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Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms

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Abstract Nitrogen (N) deficiency is a major constraint to the productivity of the African smallholder farming systems. Grain, green manure and forage legumes have the potential to improve the soil N fertility of smallholder farming systems through biological N_2-fixation. The N_2-fixation of bean (*Phaseolus vulgaris*), soyabean *(Glycine max*), groundnut (*Arachis hypogaea*), Lima bean *(Phaseolus lunatus*), lablab (*Lablab purpureus*), velvet bean (*Mucuna pruriens*), crotalaria *(Crotalaria ochroleuca*), jackbean (*Canavalia ensiformis*), desmodium (*Desmodium uncinatum*), stylo *(Stylosanthes guianensis*) and siratro (*Macroptilium atropurpureum*) was assessed using the ^{15}N natural abundance method. The experiments were conducted at three sites in western Kenya, selected on an agro-ecological zone (AEZ) gradient defined by rainfall. On a relative scale, Museno represents high potential AEZ 1, Majengo medium potential AEZ 2 and Ndori low potential AEZ 3. Rainfall in the year of experimentation was highest in AEZ 2, followed by AEZ 1 and AEZ 3. Experimental fields were classified into high, medium and low fertility classes, to assess the influence of soil fertility on N_2-fixation performance. The legumes were planted with triple super phosphate (TSP) at 30 kg P ha^{-1}, with an extra soyabean plot planted without TSP (soyabean-P), to assess response to P, and no artificial inoculation was done. Legume grain yield, shoot N accumulation, %N derived from N_2-fixation, N_2-fixation and net N inputs differed significantly ($P<0.01$) with rainfall and soil fertility. Mean grain yield ranged from 0.86 Mg ha^{-1}, in AEZ 2, to 0.30 Mg ha^{-1}, in AEZ 3, and from 0.78 Mg ha^{-1}, in the high fertility field, to 0.48 Mg ha^{-1}, in the low fertility field. Shoot N accumulation ranged from a maximum of 486 kg N ha^{-1} in AEZ 2, to a minimum of 10 kg N ha^{-1} in AEZ 3. Based on shoot biomass estimates, the species fixed 25–90% of their N requirements in AEZ 2, 23–90% in AEZ 1, and 7–77% in AEZ 3. Mean N_2-fixation by green manure legumes ranged from 319 kg ha^{-1} (velvet bean) in AEZ 2 to 29 kg ha^{-1} (jackbean) in AEZ 3. For the forage legumes, mean N_2-fixation ranged from 97 kg N ha^{-1} for desmodium in AEZ 2 to 39 kg N ha^{-1} for siratro in AEZ 3, while for the grain legumes, the range was from 172 kg N ha^{-1} for lablab in AEZ 1 to

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3 kg N ha^{-1} for soyabean-P in AEZ 3. Lablab and groundnut showed consistently greater N_2-fixation and net N inputs across agro-ecological and soil fertility gradients. The use of maize as reference crop resulted in lower N_2-fixation values than when broad-leaved weed plants were used. The results demonstrate differential contributions of the green manure, forage and grain legume species to soil fertility improvement in different biophysical niches in smallholder farming systems and suggest that appropriate selection is needed to match species with the niches and farmers' needs.

Keywords Agro-ecological zones · N_2–fixation · ^{15}N natural abundance · On-farm · Trade-offs

Introduction

Soil fertility degradation is widely acknowledged as a major factor limiting productivity of the sub-Saharan Africa smallholder farming systems (Franzel 1999; Sanchez et al. 1997; Tarawali et al. 1999). This degradation is particularly significant in the east African highlands, where rapid population growth, continuous cropping, and restricted use of organic inputs and fertilizers have led to low productivity of the systems. According to Smaling and Braun (1996), the average annual mining of nitrogen (N) in parts of Western Kenya is up to 112 kg N ha^{-1} year^{-1}. Nitrogen deficiency is therefore a major factor responsible for the low productivity of Western Kenya smallholder systems.

Manure and mineral fertilizers are options for soil fertility restoration. However, as in many parts of sub-Saharan Africa, the use of animal manure in Western Kenya is limited because the quantities available on-farm are often insufficient to maintain soil fertility (Jama et al. 1997), while the use of mineral fertilizers is constrained by unreliable returns (Ruthenberg 1980; Anderson 1992), limited access to capital by smallholders (Hoekstra and Corbett, 1995), and unreliable markets for agricultural produce (Hassan et al. 1998). Therefore, N input via biological N_2-fixation, using appropriate legume species, is a feasible alternative to N from mineral fertilizers. However, in restoring the productivity of the systems, legumes are important as a component of an integrated soil fertility management (ISFM) strategy, since phosphorus (P) has to be acquired from elsewhere. Legumes also require P for effective N_2-fixation, since P deficiency can prevent nodulation (Giller 2001). Even though legumes can play a major role in improving farm productivity in smallholder agriculture as short duration fallow species (Hudgens, 2000), current knowledge on N_2-fixation performance under the non-ideal conditions encountered in African smallholder farming systems is limited, although some estimates have recently been made in Northern Tanzania (Baijukya 2004), and Zimbabwe (Chikowo et al. 2004).

Western Kenya is typical of the agricultural conditions found in the densely populated highlands of east and central Africa. Due to this, it is one of the benchmark sites for the African Highlands Initiative (AHI), a collaborative research initiative working on key issues of natural resource management and agricultural productivity. Smallholder farms in Western Kenya are characterized by a high degree of biophysical and socio-economic heterogeneity. Not only do farmers operate under diverse agro-ecological conditions, but there is also wide diversity in within-farm soil fertility and farmers have varying resource endowments. Tittonell et al. (2005a and b) observed differences in the fertility status of fields in three sites in Western Kenya, which were generally correlated with the resource endowment status of the farmers. For example, soil-extractable P was higher in the fields of high resource endowed farmers than in the fields of those with low resource endowment. These differences may affect legume N_2-fixation and production.

Soil fertility variability and differential resource endowments give rise to niches with biophysical and socio-economic dimensions, or socio-ecological niches (Ojiem et al. 2006), into which legumes must fit in order to be widely accepted by farmers. N_2-fixation and the provision of certain goods (grains, fodder, etc.) are among the major criteria legumes must meet in order to fit into the socio-ecological niches.

A number of different methodologies are available for assessment of N_2-fixation. However, under field conditions, the ^{15}N natural abundance method (Peoples et al. 1989) has advantage over, for example, the ^{15}N enrichment method because no addition of ^{15}N fertilizer is required, and can therefore be used on-farm, provided appropriate non-N_2-fixing reference plants are present. The choice of reference plants is a major factor that can influence the reliability of the methodology (Peoples et al. 2002). Maize is among the commonly used non-N_2-fixing plants in on-farm measurements of N_2-fixation because it is often readily available.

The objectives of this study were: (i) to assess the capacities of a range of grain, green manure, and forage legumes to fix atmospheric N_2 under on-farm conditions across agro-ecological and soil fertility gradients in Western Kenya; (ii) to compare the net N contributions (N balance) of the grain, green manure and forage legume species through N_2-fixation to the smallholder farming systems in Western Kenya; and (iii) to evaluate the suitability of maize as a reference crop in on-farm N_2-fixation assessment using the ^{15}N natural abundance method.

