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ORIGINAL ARTICLE

Impacts of heterogeneity in soil fertility on legume-finger millet productivity, farmers' targeting and economic benefits

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Abstract Targeting of integrated management practices for smallholder agriculture in sub-Saharan Africa is necessary due to the great heterogeneity in soil fertility. Experiments were conducted to evaluate the impacts of landscape position and field type on the biomass yield, N accumulation and N_2-fixation by six legumes (cowpea, green gram, groundnut, mucuna, pigeonpea and soyabean) established with and without P during the short rain season of 2005. Residual effects of the legumes on the productivity of finger millet were assessed for two subsequent seasons in 2006 in two villages in Pallisa district, eastern Uganda. Legume biomass and N accumulation differed significantly ($P < 0.001$) between villages, landscape position, field type and P application rate. Mucuna accumulated the most biomass (4.8–10.9 Mg ha^{-1}) and groundnut the least (1.0–3.4 Mg ha^{-1}) on both good and poor fields in the upper and middle landscape positions. N accumulation and amounts of N_2-fixed by the legumes followed a similar trend as biomass, and was increased significantly by application of P. Grain yields of finger millet were significantly ($P < 0.001$) higher in the first season after incorporation of legume biomass than in the second season after incorporation. Finger millet also produced significantly more grain in good fields (0.62–2.15 Mg ha^{-1}) compared with poor fields (0.29–1.49 Mg ha^{-1}) across the two villages. Participatory evaluation of options showed that farmers preferred growing groundnut and were not interested in growing pigeonpea and mucuna. They preferentially targeted grain legumes to good fields except for mucuna and pigeonpea which they said they would grow only in poor fields. Benefit-cost ratios indicated that legume-millet rotations without P application were only profitable on good fields in both villages. We suggest that green gram, cowpea and soyabean without P can be targeted to good fields on both upper and middle landscape positions in both villages. All legumes grown with P fertiliser on poor fields provided larger benefits than continuous cropping of millet.

Keywords Landscape position · Field type · Legume biomass productivity · N_2-fixation ·

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P application · Farmers acceptance · Benefit cost ratios · Smallholder farms · Sub-Saharan Africa

Introduction

Heterogeneity in soil fertility is a common feature of smallholder farming systems in sub-Saharan Africa (SSA) that results from the interactions between inherent soil characteristics, and historical and current human management (Tittonell et al. 2005; Zingore et al. 2007a). Heterogeneity in soil fertility has largely been ignored in development of soil fertility management recommendations yet there is evidence that it strongly affects agronomic performance of soil management technologies (Vanlauwe et al. 2006; Tittonell et al. 2007a). In 2006, African heads of state signed the Abuja declaration to promote the use of fertilisers and increase the amounts used from 8 to 50 kg ha^{-1} throughout Africa. But we lack knowledge on how to use this extra fertiliser efficiently. Blanket fertiliser recommendations at the scale of the agroecological zone are of little value because they do not take into account the changes in soil fertility that have occurred due to management. Management is mainly at the farm scale and has resulted in large variability within farms. Recent research has shown that different fields across very short distances within African farming systems may or may not be responsive to manures and fertilisers (Tittonell 2007; Zingore et al. 2008; Vanlauwe et al. 2009). To avoid inefficient use of the resources the need for site-specific management has been emphasised (Deckers 2002; Zingore et al. 2007b). Site-specific nutrient management can yield substantial efficiency increases in use of nutrient inputs (Haefele and Wopereis 2005). Thus soil fertility improvement technologies should be evaluated on different landscapes (soilscapes) or fields (fieldscapes) within farms (Deckers 2002) to establish suitable socio-ecological niches for targeting within farming systems (Ojiem et al. 2006). This approach will increase efficiency in resource use, guide the design of management strategies to maintain or replenish soil fertility and enhance sustainable use of soil improvement technologies proven agronomically effective, socially acceptable and economically viable: the key principles of integrated soil fertility management (Vanlauwe et al. 2002, 2009).

