	–	14	17
Crotalaria	54	19	47	43	–	44	–	–
Velvet bean	50	24	39	33	–	48	–	–
Jackbean	50	24	39	40	–	43	–	–
Maize	50	22	37[b]	31	14	–	9	18

[a] Includes labour required to apply TSP.
[b] Includes labour required to apply urea; unfertilised maize required two days less for this activity.
[c] Includes shelling of groundnut.

Table 7
Returns to land (100 US$ ha^{-1}) and labour (US$ day^{-1}) for the different treatments as influenced by soil fertility for different AEZs in western Kenya, based on the average price and the minimum and maximum price recorded in a 12-month period between brackets.

Treatment	High fertility		Medium fertility		Low fertility	
	Returns to land	Returns to labour	Returns to land	Returns to labour	Returns to land	Returns to labour
AEZ1						
1. Sb-Mz	7.8 (5.1–10.6)	2.1 (1.4–2.6)	4.8 (3.1–6.5)	1.7 (1.1–2.1)	2.8 (1.9–3.8)	1.4 (0.9–1.7)
2. Sb-Mz/Bean	9.0 (5.9–12.2)	2.2 (1.5–2.7)	6.6 (4.3–9.0)	2.0 (1.4–2.5)	3.1 (2.1–4.3)	1.4 (0.9–1.7)
3. Gnut-Mz	5.7 (4.6–7.8)	1.8 (1.4–1.9)	5.0 (4.0–6.8)	1.7 (1.4–2.0)	1.5 (1.2–2.1)	1.2 (0.9–1.3)
4. Bean-Mz	4.8 (4.7–5.8)	1.7 (1.0–1.9)	1.8 (1.1–2.5)	1.2 (0.7–1.5)	1.0 (0.5–1.4)	0.7 (0.4–0.9)
5. Lima-Mz	4.7 (2.8–6.4)	1.6 (1.0–2.0)	3.0 (1.8–4.1)	1.4 (0.8–1.7)	1.7 (1.0–2.3)	1.2 (0.7–1.4)
6. Lablab-Mz	6.5 (4.0–9.0)	2.0 (1.2–2.4)	4.8 (2.9–6.6)	1.8 (1.1–2.2)	3.8 (2.3–5.2)	1.6 (1.0–1.9)
Mean	**6.4 (4.5–8.6)**	**1.9 (1.3–2.3)**	**4.3 (2.9–5.9)**	**1.6 (1.1–2.0)**	**2.3 (1.5–3.2)**	**1.2 (0.8–1.5)**
7. Crot-Mz	3.7 (2.5–5.1)	1.5 (1.0–1.8)	3.0 (2.0–4.1)	1.4 (0.9–1.7)	1.5 (1.0–2.0)	1.1 (0.7–1.3)
8. Velvet-Mz	3.8 (2.5–5.2)	1.5 (1.0–1.8)	3.1 (2.1–4.2)	1.4 (0.9–1.7)	1.8 (1.2–2.5)	1.2 (0.8–1.4)
9. Jack-Mz	2.9 (1.9–3.9)	1.3 (0.9–1.6)	2.4 (1.6–3.3)	1.3 (0.9–1.6)	1.6 (1.1–2.2)	1.2 (0.8–1.4)
Mean	**3.5 (2.3–4.7)**	**1.4 (1.0–1.7)**	**2.8 (1.9–3.9)**	**1.4 (0.9–1.6)**	**1.6 (1.1–2.2)**	**1.2 (0.8–1.4)**
10. Mz-Mz (0/0)	2.1 (1.4–2.8)	1.3 (0.8–1.5)	1.9 (1.0–2.7)	1.1 (0.7–1.3)	1.2 (0.6–1.8)	0.8 (0.5–0.9)
11. Mz-Mz (0/50)	3.3 (2.2–4.5)	1.5 (1.0–1.8)	3.0 (1.6–4.5)	1.3 (0.9–1.6)	2.3 (1.2–3.4)	0.9 (0.8–1.1)
12. Mz-Mz (50/50)	5.4 (3.6–7.3)	1.7 (1.1–2.1)	4.5 (2.4–6.8)	1.5 (1.0–1.8)	3.5 (1.8–4.3)	1.1 (1.0–1.4)
AEZ2						
1. Sb-Mz	14.0 (12.1–21.3)	3.0 (2.5–3.6)	9.7 (8.4–14.8)	2.4 (2.1–2.9)	7.6 (6.6–11.5)	2.1 (1.9–2.6)
2. Sb-Mz/Bean	15.6 (13.7–24.1)	3.1 (2.7–3.8)	11.1 (9.6–16.9)	2.5 (2.2–3.1)	8.0 (6.9–12.2)	2.2 (2.9–2.6)
3. Gnut-Mz	14.9 (12.5–22.6)	2.9 (2.5–3.6)	12.8 (10.7–19.5)	2.7 (2.3–3.3)	8.8 (7.3–13.3)	2.4 (2.0–2.9)
4. Bean-Mz	5.4 (4.5–8.2)	1.8 (1.5–2.5)	3.2 (2.7–4.9)	1.5 (1.2–2.1)	1.3 (1.1–2.0)	1.1 (0.9–1.6)