Materials and methods

Sites description

The experiments were conducted on-farm in Museno, Majengo and Ndori in Western Kenya. The three sites were selected along an agro-ecological zone (AEZ) gradient and designated high, medium and low rainfall, based on a relative scale: Museno (high rainfall, AEZ 1), located in Kakamega district at 00°14′ N and 34°44′ E at an altitude of 1570 m above sea level (masl), with a mean annual rainfall of 2000 mm; Majengo (medium rainfall, AEZ 2), located in Vihiga district at 00°00′ N and 34°41′ E at an altitude of 1385 masl, with a mean annual rainfall of 1600 mm; Ndori (low rainfall, AEZ 3) is located in Bondo district at 00°02′ and 34°20′ E at an altitude of 1170 masl, with a mean annual rainfall of 1200 mm. All the sites have bimodal rainfall pattern, with the first season (the long rains) extending from March to August, and the second (the short rains), from September to December.

In each site, experimental fields were selected to capture the within-farm soil fertility variability, which is a common feature within smallholder systems (Tittonell et al. 2005a). Three fields each were chosen to represent high, medium and low soil fertility conditions. The selections were based on farmer knowledge of within-farm soil fertility variability and the history of crop performance. However, further soil fertility characterization was done by sampling the soil in all fields in each site, prior to sowing the legumes, for laboratory analysis. Composite soil samples (0–20 cm depth) were taken from nine spots and bulked. A subsample of about 1 kg for each field was then taken for chemical and physical analysis. The soil samples were air dried, crushed and ground to pass through a 2 mm sieve and analysed for pH (1:2.5 soil/water suspension), texture (hydrometer method), extractable P (bicarbonate-EDTA), total soil organic carbon (Walkley-Black) and calcium, magnesium and potassium extracted in ammonium acetate (Anderson and Ingram 1993). Total N (macro-Kjeldahl) and δ^{15}N were also determined as indicated below for plant material. Although some soil fertility parameters did not show much variation, relatively large differences were observed in phosphorus (P), organic carbon (OC) and total N contents, especially between the high and the low fertility fields (Table 1). The farmer soil fertility classification took into consideration factors such as drainage properties of the field, soil depth, stoniness, presence of noxious weeds, etc, which are not captured in laboratory analysis but can affect crop performance.

Experimental design and plots establishment

The experiments were laid out in each field in randomized complete block design (RCBD) replicated in two blocks. Grain legume species: bean (*Phaseolus vulgaris* (L.)) variety KK20; soyabean (*Glycine max* (L.) Merr.) variety SB20; groundnut (*Arachis hypogaea* L.) variety CG 7; Lima bean (*Phaseolus lunatus* L.); and lablab (*Lablab purpureus* (L.) Sweet) variety cv *Rongai*; green manure legumes: velvet bean (*Mucuna pruriens*

Table 1 Soil fertility parameters of the three categories of fields identified by farmers for experimentation in three agro-ecological zones in Western Kenya, ($n = 3$)

Soil fertility category	pH (H_2O)	% Total OC	% Total N	C:N ratio	P mg kg^{-1} soil	Ca cmol $_{(c)}$ kg^{-1}	Mg cmol $_{(c)}$ kg^{-1}	K cmol $_{(c)}$ kg^{-1}	% Clay	% Sand	% Silt
AEZ 1											
High	5.95	1.64	0.17	10:1	8.78	6.30	1.48	0.40	24	35	45
Medium	5.86	1.63	0.16	10:1	4.27	6.35	1.73	0.35	22	43	38
Low	6.20	1.48	0.13	11:1	3.37	5.43	1.93	0.23	21	38	41
AEZ 2											
High	5.86	1.50	0.19	8:1	15.42	6.96	2.10	0.36	22	33	48
Medium	5.43	1.46	0.17	9:1	8.00	5.82	1.65	0.43	16	36	46
Low	5.63	1.28	0.14	9:1	3.50	5.90	1.75	0.17	29	36	35
AEZ 3											
High	5.84	1.52	0.17	9:1	2.48	6.40	2.30	0.39	37	28	30
Medium	6.24	1.23	0.16	8:1	1.20	6.45	3.28	0.36	35	28	40
Low	5.70	1.32	0.16	9:1	1.15	6.40	2.55	0.30	25	45	30

(L.) Walp); crotalaria (*Crotalaria ochroleuca* G. Don); and jackbean (*Canavalia ensiformis* (L.) DC.); and forage legumes: desmodium (*Desmodium uncinatum* (Jacq.) DC.); stylo (*Stylosanthes guianensis* (Aublet) Sw)*;* and siratro (*Macroptilium atropurpureum* (DC.) Urban) were planted in mid September 2003 in plots measuring 4.5 m wide by 5.0 m long. The species and varieties were selected from a legume screening trial the season before (Ojiem 2006). All the legumes were planted at recommended spacing. Soyabean was planted in rows spaced 0.50 m at 0.05 m intra-row spacing, while groundnut and bean were spaced 0.50 m inter-row and 0.10 m intra-row. Lima bean was spaced 0.25 m inter-row, with 0.10 m intra-row spacing, while velvet bean, jackbean and lablab were planted in rows spaced at 0.60 m inter-row and 0.30 m intra-row. Crotalaria was drilled in rows spaced 0.30 m wide at a seed rate of 4 kg ha^{-1}. The legume seeds were not inoculated at planting because there is no existing infrastructure for supply of inoculants to smallholder farmers in the target area. In addition, previous research (Mureithi et al. 2003) did not demonstrate the need for artificial inoculation of similar legume species in several sites in Western Kenya. In all legume plots, except crotalaria, two seeds were placed in each planting hole, later thinned to one seed per plant at first weeding. Maize was planted as a control, spaced 0.75 m inter-row and 0.30 m intra-row. Phosphorus (P) was applied at the rate of 30 kg P ha^{-1} to all legume plots and the maize plots. One soyabean plot was fertilized with P (soyabean+P) and an extra soyabean plot with no P fertilization (soyabean–P) was included in the trial to check response to P.

Biomass production assessment

All the plots were sampled to determine legume biomass production. The above ground biomass was determined at near maximum dry matter accumulation, at mid pod filling stage. Biomass was determined by destructive sampling of plants in a 0.5 m by 0.5 m quadrat in 3 randomly selected positions within each plot, excluding the border rows. Biomass was immediately weighed in the field to determine fresh weight and then divided into two. One sub-sample was weighed with an electronic balance and then oven-dried at 65°C for 4 days to determine dry weight and moisture content, which were used to calculate dry matter production. The other sub-sample was processed and used for quantification of N_2-fixation.

N_2-fixation methodology and calculations

The proportion of legume N derived from N_2-fixation was determined using the ^{15}N natural abundance method (Peoples et al. 1989). This method is based on the principle that provided the ^{15}N enrichment ($\delta^{15}N$) of the plant-available soil N differs from atmospheric N_2, the %N from N_2-fixation can be determined. The %N from N_2-fixation calculated using the equation of Shearer and Kohl (1986) and Peoples et al. (1997) as follows:

$$\%N\,from\,N_2-fixation=100\left(\frac{\delta^{15}N_{ref}-\delta^{15}N_{legume}}{\delta^{15}N_{ref}-B}\right) \tag{1}$$

where $\delta^{15}N_{ref}$ is the ^{15}N natural abundance of the shoots of a non-N_2-fixing reference plant deriving its entire N from the soil N; $\delta^{15}N_{legume}$ is the ^{15}N natural abundance of the shoots of the N_2-fixing legume plant growing in the same soil; and *B* is the $\delta^{15}N$ of the test legume fully dependent on N_2-fixation for growth, and a correction for isotopic fractionation during N_2-fixation.