In most smallholder farming systems in SSA, N and P are the major nutrients limiting crop productivity (Sanchez et al. 1997). Mineral fertilisers could be used to address these limitations but their scarcity, high costs and poor profitability have curtailed their widespread use (Morris et al. 2007). Legumes can provide substantial amounts of N through N_2-fixation, and contribute N to subsequent crops in rotation in low input farming systems (Giller 2001). They also can improve other soil chemical and biological properties creating better growth conditions for the subsequent crop (Yusuf et al. 2009). Many studies report cereal yield increases after legumes in smallholder African farming systems (e.g. Osunde et al. 2003; Ncube 2007; Ojiem et al. 2007). To realise such benefits, however, constraints to legume growth such as soil acidity and poor phosphorus availability have to be ameliorated through application of lime and inorganic P fertilisers respectively (Vanlauwe and Giller 2006).

Legume effectiveness to improve crop productivity in smallholder farming systems has largely been assessed on large spatial scales, covering agro-ecological units (Baijukya 2004; Kaizzi et al. 2006; Ojiem et al. 2007). Comprehensive evaluations of the impacts of between and within-farm variability on the contribution of legumes to the productivity of subsequent cereal crops in rotation are scarce (Ojiem et al. 2007). Our focus was therefore to identify the most appropriate niches for different legumes within the Teso farming system of eastern Uganda. We explored potential landscape positions and field types to target production of legume species with or without P application, and their residual effects on production of finger millet (*Eleusine coracana* [L.] Gaertn), the major staple cereal crop. The Teso farming system is characterised by poor crop productivity due to little nutrient input use, with N and P being the major limiting nutrients (Wortmann and Eledu 1999). The specific objectives of the study were: (1) to evaluate biomass production, nitrogen fixation and N accumulation by the legume species; (2) to estimate grain yield response and N use efficiency by finger millet crop following incorporation of legume biomass; (3) to assess farmers' preference and targeting of legumes to different types of fields; and (4) to determine economic benefits of legume–finger millet rotations. Experiments were established in two villages on upper and middle landscape positions and on fields classified by farmers as ‘good’ and ‘poor’ in soil fertility to encompass the range of soil fertility encountered in the study area.

Materials and methods

Study sites

The study was conducted in Chelekura A village (1°24′ N; 33°30′ E) and Onamudian (1°11′ N; 33°43′ E) village in Pallisa district (1°13′ N; 31°42′ E), eastern Uganda. These sites represented the low input crop-livestock Teso farming system, supporting 5% of Uganda’s population. Farmers had already been exposed to alternative soil fertility management practices through an integrated nutrient management project using the farmer field school approach (INMASP). Finger millet is the main staple grain grown in the Teso farming system and the second most important cereal after maize in Uganda. It is a food security crop and major source of income for smallholders through its use for local brewing (NARO/SAARI 1991).

The study area is situated between 1000 and 1100 masl and is characterised by gently sloping toposequences on broad, rounded and flat-topped uplands. Mean annual rainfall (950–1,100 mm) is distributed in a bimodal pattern, with the long rains from March to June (550–600 mm) and the short rains from September to October/November (400–500 mm), and a marked dry period from December to February. During the experimentation period, cumulative daily total rainfall received in the short rains of 2005 in the study villages (500 mm) was poorly distributed, but above normal in both seasons in 2006 (ca. 1,600 mm annual total) (Fig. 1). Heterogeneity is large within and between farms in the study sites and the soils on the raised lands and valley bottoms are generally classified as Ferralsols and Fluvisols, respectively (Ebanyat 2009).