5. Lima-Mz	5.9 (4.9–9.0)	1.8 (1.5–2.5)	5.6 (4.7–8.6)	1.8 (1.5–2.5)	3.5 (2.9–5.3)	1.5 (1.2–2.0)
6. Lablab-Mz	13.6 (11.3–20.6)	2.8 (2.3–3.8)	10.1 (8.4–15.3)	2.4 (2.0–3.3)	6.9 (5.7–10.5)	2.1 (1.7–2.9)
Mean	**11.6 (9.8–17.6)**	**2.6 (2.2–3.3)**	**8.8 (7.4–13.3)**	**2.2 (1.9–2.9)**	**6.0 (5.1–9.2)**	**1.9 (1.6–2.4)**
7. Crot-Mz	6.0 (5.5–9.1)	1.8 (1.6–2.3)	5.7 (5.2–8.7)	1.7 (1.6–2.2)	4.3 (4.0–6.6)	1.6 (1.4–2.0)
8. Velvet-Mz	7.0 (6.4–10.7)	1.9 (1.7–2.4)	6.2 (5.7–9.5)	1.8 (1.6–2.3)	4.6 (4.2–6.9)	1.6 (1.4–2.1)
9. Jack-Mz	5.3 (4.8–8.0)	1.7 (1.5–2.2)	4.8 (4.4–7.3)	1.6 (1.5–2.1)	4.1 (3.7–6.2)	1.5 (1.4–2.0)
Mean	**6.1 (5.6–9.3)**	**1.8 (1.6–2.3)**	**5.6 (5.1–8.5)**	**1.7 (1.6–2.2)**	**4.3 (3.9–6.6)**	**1.6 (1.4–2.0)**
10. Mz-Mz (0/0)	2.5 (2.3–3.7)	1.4 (1.3–1.8)	1.8 (0.9–2.6)	1.2 (1.1–1.5)	1.4 (0.8–2.1)	0.9 (0.8–1.1)
11. Mz-Mz (0/50)	5.1 (4.7–7.8)	1.8 (1.6–2.4)	3.3 (3.0–5.0)	1.5 (1.4–2.0)	2.9 (1.5–4.3)	1.3 (1.2–1.7)
12. Mz-Mz (50/50)	6.0 (5.5–9.1)	1.9 (1.7–2.4)	4.3 (3.9–6.5)	1.6 (1.5–2.1)	4.1 (2.2–5.0)	1.5 (1.4–2.0)
AEZ3						
1. Sb-Mz	2.5 (2.0–3.4)	1.4 (1.1–1.5)	1.6 (1.3–2.2)	1.2 (0.9–1.3)	1.2 (0.6–1.7)	0.7 (0.6–0.8)
2. Sb-Mz/Bean	3.1 (2.4–4.2)	1.4 (1.1–1.6)	1.9 (1.5–2.6)	1.2 (1.0–1.4)	1.4 (0.8–2.1)	0.8 (0.6–0.9)
3. Gnut-Mz	2.9 (2.4–4.0)	1.4 (1.2–1.8)	1.0 (0.8–1.3)	1.1 (0.9–1.3)	0.8 (0.5–1.1)	0.9 (0.8–1.1)
4. Bean-Mz	1.1 (0.6–1.6)	0.9 (0.7–1.1)	0.9 (0.5–1.4)	0.6 (0.4–0.7)	0.6 (0.3–0.9)	0.4 (0.3–0.5)
5. Lima-Mz	0.9 (0.7–1.3)	1.0 (0.8–1.3)	1.0 (0.5–1.5)	1.0 (0.7–1.2)	0.8 (0.5–1.3)	0.8 (0.6–0.8)
6. Lablab-Mz	2.0 (1.5–2.7)	1.3 (1.0–1.6)	1.7 (0.9–2.6)	1.1 (0.9–1.4)	1.5 (0.8–2.3)	0.7 (0.5–0.7)
Mean	**2.1 (1.6–2.9)**	**1.2 (1.0–1.5)**	**1.3 (0.9–1.9)**	**1.0 (0.8–1.2)**	**1.1 (0.6–1.6)**	**0.7 (0.6–0.8)**
7. Crot-Mz	1.9 (1.5–2.6)	1.2 (1.0–1.4)	0.1 (0.1–0.1)	0.9 (0.7–1.0)	−1.7 (−2.3 to −1.3)	0.7 (0.5–0.8)
8. Velvet-Mz	2.7 (2.2–3.7)	1.3 (1.1–1.6)	1.0 (0.8–1.3)	1.0 (0.8–1.2)	−2.4 (−3.3 to −1.9)	0.5 (0.4–0.6)
9. Jack-Mz	1.9 (1.5–2.5)	1.2 (1.0–1.4)	−0.7 (−1.0 to −0.5)	0.7 (0.6–0.8)	−1.9 (−2.6 to −1.5)	0.6 (0.5–0.7)
Mean	**2.2 (1.7–2.9)**	**1.3 (1.0–1.5)**	**0.1 (0.0–0.3)**	**0.9 (0.7–1.0)**	**−2.0 (−2.7 to −1.6)**	**0.6 (0.5–0.7)**
10. Mz-Mz (0/0)	0.8 (0.5–1.2)	0.5 (0.4–0.6)	0.6 (0.3–0.8)	0.3 (0.2–0.3)	0.4 (0.2–0.6)	0.3 (0.2–0.4)
11. Mz-Mz (0/50)	0.8 (0.4–1.2)	0.7 (0.6–0.8)	0.8 (0.4–1.2)	0.7 (0.5–0.8)	0.6 (0.3–0.9)	0.4 (0.3–0.5)
12. Mz-Mz (50/50)	1.4 (0.8–2.1)	0.7 (0.6–0.9)	1.3 (0.7–1.9)	0.7 (0.5–0.8)	1.1 (0.5–1.5)	0.5 (0.4–0.7)
SED (AEZ × Rotation × Fertility)	0.41	0.41	0.14	0.41	0.41	0.41