The legume shoot samples were air-dried to constant weight, ground to <1 mm in an electric mill in preparation for ^{15}N analysis. The ^{15}N analysis was done at the UC Davis Stable Isotope Facility, CA, USA, using a PDZ Europa 20–20 mass spectrometer. The ^{15}N natural abundance of the samples was computed using the equation of Shearer and Kohl (1986) as follows:

$$\delta^{15}N(‰)=1000\left[\left(R_{sample}/R_{standard}\right)-1\right] \tag{2}$$

where $\delta^{15}N$ is the ^{15}N natural abundance of the samples expressed as parts per thousand (‰); and *R* is the ration of $^{15}N/^{14}N$ in the sample; and the atmospheric N_2 was used as the standard ($R_{standard}$). By definition, the $\delta^{15}N$ of the atmosphere is zero. A range of broad-leaved weed plants and maize, growing in the same fields as the legumes, were used as reference plants, while *B* values were obtained from the literature (see Table 4).

Grain production assessment

Grain production was assessed in all the fields at each site. The species matured at different times and were harvested between November and December, 2003. The pods were sun-dried for several days and then threshed. Grain was then weighed and grain moisture content determined using an electronic moisture meter. Grain yield was calculated at 12% moisture content.

Statistical analysis

Data was subjected to analysis of variance (ANOVA) procedure using SAS statistical software (SAS Institute Inc, Cary, NC, U.S.A.). A cross-site analysis was performed using agro-ecological zones, soil fertility and legumes as factors. Legume shoot ^{15}N natural abundance, %N derived from N_2-fixation, legume biomass, shoot N content and grain yield were analysed. Where significant differences were detected between means, standard error of difference (SED) values were calculated and used to compare means.

Results

Legume establishment and performance

There was good legume emergence and growth at all sites. The legumes were well adapted to the agro-environmental conditions in the three agro-ecological zones and as a result, only minor incidence of pest and diseases were observed. The total amounts of rainfall received in AEZs 1 and 2 during the short rains 2003 season were nearly the same (Fig. 1a and b). However, in AEZ 2, a total of 788 mm of rainfall was received in the period between sowing (September) and harvesting (December), while in AEZ 1 only 428 mm was received over the same period. However, relatively higher rainfall was recorded in AEZ 1 in August, before legume sowing, which should have

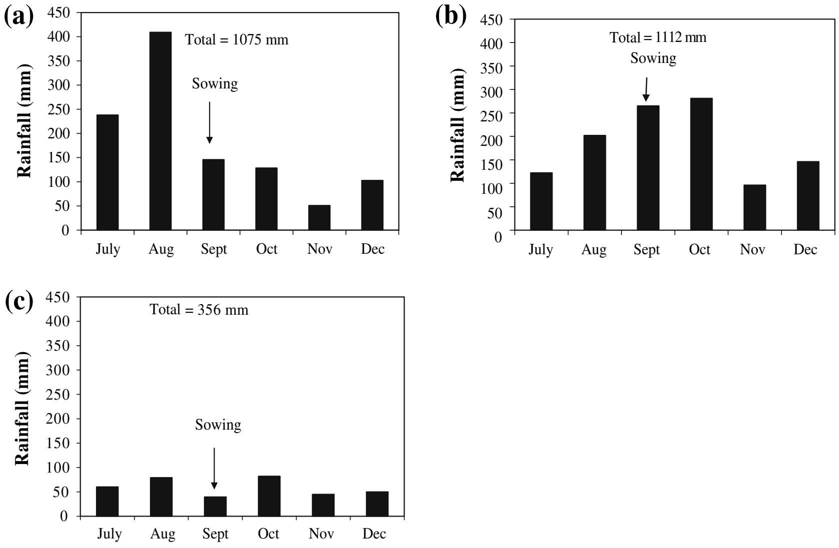

Fig. 1 Rainfall recorded during the experimentation period in: (**a**) Museno (AEZ 1); (**b**) Majengo (AEZ 2); and (**c**) Ndori (AEZ 3) study sites in Western Kenya

recharged the soil with moisture. Nevertheless, the legume performance was relatively better in AEZ 2 than in AEZ 1. Rainfall was low in AEZ 3 (Fig. 1c). A total of 356 mm of rainfall was recorded during the season, about 50% of the normal rainfall for the zone. The rainfall gradient in 2003 was therefore considered to be in the sequence AEZ 2-AEZ 1-AEZ 3.

Legume grain yield performance

Grain yield significantly (P<0.001) differed with species, AEZ and soil fertility (Table 2). Mean grain yield generally decreased with decreasing rainfall, ranging from 0.86 Mg ha^{-1} in AEZ 2, to 0.30 Mg ha^{-1} in AEZ 3. Similarly, grain yield consistently decreased with soil fertility. For example, in AEZ 1, grain yield of bean ranged from 1.25 Mg ha^{-1} in the high fertility field to 0.37 Mg ha^{-1} in the low fertility field. Similarly, the grain yield of soyabean+P ranged from 1.13 Mg ha^{-1} in the high fertility field to 0.68 Mg ha^{-1} in the low fertility field. Similar reductions in grain yield were observed in AEZs 2 and 3. In AEZ 1, bean (0.82 Mg ha^{-1}), lablab (0.77 Mg ha^{-1}) and soyabean+P (0.85 Mg ha^{-1}) had the best grain yield performance, while in AEZ 2, soyabean+P (1.04 Mg ha^{-1}), lablab (1.05 Mg ha^{-1}) and groundnut (1.06 Mg ha^{-1}) performed best. In AEZ 3, the best grain yield was found with groundnut (0.31 Mg ha^{-1}), Lima (0.33 Mg ha^{-1}) and soyabean+P (0.34 Mg ha^{-1}).

^{15}N natural abundance of the soil and reference plants

The detected ^{15}N natural abundance signatures (δ^{15}N) for soil and non-N$_2$-fixing reference plants varied between species in all AEZs (Table 3). Generally, δ^{15}N signatures of maize plants of the same age as legumes, and growing in the same field, were lower than those of similar aged broad-leaved weeds growing in the same field. In AEZ 1, the δ^{15}N values for all reference plants ranged from +2.78 to +6.85‰. The mean for maize samples was +3.20‰, while the broad-leaved reference samples had a mean of +5.89‰. The δ^{15}N signatures for all reference plants were slightly higher in AEZ 2 compared with AEZ 1. The maize reference plants had a mean value of +3.61‰, while the mean for broad-leaved weeds was +6.29‰. Maize had relatively higher δ^{15}N signatures in AEZ 3, with a mean of +4.14‰. The mean for broad-leaved weeds was +5.74‰. The δ^{15}N signatures in the soils showed little variation between sites, with mean values ranging from +7.96‰ in AEZ 1 to +6.54‰ in AEZ 3. However, no consistent trends were observed in the relationship between δ^{15}N and soil fertility status of the trial fields.