Field selection, soil sampling and preparation

Farmers’ fields across the villages located on the upper landscape positions (slopes 5–8%) and middle landscape positions (slopes 3–5%) were classified by farmers as of good or poor fertility. The study area is described in detail by Ebanyat (2009). Fields were selected for the experiments based on farmers’ long-term knowledge of fertility status, and only fields where finger millet had been grown in the previous season were used. Field selection was restricted to

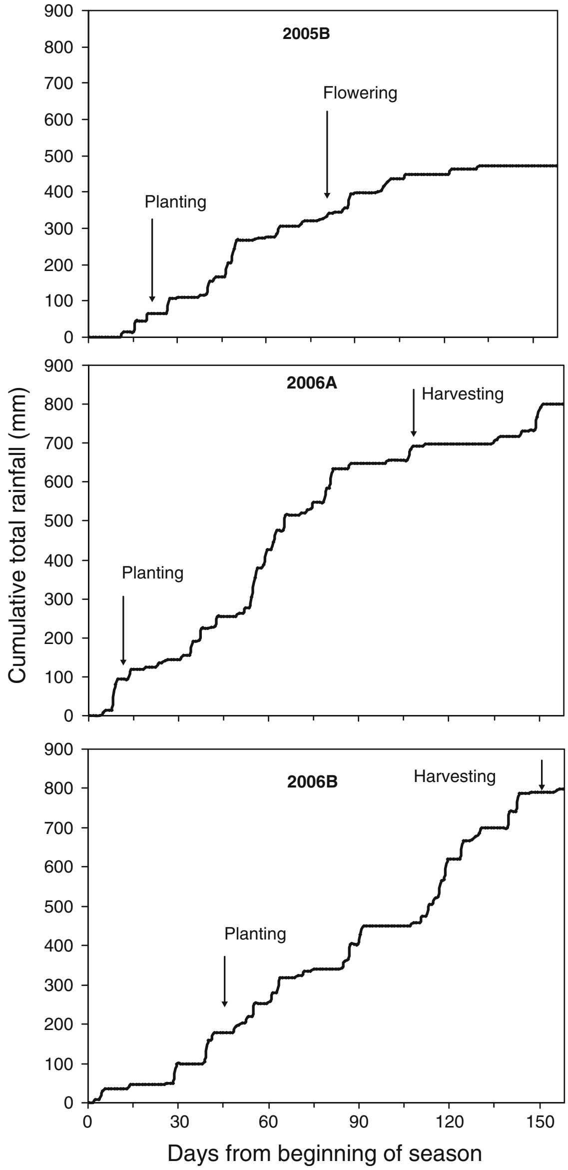

Fig. 1 Cumulative total rainfall during the experimentation seasons in the study area. Legumes were grown in the short rains (2005B) of 2005 followed by finger millet in the long (2006A) and short rains (2006B). Note that in 2005B no grains were harvested due to drought. Day 0 is day 1 of August (seasons 2005B and 2006B) and March (season 2006A)

these landscape positions as legumes are not grown in the lower landscape positions that are prone to flooding. In total, 56 fields were selected (7 each of good and poor fertility in the upper and middle landscape positions in each village). Soil samples were randomly taken in each field at a depth of 0–20 cm from five spots, to obtain composite samples of approximately 0.5 kg. The composite samples were air-dried, ground and sieved through 2 mm.