4. Discussion

The productivity of legumes and maize varied with AEZ and soil fertility status. As differences in soil fertility between AEZs were confounded with differences in rainfall and possibly other relevant growth factors, inferences on the impact of soil fertility on yield and economic returns could only be made within AEZs. Soil C and available P were generally greater in fields in higher fertility classes (Table 3). Higher soil C suggests that trial fields in better soil fertility classes had received more organic inputs in the past. Animal manure, the main resource for soil fertility management in Western Kenya smallholder systems, is applied preferentially to different types of fields (Tittonell et al., 2005b; Vanlauwe et al., 2006). Fields close to the homestead (usually high fertility fields) receive more manure than fields farther away. P deficiencies were likely corrected by a uniform application of 30 kg P ha^{-1} in legumes and 50 kg P ha^{-1} in maize, except for the Mz-Mz (0/0) treatment. The clear differences in crop productivity between soil fertility classes could have been due to different availabilities of nutrients other than P applied through manure, though probably not the cations K, Ca or Mg, which appeared to be sufficiently available in all soils (Table 3). Moreover, other crop growth enhancing effects of increased soil C, such as better soil structure and higher soil moisture retention, could have benefited crops at high fertility sites. In addition, the low fertility fields were sometimes poor in other ways, such as shallow soils or poor drainage, which was not captured through soil analyses. Differences in legume productivity and amount of legume residues incorporated into the soil before maize planting reinforced growth responses of maize to the soil fertility differences in the second season.