Table 2 Effect of agro-ecological zone and soil fertility on legume species grain yield (at 12% moisture content) in Western Kenya, short rains 2003 season

Species	Grain yield (Mg ha^{-1})											
	AEZ 1				AEZ 2				AEZ 3			
	High fertility field	Medium fertility field	Low fertility field	Mean	High fertility field	Medium fertility field	Low fertility field	Mean	High fertility field	Medium fertility field	Low fertility field	Mean
Bean	1.25	0.83	0.37	0.82	0.94	0.69	0.49	0.71	0.38	0.33	0.29	0.33
Groundnut	0.71	0.56	0.53	0.60	1.25	1.12	0.80	1.06	0.34	0.30	0.31	0.32
Lablab	0.84	0.69	0.78	0.77	1.40	0.96	0.78	1.05	0.05	0.07	0.05	0.06
Lima	0.76	0.72	0.61	0.70	0.49	0.53	0.41	0.48	0.50	0.45	0.33	0.43
Soyabean (+P)	1.13	0.74	0.68	0.85	1.39	0.94	0.79	1.04	0.53	0.42	0.34	0.43
Soyabean (–P)	0.84	0.57	0.44	0.62	1.05	0.84	0.54	0.81	0.30	0.29	0.13	0.24
Mean	0.92	0.69	0.57	0.73	1.09	0.85	0.64	0.86	0.35	0.31	0.24	0.30
***SED$_{(Species)}$					0.08							
***SED$_{(Fertility)}$					0.06							
***SED$_{(AEZ)}$					0.04							

SED = standard error of the difference in means, *** $P<0.001$

^{15}N natural abundance of legumes and estimates of N$_2$-fixation

There was no consistent trend between shoot ^{15}N natural abundance of the legume shoots and rainfall (Table 4). However, the mean δ^{15}N of the green manure species (+0.48‰) showed less enrichment than that of the grain (+0.97‰) and forage legumes (+1.55‰) in AEZ 1. A similar trend was observed in AEZ 2. However, in AEZ 3, the forage legume shoots showed relatively lower enrichment (+1.40‰) than the grain legumes (+2.71‰) and green manure legumes (+1.93‰). Among the grain legumes, soyabean-P (+0.15‰), soyabean+P (+0.37‰) and lablab (+0.82‰) showed the least shoot enrichment in AEZ 1, while in AEZ 2, soyabean-P (+1.36‰), soyabean+P (+1.51‰) and groundnut (+1.68‰) were the least enriched. In AEZ 3, groundnut (+1.58‰), lablab (+1.83‰) and Lima (+2.47‰), showed the least shoot enrichment. Among the green manure legumes, velvet bean (–0.70‰) showed least shoot enrichment in AEZ 1, jack-bean (–0.31‰) in AEZ 2, and crotalaria (+0.49‰) in AEZ 3, while for forage legumes, stylo was least enriched in AEZ 1 (+1.23‰) and AEZ 2 (+1.42‰), while siratro (+1.25‰) was least enriched in AEZ 3.

The % N derived from atmospheric N$_2$-fixation was significantly ($P<0.01$) influenced by AEZ and legume species (Table 4). The use of maize as reference plant consistently resulted in smaller values of %N derived from N$_2$-fixation than when broad-leaved weeds were used. The δ^{15}N signatures of the broad-leaved weed plants, which were relatively consistent around 6‰, were closer to the total soil δ^{15}N (about 8‰) than the δ^{15}N signatures of maize, which were around 3.5‰. Based on this, the broad leaved weed reference plants were considered better indicators of the δ^{15}N signatures of the available soil N, hence providing more accurate estimates of N$_2$-fixation than maize. Therefore, based on broad-leaved weeds as reference plants, the legumes derived 35–90% of their N requirements from atmospheric N$_2$-fixation in AEZ 1, 48–90% in AEZ 2 and 1–77% in AEZ 3. Averaged over species, the %N from N$_2$-fixation was higher for green manure legumes than for grain and forage

Table 3 Estimates of the ^{15}N natural abundance signatures detected in soil, maize and broad-leaved non-N_2-fixing reference plants in different agro-ecological zones and soil fertility conditions in Western Kenya

Site	Farm No.	Soil fertility status	Soil $\delta^{15}N$ (‰)	Reference plant	$\delta^{15}N$ (‰)	
					Maize	Weeds
Museno: High rainfall zone (AEZ 1)	1	Low	8.61	*Zea mays*	3.82	–
				Bidens pilosa	–	6.20
	2	High	7.80	*Zea mays*	3.36	–
				Bidens pilosa	–	6.85
	3	High	7.55	*Zea mays*	2.78	–
				Bidens pilosa	–	3.98
	4	Low	7.72	*Zea mays*	2.79	–
				Bidens pilosa	–	6.00
				Galinsoga spp.	–	5.79
	5	High	8.05	*Zea mays*	3.17	–
				Bidens pilosa	–	5.63
	6	Medium	7.34	*Zea mays*	3.78	–
				Bidens pilosa	–	6.11
	7	Medium	9.19	*Zea mays*	2.97	–
				Bidens pilosa	–	6.16
	8	Low	7.71	*Zea mays*	2.99	–
				Lantana trifolia	–	5.83
				Bidens pilosa	–	6.11
	9	Medium	7.73	*Zea mays*	3.15	–
				Lantana trifolia	–	6.17
		Mean	7.96	–	3.20	5.89
Majengo Medium rainfall zone (AEZ 2)	1	High	6.87	*Zea mays*	4.19	–
				Bidens pilosa	–	5.88
	2	Low	7.56	*Zea mays*	3.58	–
				Lantana trifolia	–	5.14
	3	Medium	8.25	*Zea mays*	3.13	–
				Lantana trifolia	–	7.23
	4	High	7.72	*Zea mays*	3.24	–
				Bidens pilosa	–	6.15
	5	High	8.38	*Zea mays*	3.89	–
				Galinsoga spp.	–	6.81
	6	Low	7.93	*Zea mays*	2.21	–
				Bidens pilosa	–	6.39
	7	Medium	7.87	*Zea mays*	6.19	–
				Bidens pilosa	–	6.82
	8	Medium	7.54	*Zea mays*	3.05	–
				Conyza banariensis	–	6.42
	9	Low	7.15	*Zea mays*	3.05	–
				Conyza banariensis	–	5.80
		Mean	7.69	–	3.61	6.29
Ndori Low rainfall zone (AEZ 3)	1	Low	6.83	*Zea mays*	4.13	–
				Bothriocline laxa	–	5.76
	2	High	5.93	*Zea mays*	4.23	–
				Leonoptis nepetifolia	–	5.82
	3	Medium	5.45	*Zea mays*	4.40	–
				Bidens pilosa	–	5.59
	4	Low	8.07	*Zea mays*	4.40	–
				Bidens pilosa	–	5.82
	5	Low	6.30	*Zea mays*	3.89	–
				Leonoptis nepetifolia	–	3.82
	6	Medium	6.06	*Zea mays*	4.40	–
				Leonoptis nepetifolia	–	6.30

Table 3 continued

Site	Farm No.	Soil fertility status	Soil δ^{15}N (‰)	Reference plant	δ^{15}N (‰)	
					Maize	Weeds
	7	High	6.60	*Zea mays*	3.92	–
				Bidens pilosa	–	6.30
	8	Medium	6.61	*Zea mays*	3.89	–
				Bidens pilosa	–	6.25
	9	High	7.05	*Zea mays*	4.03	–
				Leonoptis nepetifolia	–	6.44
				Bothriocline laxa	–	5.30
		Mean	6.54	–	4.14	5.74

legumes in AEZs 1 and 2. In AEZ 3, however, the %N from N_2-fixation was higher for forage legumes than for green manure and grain legumes. Bean showed the least dependence on N_2-fixation for its N requirements in AEZs 1 and 2, while in AEZ 3, soyabean+P showed the least dependence on N_2-fixation for its N requirements.