Establishment of researcher-managed experiments

Field experiments were conducted on farmers' fields for three seasons; short rains of 2005 (2005B), long rains of 2006 (2006A) and short rains of 2006 (2006B). The experiments were managed by researchers to ensure uniformity of management as the principal aim was to examine effects of heterogeneity in soil fertility on treatment response. Selected fields were ox-ploughed twice and plots of 5 × 5 m demarcated prior to establishment of the legume experiments in 2005B. Six legume species were planted using recommended spacing: soyabean (*Glycine max* [L.] Merr.), variety TGX 1740-2F or SB 19 (0.75 × 0.10 m); cowpea (*Vigna unguiculata* [L.] Walp.), variety SEKO 1 (0.6 × 0.15 m); green gram (*Vigna radiata* [L.] R. Wilczek), local variety (0.6 × 0.15 m); groundnut (*Arachis hypogaea* L.), variety SERENUT 3R (0.45 × 0.10 m); pigeonpea (*Cajanas cajan* [L.] Millsp.), variety SEPI 1(0.75 × 0.30 m); and mucuna (*Mucuna pruriens* [L.] DC.) (0.75 × 0.6 m). All legumes were improved varieties, except green gram. A weedy fallow and the finger millet variety U15 or SEREMI 2 (0.45 × 0.05 m) treatment were also included. The legumes were planted between 22nd and 27th August 2005 (season 2005B). Each legume species was established with and without basal application of 30 kg P ha^{-1} supplied as single super phosphate (SSP) while the continuous finger millet and weedy fallow treatments received no basal fertiliser. This gave 14 treatments in total. Legumes were maintained at 2 plants per hill except for soyabean and groundnut (1 plant per hill). Millet was thinned to 0.05 m within rows at first weeding i.e. 14 days after planting (DAP). Further weed control was by hand hoeing at 28 DAP. In the 2005B season, the legumes and finger millet did not produce grain due to drought at pod initiation and grain filling (Fig. 1). Total rainfall received during the legume growth was 410 mm. After legumes, the same finger millet variety (SEREMI 2) was planted between 15th and 22nd March 2006 (season 2006A) and between 15th and 19th September 2006 (season 2006B) on all the plots, thus the overall crop sequence was legume-millet–millet. Weeding was done twice in each season. Total rainfall received during the growing period of millet was 580 mm (2006A) and 615 mm (2006B).

Plant sampling and preparation

At 50% flowering of the legume species, biomass samples were obtained from two locations along three middle rows using 1 m^2 quadrats for determination of dry matter accumulation, N_2-fixation and N uptake. Millet and weedy fallow treatments were also sampled at 120 DAP and biomass determined. Millet samples were obtained from within the three middle rows of each plot, and randomly within plot centres of the weedy fallow treatments. At maturity, the millet heads were harvested using small knives, and the straw cut at 0.05 m above the soil surface. All plant samples were oven dried at 65°C for 72 h and dry weights obtained. Millet heads were threshed in special cloth bags to minimise losses of the husks and the respective grain weights obtained. The grain and biomass samples were ground to pass through a 1 mm sieve prior to laboratory analysis.

Soil and plant analysis

Soil and plant samples were analysed at the World Agroforestry Centre (ICRAF), Nairobi, Kenya. Diffuse reflectance spectra were recorded for the soil and plant samples using a Field Spec FR Spectroradiometer (Analytical Spectral Devices Inc, Boulder CO) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1 nm. The optical set up for soil analysis procedures are described in detail by Shepherd and Walsh (2002) and for plant analysis by Shepherd et al. (2003).

Soil chemical properties (pH, Olsen P, Exchangeable Ca, Mg and K, CEC) and soil particle composition (sand, silt and clay) were determined using standard methods for tropical soils (Anderson and Ingram 1993) while total organic C and nitrogen were determined using a ThermoQuest EA 1112 elemental analyser on 20 (i.e. approximately one-third) randomly selected samples from the total number of soil samples. Total N in legume and N and P in millet samples were determined from micro-Kjeldahl digests with H_2SO_4 and H_2O_2 by steam distillation and titration with HCl for N and by colorimetry (molybdenum-blue) for P.

Partial Least Squares Regressions (PLSR) were used to relate spectral reflectance to measured soils or plants properties and calibration models for each property developed on a random two-thirds of samples (20 soil samples and 300 plant samples) analysed by wet chemistry. Cross-validation was applied to prevent over-fitting of the models. The prediction performance of the models was evaluated on predicted and measured values of soil and plant attributes using the coefficient of determination (R^2) and root mean square error (RMSE).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum (x_i - y_i)^2} \tag{1}$$

where $(x_i - y_i)$ is the difference between the measured value by chemical analysis and predicted value by PLSR, n is the total number of samples in the test (Naes et al. 2002). The analysis was performed using OPUS version 6.5 (copyright © Bruker Optik GmbH 1997–2007). The models for prediction of soil properties were good for: SOC, total N, CEC, total P and silt ($R^2 = 0.90{-}0.96$; RMSE $= 0.11{-}0.75$); for exchangeable Ca, sand and clay ($R^2 = 0.85{-}0.87$; RMSE $= 0.04{-}1.69$); and, soil pH, exchangeable K and exchangeable Mg ($R^2 = 0.72{-}0.75$; RMSE $= 0.22{-}0.39$). However, prediction of extractable P was less reliable and consequently, all samples were analysed for extractable P using wet chemistry and these data are subsequently used. The models were good for N in both millet ($R^2 = 0.8$, RMSE $= 0.08$) and legume ($R^2 = 0.59$, RMSE $= 1.57$) samples.