Differences in crop productivity between AEZs reflected differences in rainfall and soil parameters, but the individual impact of these confounded factors could not be assessed in this study. The use of grain legumes and green manures in rotations resulted in strong increases in yield of the subsequent maize, compared with continuous maize fertilised only with P. Such yield benefits of legume–maize rotations have been commonly observed before in the region (Baijukya et al., 2005; Anyanzwa et al., 2010; Kihara et al., 2010; Vanlauwe et al., 2008). The yield benefit of maize after green manure in our study generally did not exceed the yield foregone in the season when the green manure is grown (Fig. 3), except for the high fertility site in AEZ3, as also observed by Bünemann et al. (2004) in western Kenya. According to the calculated response curves in Fig. 2, the predicted maize yield after the application of 50 kg legume-N is 2.76, 3.49 and 2.45 t ha^{-1} in AEZ1, AEZ2, and AEZ3, respectively. The average yield in the continuous maize treatment (50 N/50P) was 3.26, 3.62 and 1.55 t ha^{-1} in AEZ1, AEZ2, and AEZ3, respectively (Table 4). Thus, while 50 kg legume-N had a slightly lower impact on maize yield than 50 kg urea-N in AEZ1 and AEZ2, the apparent impact of legume-N in AEZ3 is much higher than that of urea-N. This indicates that effects other than improved N availability, for instance biotic factors (Bagayoko et al., 2000), also enhanced maize yields in legume–maize rotation in AEZ3.

Subsequent crops generally recover 10–20% of N applied as legume residues in the first season after application (Giller and Cadisch, 1995). The asymptotic curves describing the relation between legume-N applied and maize yield (Fig. 2) demonstrate diminishing returns to increasing amounts of legume-N applied. Incorporation of large amounts of legume N, e.g. through the incorporation of velvet bean biomass (up to 450 kg N ha^{-1}), led to large amounts of mineral N being available at sowing (Table 5) before maize roots were sufficiently developed and maize growth was sufficiently vigorous to utilise the available N. High amounts of legume N applied thus resulted in low N use efficiencies by maize. The maximum yields of maize observed differed among the AEZs. In the high rainfall areas, maize was better able to take advantage of large amounts of legume-N applied than in the low rainfall area. The diminishing return to increasing legume-N inputs suggest that with a high legume biomass production, part of the legume residues could be removed for livestock feed, without affecting maize grain yield in the subsequent season. The relative amounts of legume biomass that could be removed without compromising the growth of maize differed among the AEZs and are likely to be affected by seasonal differences in rainfall and other climatic factors. Livestock is an important component of the farming system in western Kenya and the use of maize and legume residues as feed is common. Residues of certain legumes, e.g. that of groundnut, are more likely to be removed for feed than those of e.g. soybean and lablab, which farmers usually leave the residues in the field. The use of residues as feed creates a potential trade-off between the use of legume residues for soil fertility improvement or for feed. In the latter case, the ability of the farmer to return manure from their livestock to their fields and handle feed and manure well during storage and transport strongly affect carry-over rates of nutrients and carbon and impacts on soil fertility (Lekasi et al., 2003; Rufino et al., 2006).