Biomass production and N_2-fixation by the green manure and forage legumes

Biomass production, shoot N yield and biological N_2-fixation by the green manure and forage legume species were significantly ($P<0.01$) influenced by AEZ and soil fertility (Table 5). However, performance was generally better in AEZ 2 than in AEZ 1 due to greater rainfall received in AEZ 2. Mean biomass production was highest (6.86 Mg ha^{-1}) in AEZ 2 and lowest (3.28 Mg ha^{-1}) in AEZ 3. Similar to biomass production, shoot N accumulation by the legumes was best (177 kg N ha^{-1}) in AEZ 2 and worst (85 kg N ha^{-1}) in AEZ 3.

N_2-fixation estimates reported are based on the above ground legume biomass. While estimates of total crop N fixed would provide a better assessment of the contributions of legumes, such an assessment is made difficult by the complications associated with the recovery of complete root systems. The capacity of the legumes to fix atmospheric N_2 differed significantly ($P<0.01$) with AEZ, soil fertility and legume species. The green manure legumes generally fixed greater quantities of N_2 than the forage legumes. For example, in AEZ 2, where the best N_2-fixation performance was recorded, mean N_2-fixation by the forage legumes (estimated using broad-leaved weeds as reference plants) was 35–37% of that of the green manure legumes, while in AEZ 3, where least N_2-fixation was recorded, mean N_2-fixation of forage legumes estimated by broad-leaved weeds was 12–21% of that of green manure species. N_2-fixation reduced by 12% from high fertility field to medium fertility field, and by 22% from medium fertility field to low fertility field. Velvet bean and crotalaria had greater N_2-fixation than jackbean, among the green manure legumes. Crotalaria had the best N_2-fixation in AEZ 1, fixing 154–232 kg N ha^{-1}, while in AEZ 2, velvet bean had the best performance, fixing 163–319 kg N ha^{-1}. N_2-fixation was also best with crotalaria in AEZ 3 (56–95 kg N ha^{-1}). The amount of N contained in legume root biomass accounts for about 30% of the total plant N (Khan et al. 2002; McNiel et al. 1997). When this contribution by the below ground biomass is taken into account, the N_2-fixation estimates for crotalaria can be considered to be about 200–302 kg N ha^{-1} in AEZ 1, and that for velvet bean in AEZ 2 about 212–415. Similarly, the contribution for crotalaria in AEZ 3 can be considered to be about 73–124 kg N ha^{-1}. Among the forage legumes, N_2-fixation was greater with desmodium and stylo than with siratro.

The use of maize as reference crop consistently underestimated N_2-fixation compared with broad-leaved weeds. Averaged over species and soil fertility, mean N_2-fixation estimated by broad-leaved weeds, ranged from 139 kg N ha^{-1} in AEZ 2 to 51 kg N ha^{-1} in AEZ 3, compared with mean N_2-fixation estimated using maize, which ranged from 94 kg N ha^{-1} in AEZ 2 to 40 kg N ha^{-1} in

Table 4 *B* values, shoot ^{15}N natural abundance and estimates of N derived from atmospheric N_2–fixation for grain, green manure and forage legumes in three agro-ecological zones in Western Kenya, short rains 2003 season

Species	*B*-value	AEZ 1				AEZ 2				AEZ 3			
		Shoot δ^{15}N (‰)	%N from N_2-fixation			Shoot δ^{15}N (‰)	%N from N_2-fixation			Shoot δ^{15}N (‰)	%N from N_2-fixation		
			[f]Maize	[g]Weeds	[h]Mean		[f]Maize	[g]Weeds	[h]Mean		[f]Maize	[g]Weeds	[h]Mean
Grain legumes													
Bean	–1.00[a]	2.22	23	35–59	53	2.44	25	48–61	56	3.24	18	12–43	37
Groundnut	–1.40[b]	0.89	50	57–72	69	1.68	39	65–73	70	1.58	46	43–62	58
Soyabean (-P)	–2.00[ac]	0.15	59	64–76	73	1.36	40	70–77	74	3.41	12	7–36	30
Soyabean (+P)	–2.00[ac]	0.37	54	60–73	70	1.51	37	67–74	71	3.74	7	1–32	26
Lima	–1.00[d]	1.35	44	53–70	66	2.46	25	62–71	68	2.47	32	28–53	49
Lablab	–1.36[c]	0.82	52	59–73	70	1.75	37	66–75	72	1.83	42	38–59	55
Mean	–	0.97	47	55–71	67	1.87	34	63–72	69	2.71	26	22–48	43
Green manure legumes													
Velvet bean	–2.09 [b]	–0.70	74	77–84	83	0.12	61	81–85	83	0.55	58	55–69	66
Jackbean	–1.00[d]	1.41	43	52–69	65	–0.31	85	61–71	67	3.37	15	9–41	35
Crotalaria	–1.31[e]	–0.46	81	84–90	88	1.41	45	87–90	89	0.49	67	65–77	74
Mean		0.48	66	71–81	77	0.55	64	76–82	78	1.93	47	43–62	55
Forage legumes													
Desmodium	–1.55[c]	1.46	37	46–64	60	1.84	34	55–66	62	1.54	46	42–61	58
Siratro	–1.99[c]	1.63	30	39–59	54	1.53	37	49–61	56	1.25	47	44–62	58
Stylo	–0.74[c]	1.23	50	58–74	70	1.42	50	66–75	72	1.45	55	52–69	66
Mean		1.55	39	48–66	61	1.69	41	57–67	63	1.40	49	46–64	61
Mean	–	1.01	48	57–72	67	1.51	42	65–73	69	2.17	36	34–56	50
$SED_{(species)}$						0.43	9	–	9				
$SED_{(AEZ)}$						0.15	3	–	3				
$SED_{(AEZ \times species)}$						0.19	4	–	4				

[a] Value from Peoples, 2005 (personal communication)

[b] Okito et al. (2004)

[c] Boddey et al. (2000)

[d] Assumed

[e] Gathumbi et al. (2002)

[f] Percent N derived from atmospheric fixation estimated using maize as reference plant

[g] Percent N derived from atmospheric fixation estimated using several broad-leaved weed plants presented in Table 3 as reference plants

[h] Mean percent N derived from atmospheric fixation calculated using the mean Shoot δ^{15}N values of the broad-leaved weed reference plants

Table 5 Shoot biomass, N yield, and N_2-fixation by green manure and forage legume species grown in fields of different soil fertility status in three agro-ecological zones in Western Kenya, short rains, 2003 season

Species	AEZ 1					AEZ 2					AEZ 3				
	[a]Shoot biomass (Mg ha^{-1})	Shoot N yield (kg ha^{-1})	N_2-fixed (kg N ha^{-1})			[a]Shoot biomass (Mg ha^{-1})	Shoot N yield (kg ha^{-1})	N_2-fixed (kg N ha^{-1})			[a]Shoot biomass (Mg ha^{-1})	Shoot N yield (kg ha^{-1})	N_2-fixed (kg N ha^{-1})		
			Maize	weeds	[b]Mean			Maize	Weeds	[b]Mean			Maize	Weeds	[b]Mean
High fertility field															
Velvet bean	6.68	141	104	109–118	117	14.86	384	234	311–326	319	2.87	74	43	41–51	49
Jackbean	4.46	102	44	53–70	66	7.03	153	130	93–109	103	4.93	128	19	12–52	45
Crotalaria	8.01	264	214	222–238	232	9.48	311	140	140–271	277	3.64	76	51	49–59	56
Mean: GM legumes	*6.38*	*169*	*121*	*128–142*	*138*	*10.46*	*283*	*168*	*181–235*	*233*	*3.81*	*93*	*38*	*34–54*	*50*
Desmodium	5.76	153	57	70–98	92	5.92	157	53	86–104	97	3.07	81	37	34–49	47
Siratro	4.74	118	35	46–70	64	5.05	125	46	61–76	70	2.79	69	32	30–43	40
Stylo	4.94	126	63	73–93	88	5.18	133	67	88–100	96	3.17	81	45	42–56	53
Mean: forage legumes	*5.15*	*132*	*52*	*63–87*	*81*	*5.38*	*138*	*55*	*78–93*	*88*	*3.01*	*77*	*38*	*35–49*	*47*
Medium fertility field															
Velvet bean	7.23	146	108	112–123	121	13.96	334	204	271–284	277	3.18	67	39	37–46	44
Jackbean	2.57	70	30	36–48	46	4.18	100	85	61–71	67	3.24	82	12	7–34	29
Crotalaria	5.55	187	151	157–168	165	10.42	302	136	263–272	269	3.59	128	86	83–99	95
Mean: GM legumes	*5.12*	*134*	*96*	*102–113*	*111*	*9.52*	*245*	*142*	*198–209*	*204*	*3.34*	*92*	*46*	*44–60*	*56*
Desmodium	4.54	120	44	55–77	72	4.10	105	36	58–69	65	3.10	82	38	34–50	48
Siratro	4.34	108	32	42–64	58	4.49	112	41	55–68	63	2.72	67	31	29–42	39
Stylo	4.66	119	60	69–88	83	4.65	119	60	79–89	86	3.07	79	43	41–55	52
Mean: forage legumes	*4.51*	*116*	*45*	*55–76*	*71*	*4.41*	*112*	*46*	*64–75*	*71*	*2.96*	*76*	*37*	*35–49*	*46*
Low fertility field															
Velvet bean	8.42	178	132	137–150	148	8.37	196	120	159–167	163	3.85	73	42	40–50	48
Jackbean	5.82	120	52	62–83	78	7.39	155	132	95–110	104	4.10	113	17	10–46	40
Crotalaria	6.05	175	142	147–158	154	7.84	238	107	207–214	212	3.20	109	73	71–84	81
Mean: GM legumes	*6.76*	*158*	*109*	*115–130*	*127*	*7.87*	*196*	*120*	*154–164*	*160*	*3.72*	*98*	*44*	*40–60*	*56*
Desmodium	5.00	133	49	61–85	80	4.07	104	35	57–69	64	2.86	76	35	32–46	44
Siratro	4.35	108	32	42–64	58	3.03	75	28	37–46	42	3.14	78	37	34–48	45
Stylo	4.32	112	56	65–83	78	3.37	86	43	57–65	62	2.57	66	36	34–46	44
Mean forage legumes	*4.56*	*118*	*46*	*56–77*	*72*	*3.49*	*88*	*35*	*50–60*	*56*	*2.86*	*73*	*36*	*33–47*	*44*
Mean	5.41	138	78	87–104	100	6.86	177	94	121–139	135	3.28	85	40	37–51	50
**$SED_{(Legumes)}$						0.67	20	–	–	21					
**$SED_{(Fields)}$						0.28	9	–	–	9					
**$SED_{(AEZ)}$						0.15	5	–	–	5					

SED = Standard error of difference between means, ** $P<0.01$, GM = green manure

[a] The above ground biomass

[b] Mean N_2-fixation computed using broad-leaved weeds as reference plants

AEZ 3. Factoring in the contributions of the below ground biomass would increase these N_2-fixation estimates by about 30%, as discussed above. Averaged over all species and soil fertility, N_2-fixation estimated by maize and that estimated by broad-leaved weeds differed by 20–30% (Table 5). In AEZ 1, mean N_2-fixation estimated by maize was 78% of that estimated by broad-leaved weeds, while in AEZs 2 and 3, mean N_2-fixation estimated by maize was 70% and 80% of that estimated by broad-leaved weeds, respectively.

N_2-fixation, N export and net N contributions of the grain legumes

The grain legumes shoot N yield, grain N accumulation and net N inputs from N_2-fixation significantly ($P<0.01$) decreased with rainfall and soil fertility status (Table 6). Averaged over species and soil fertility, mean shoot N accumulation was greatest in AEZ 2 (135 kg N ha^{-1}) and least in AEZ 3 (40 kg N ha^{-1}). In contrast, mean N_2-fixation estimated by broad-leaved weeds was greatest in AEZ 1 (76 kg N ha^{-1}) and least in AEZ 3 (20 kg N ha^{-1}).

Significant ($P<0.01$) differences were observed between the grain legumes in shoot N accumulation, N_2-fixation and net N contributions to soil N fertility. Generally, shoot N accumulation, N_2-fixation and net N inputs were best with lablab and groundnut and worst with bean in AEZ 1. In AEZ 2, lablab and soyabean+P generally had the best shoot N accumulation and N_2-fixation. However, net N contribution to soil N fertility was negative for all the legumes in the high fertility field, except lablab, which had +42 kg N ha^{-1} contribution to soil N fertility. Generally, the grain legumes had small positive or negative net N contributions to soil N fertility in AEZ 2. In AEZ 3, most of the grain legumes had negative net N inputs, which indicated mining of soil N. When the N contributed by the below ground legume biomass would be taken into account all legumes would give positive net N inputs. Soil N mining was relatively greater with soyabean+P (–27 kg N ha^{-1}) and bean (–25 kg N ha^{-1}).