Labour estimates were obtained from observations in the trials and cross-validated with participating and neighbouring farmers. For some crops that were not commonly grown by farmers, such as green manure legumes, cross-validation was difficult. Reliable labour data from smallholders are difficult to obtain in general. Our labour data for maize and grain legumes however compared well with observations in other studies among smallholders (van Heemst et al., 1981; Franke et al., 2010). Among the grain legumes, rotations with soybean, groundnut and lablab generally resulted in the best returns to land and labour across AEZs and soil fertility gradients, while bean–maize rotations gave the lowest returns. The superior returns of rotations with soybean and groundnut were due to the higher prices of these crops, relative to bean, and probably the poor N fixation rate by bean (Pilbeam et al., 1995; Ojiem et al., 2007) and the low subsequent maize yield. Possibly, bean performed poorly due to an absence of inoculation (Ndakidemi et al., 2006). Bean is nevertheless an important crop in eastern African farming systems, although bush bean is usually grown in mixed cropping systems, which increased total productivity and economic returns. Lima bean and lablab are relatively new legume species in western Kenya and markets may be inelastic if many farmers increase their production. Lablab achieved higher grain yields, residual biomass yields and economic returns than lima bean and therefore appeared to be more promising. In AEZ3 however, limited rainfall greatly reduced lablab grain yield. Seed availability is likely to be a major limitation to adoption of these relatively new legumes. This is less the case for legumes more commonly grown in the area, such as bean, soybean and groundnut, which have formal and informal seed markets.

Returns to labour were often less than the wage for casual work of around US$ 1.30 per day prevailing in the area, especially in AEZ3 and the low fertility site of AEZ1 (Table 7). Given that this was the case for almost all rotations in AEZ3, even if farmers would sell when prices are highest, this suggests that farmers in this zone earn more income by working outside the farming sector or on other people's land. However, off-farm labour opportunities are scarce and poor rural people highly value the production of their own food, reducing transaction costs associated with selling and buying food and reducing their dependence on markets with fluctuating prices.

In the trial, fertile fields and AEZs with higher rainfall generally provided higher returns to land and labour than poorly fertile fields. Even though legume–maize rotations on the medium and poorly fertile soils in AEZ3 gave a better agronomic and economic performance than continuous maize, none of the rotations yielded well or was economically attractive. Moreover, the technologies tested in this trial (fertiliser use in maize, cultivation of legumes) gave higher absolute increases in yield and economic returns, using continuous maize without fertiliser as a baseline, on more fertile fields and in AEZs with higher rainfall. While it is expected that higher rainfall allows greater responses to technologies improving soil fertility than lower rainfall, it is not obvious that low fertility sites give lower responses than high fertility sites. For instance, soils with a poorer ability to supply N and P to crops are expected to show a greater response to technologies increasing N and P availability. Soil factors not addressed by the technologies tested in this trial probably limited responses on poorly fertile sites. Investments that improve the overall fertility of infertile fields are likely to result in higher returns and greater responses to the technologies tested. In addition, interventions such as an improved water management may be needed to improve responses. It often takes several years before such interventions lead to substantial yield increases. For instance, to improve soil C and P levels applications of organic inputs and often mineral fertiliser need to be repeated over several seasons (e.g. Franke et al., 2008b; Rusinamhodzi et al., 2013). Thus, while legumes offer scope to immediately improve productivity and economic returns also in low potential areas and fields, the relatively poor responses and the time and investments that are probably required to improve responses are likely to impede adoption.

5. Conclusions

Legume and maize productivity, returns to land and labour, and the relative performance of different rotations all varied strongly among AEZs and along soil fertility gradients within these zones. Areas with lower rainfall and poorer soil fertility gave lower legume and maize yields, and less returns to land and labour. The differences between AEZs were often greater than the differences between legume–maize rotations within AEZs. AEZ-specific response curves were found between N applied through legume residues and maize yield with diminishing returns to increasing legume-N application rates, and less returns in lower rainfall areas. Green manures left behind more N in residues than grain legumes, resulting in larger maize grain yields in the subsequent season. Yet the economic analyses indicated that rotations with grain legumes provided higher returns in most instances. Intensification of cropping systems through the incorporation of grain legumes seems more promising in high potential zones with high rainfall and good soil fertility. On poorer soils in low rainfall areas, benefits of incorporating legumes are smaller and additional interventions would be needed to make farming economically attractive.

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