Discussion

N_2-fixation by the legumes in response to AEZ and soil fertility

The ^{15}N natural abundance signatures detected in the legume shoots varied with AEZ (Table 4). The enrichment of the grain, green manure and forage legume shoots decreased with increasing rainfall, demonstrating greater N_2-fixation potential by the legumes in AEZ 2 than in AEZs 1 and 3. Similarly, legume biomass production also varied with rainfall (Table 5). The higher rainfall received in AEZ 2 greatly enhanced legume growth, with biomass production ranging from 3.0 Mg ha^{-1} to 14.8 Mg ha^{-1}, which was much greater than the range from 2.5 Mg ha^{-1} to 8.4 Mg ha^{-1} for AEZ 1. In AEZ 3, where only about half the normal rainfall was recorded during the experimentation period, the species showed considerable reduction in performance. Biomass production ranged from 2.5 Mg ha^{-1} to 4.9 Mg ha^{-1}. Consequently, N_2-fixation in AEZ 2 was generally greater than that in AEZs 1 and 2. The study was carried out for only one season and seasonal fluctuations can affect legume performance. However, the trends observed confirmed that rainfall is an important factor in legume productivity and suggest that the impact of the legumes on smallholder productivity, especially of the soil improving green manure species, is likely to diminish with rainfall.

The N_2-fixation by the green manure, forage and grain legume species generally decreased with soil fertility status (Tables 5 and 6). Compared with the high fertility field, N_2-fixation by the green manure and forage legume species reduced by up to 36% in the low fertility field, while that of grain legume species reduced by up to 44% in the low fertility field, compared with the high fertility field. This significant reduction in N_2-fixation with soil fertility suggests that the N benefit of legumes is likely to be small in smallholder systems characterized by poor soil fertility.

N_2-fixation performance of the species showed interaction with AEZ and soil fertility. For the green manure legumes, crotalaria was the best species in N_2-fixation across the soil fertility

Table 6 Legume shoot N yield, N_2-fixation, N harvest index, N export, and net N contribution to the N fertility of soils (considering only above-ground inputs) under variable soil fertility and agro-ecological conditions in Western Kenya, short rains, 2003 season

Species	AEZ 1					AEZ 2					AEZ 3				
	[a]Shoot N yield (kg ha^{-1})	[b]Fixed N (kg ha^{-1})	Grain N (kg ha^{-1})	N harvest index (%)	Net N input (kg ha^{-1})	[a]Shoot N yield (kg ha^{-1})	[b]N fixed (kg ha^{-1})	Grain N (kg ha^{-1})	N harvest index (%)	Net N input (kg ha^{-1})	[a]Shoot N yield (kg ha^{-1})	[b]N fixed (kg ha^{-1})	Grain N (kg ha^{-1})	N harvest index (%)	Net N input (kg ha^{-1})
High fertility field															
Bean	58	31	39	67	–8	45	14	39	87	–25	21	8	13	62	–5
Groundnut	179	124	35	20	+89	140	43	50	36	–7	70	41	12	17	+29
Soyabean (–P)	102	74	53	52	+21	120	43	64	53	–21	21	6	14	67	–8
Soyabean (+P)	160	112	73	46	+39	158	46	73	46	–27	39	10	28	72	–18
Lima	107	71	29	27	+42	82	10	23	28	–13	26	12	11	42	+1
Lablab	246	172	41	17	+131	486	86	44	9	+42	76	42	–	–	+42
Mean	*142*	*97*	*45*	*38*	*52*	*172*	*40*	*49*	*43*	*–9*	*42*	*20*	*16*	*52*	*+7*
Medium fertility field															
Bean	34	18	19	56	–1	46	18	19	41	–1	14	5	10	71	–5
Groundnut	149	103	21	14	+82	113	50	58	51	–8	69	40	12	17	+28
Soyabean (–P)	62	45	26	42	+19	112	59	61	54	–2	24	7	15	63	–8
Soyabean (+P)	82	57	40	49	+17	145	79	64	44	+15	25	7	17	68	–10
Lima	79	52	17	22	+35	89	43	16	18	+27	28	13	15	54	–2
Lablab	201	141	32	16	+109	267	165	59	22	+106	81	45	-	-	+45
Mean	*101*	*69*	*26*	*33*	*44*	*129*	*69*	*46*	*38*	*23*	*40*	*20*	*12*	*55*	*+8*
Low fertility field															
Bean	23	12	10	43	+2	29	9	10	34	–1	18	7	9	50	–2
Groundnut	115	79	20	17	+59	123	50	33	27	+17	63	37	13	21	24
Soyabean (–P)	63	46	29	46	+17	106	58	30	28	+28	10	3	5	50	–2
Soyabean (+P)	99	69	41	41	+28	125	55	41	33	+14	17	4	13	76	–9
Lima	70	46	18	26	+28	38	32	10	26	+22	27	12	14	52	–2
Lablab	163	114	28	17	+86	210	94	26	12	+68	98	54	-	-	+54
Mean	*89*	*61*	*24*	*32*	*37*	*105*	*50*	*25*	*27*	*25*	*39*	*20*	*9*	*50*	*+11*
Mean	111	76	32	34	44	135	53	40	36	13	40	20	13	52	8
**SED$_{(legumes)}$						20	18	5							
**SED$_{(fields)}$						9	9	2							
SED$_{(AEZ)}$						5	5	1							

[a] The above ground biomass

[b] Mean N_2-fixation computed using broad-leaved weeds as reference plants

** $P<0.01$

gradient in AEZ 1 (Table 5). In AEZ 2, however, velvet bean was the best in the high and medium fertility fields, while crotalaria was the best in the low fertility field. In AEZ 3, similar to AEZ 1, crotalaria had the best N_2-fixation across the fertility gradient. For forage legumes (Table 5), desmodium was best in the high and low fertility fields in AEZs 1 and 2, while stylo was best in the medium fertility fields in the same zones. In AEZ 3, however, stylo was the best species in the high and the medium fertility fields, while siratro was the best in the low fertility field. For the grain legumes (Table 6), N_2-fixation was best with lablab and groundnut across the fertility gradient in AEZs 1 and 3, while in AEZ 2, lablab and soyabean were the best species in N_2-fixation across the fertility gradient. These observations have significant implications for species selection for the various biophysical niches.

There were strong linear relationships between legume shoot biomass and the computed N_2-fixation in all the AEZs (Fig. 2), suggesting that N_2-fixation was highly dependent on the capacities of the legumes for growth and biomass accumulation in the different AEZs. There were differences in the N_2-fixation efficiencies in the three AEZs. The species fixed about 26 kg N per Mg of legume biomass in AEZs 1 and 2, and 14 kg per Mg of biomass in AEZ 3. These figures are in reasonable agreement with those obtained in the high and low rainfall zones in Bukoba in northern Tanzania (Baijukya 2004), and those obtained in different farming systems in eastern Australia (Peoples et al. 2001). Biomass production below about 2 Mg ha^{-1} resulted in virtually no N_2-fixation.

Net N contributions to soil N fertility through N_2-fixation

Net N inputs by the grain legume species varied with AEZ and soil fertility (Table 6), indicating differential contributions by the legumes to soil N fertility maintenance in the AEZs. Mean net N input generally decreased with rainfall, ranging from 44 kg N ha^{-1} in AEZ1, to 8 kg N ha^{-1} in AEZ 3. This suggests that the capacity of the grain legumes to improve productivity could be fairly limited in the relatively lower rainfall AEZ 3, especially during a season with sub-normal precipitation. The performance of the individual species varied with AEZ. In AEZs 1 and 3, lablab and groundnut had consistently the greatest net N inputs across the soil fertility gradient, while in AEZ 2, lablab and groundnut had the greatest inputs in the high fertility field, lablab and Lima in the medium fertility field, and lablab and soyabean+P the greatest inputs in the low fertility field. In AEZ 3, only lablab and groundnut had positive net N inputs (Table 6). The net N inputs of the rest of the grain legumes were negative, with soyabean+P showing relatively greater soil N mining potential than the rest of the grain legumes. These results suggest that lablab and groundnut have the potential to make substantial contributions to the improvement of soil N fertility, besides contributing to the household food needs.

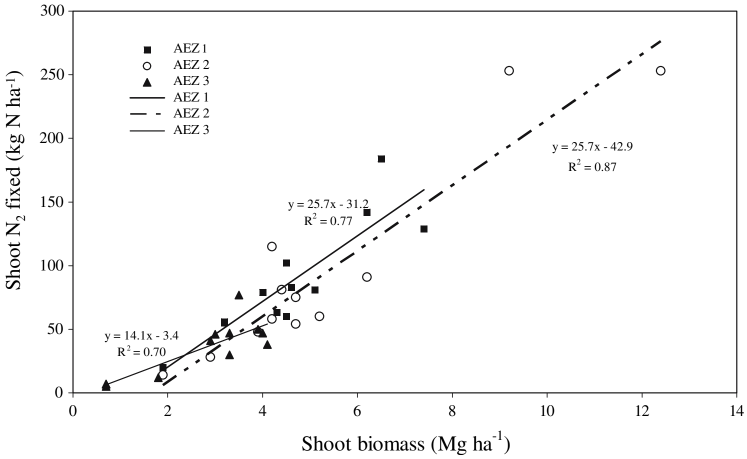

Fig. 2 Relationship between shoot biomass production and shoot N fixed by the legume species in the three agro-ecological zones in Western Kenya, short rains 2003 season

The relatively large net N contribution by lablab resulted from its high N_2-fixation capacity but relatively low N export (Table 6). However, lablab is a poor grain producer in certain environments, e.g. AEZ 3 (Table 2), hence farmers would be better off with groundnut, which had a lower net N input in AEZ 3 (24–29 kg N ha^{-1}) compared with lablab (42–54 kg N ha^{-1}) (Table 6) but a relatively much greater grain yield (Table 2). A general assessment of such trade-offs was done for the grain legumes (Fig. 3). Legume grain yield and net N inputs to soil N fertility showed strong linear relationships in all AEZs. Grain yield was negatively correlated with net N input, indicating that the more grain a legume produces the less its contribution to soil N fertility. The relationships also indicated differences between the AEZs in the trade-offs between grain yield and N inputs for soil N fertility improvement. In AEZ 1, 128 kg N was traded-off for every 1 Mg of grain harvested, while in AEZ 2, 98 kg N was traded-off for every Mg of grain harvested. In AEZ 3, 143 kg N was traded-off for every Mg of grain harvested. In AEZ 1, net N input become negative at grain yield of 1.0 Mg ha^{-1}, while in AEZs 2 and 3, net N inputs were zero at grain yields of 0.90 Mg ha^{-1}, and 0.40 Mg ha^{-1}, respectively (Fig. 3). This shows that in AEZs 1 and 2, grain yields of up to 1 Mg ha^{-1} can be produced without much concern about soil N mining, while in AEZ3, yields of 0.5 Mg ha^{-1} are likely to result in soil N mining of about 20 kg ha^{-1}. Since grain legumes showed grain yield potential of up to 1.40 Mg ha^{-1} in AEZs 1 and 2 (Table 3), potential for soil N mining is high and a critical consideration of these trade-offs is essential in deriving suitable legume options for smallholder systems with competing objectives of food production and soil fertility management.

The ^{15}N natural abundance methodology and on-farm N_2-fixation assessment

The flexibility of the ^{15}N natural abundance method (since no addition of ^{15}N-enriched fertilizer is required) makes it ideal for N_2-fixation assessments on-farm. However, the reliability of the method depends on the choice of appropriate reference species (Peoples et al. 2002). The $\delta^{15}N$ signatures of maize and the broad-leaved weeds used as reference species differed considerably. Except for one or two cases, the $\delta^{15}N$ values for broad-leaved weeds plants were much greater than those for maize, and were closer to the $\delta^{15}N$ signatures of the total soil N (Table 3). Due to this, large variations were obtained in the estimates of %N derived from N_2-fixation. The %N derived from N_2-fixation values computed using maize as reference plant were consistently smaller than those computed using broad-leaved weeds (Table 4), indicating that the use of maize as a reference crop underestimated N_2-fixation by the legumes. The ^{15}N signatures detected in the soil varied slightly with field and AEZ. However, the values were between 5.93‰ and 9.19‰, which was within the range recommended for the use of the ^{15}N natural abundance method for N_2-fixation (Peoples et al. 1989).

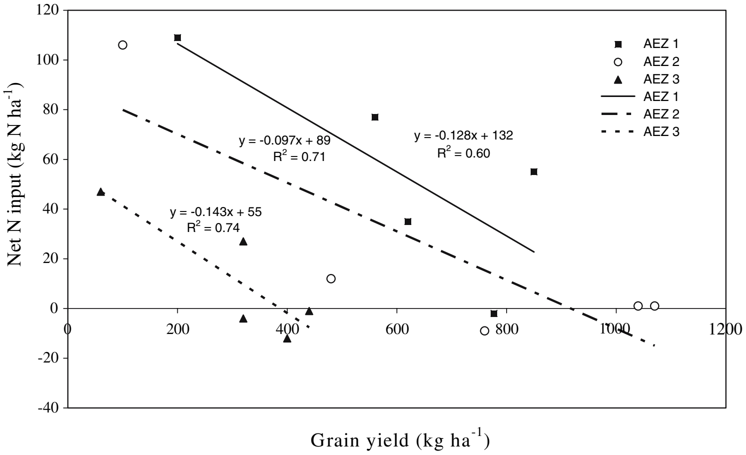

Fig. 3 Relationship showing the trade-off between legume grain yield and net N contributions to soil N fertility considering only above-ground N contributions in the three agro-ecological zones in Western Kenya, short rains 2003 season. If the below-ground contributions would be considered the net inputs will be greater

Conclusions

The productivity of the legumes varied greatly with agro-ecological zones and soil fertility, suggesting that different legumes are needed for the improvement of productivity of smallholder farms in different agro-ecological zones and soil fertility conditions in Western Kenya. All the legume species (green manure, forage and grain legumes) studied were capable of fixing atmospheric N_2 on-farm without artificial inoculation. Mean N_2-fixation by the legume species differed greatly in the three agro-ecological zones, and ranged from 14–253 kg ha^{-1} in AEZ 2, to 5–77 kg N ha^{-1} in AEZ 3. Lablab and groundnut showed the greatest resilience in N_2-fixation and net N input across the agro-ecological and soil fertility gradients. The results of the study indicate that maize is less appropriate as a non-N_2-fixing reference species than the tested broad-leaved weeds in N_2-fixation assessment using the ^{15}N natural abundance method. The study demonstrates that the green manure, forage and grain legumes studied have the potential for making significant contributions to the N economy and productivity of the smallholder systems through atmospheric N_2-fixation. However, the potential of species vary in the different biophysical niches and careful selection is therefore needed to optimize productivity.

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