Determination of N_2-fixation

Nitrogen fixed from the atmosphere was computed by the N-difference method that assumes both the legume and the non-leguminous reference crop derive the same amount of N from the soil. The method works reasonably well for soils with low capacity to supply N (Unkovich et al. 2008), conditions that held in Pallisa. Two fields in Onamudian village, where the reference crop accumulated substantially higher N than the legume treatments were excluded from the computations. The proportion of N_2-fixed was calculated as:

$$\begin{aligned}\%\mathrm{N_2\text{-}fixed} &= 100 \\ &\times \left[\mathrm{TotN_{legume}} - \mathrm{TotN}_{\mathrm{nonlegume}}\right]/\mathrm{TotN_{legume}}\end{aligned} \tag{2}$$

Finger millet was used as the non-fixing reference. The amount of N_2-fixed by the legume was calculated as:

$$\begin{aligned}\mathrm{N_2\text{-}fixed}\left(\mathrm{kg\ ha^{-1}}\right) &\\ &= [\%\ \mathrm{N\ derived\ from\ N_2\text{-}fixation}/100] \\ &\times \mathrm{total\ N\ in\ legume\ biomass}\end{aligned} \tag{3}$$

Legume and reference samples were analysed for $\delta^{15}N$ with the intention of calculating inputs from N_2-fixation using the ^{15}N natural abundance method, but legume samples had highly variable ^{15}N-enrichment, often greater than that in the reference millet samples (data not presented), which precluded calculation of N_2-fixation. Below-ground N contributions of legumes are not considered in this paper but root N contributions of legumes are estimated to be roughly 30% of total N_2-fixed (McNeill et al. 1998).

Nitrogen use efficiency

Nitrogen use efficiencies of N derived from legume residue in finger millet following incorporation of legume biomass was determined using average yields of millet for the two seasons and the amounts of legume N as:

$$\mathrm{NUE} = \frac{GY_{\mathrm{treatment}} - GY_{\mathrm{millet}}}{LN_{\mathrm{treatment}}} \tag{4}$$

where NUE is N use efficiency, GY is grain yield (kg ha^{-1}) and LN is the legume N (kg ha^{-1}) incorporated.

Farmers' preference and targeting of legumes

Participatory evaluations were conducted with farmers that were in farmer field schools on integrated nutrient management and had previously learned about a majority of the legume species tested in this study and other technologies including fertiliser through the INMASP project between 2002 and

2005. Criteria that farmers used in selection and preference ranking of the legumes were identified through group discussions. The direct matrix ranking method (Theis and Grady 1991) was used in the legume species evaluation. This approach eliminates bias that can occur through group evaluations since each farmer individually rates the individual attributes of a technology. Each legume species was ranked by each farmer according to each of the attributes (biomass production, drought tolerance, pest and disease resistance, and weed suppression, improvement of yields of subsequent crops, and additional benefits such as household nutrition and income source) on the scale: 1 = poor, 2 = fair, 3 = good, 4 = very good and 5 = excellent. A total score of the attributes was obtained and an overall rank position by each farmer obtained. Frequencies of the number of times each of the 6 legume species was ranked in a given position (i.e. 1 = most preferred and 6 = least preferred) were then established and the probability of a particular species being ranked in a certain position was calculated as:

$$\text{Probability} = \text{frequency}/\text{total number of observations} \tag{5}$$

Cumulative probabilities of each species (the sum of the probability for that rank and the probabilities for all previous ranks) were then computed. Each farmer also gave a score of 1 to a preferred field type for production of a given legume and a reason (s) for the preference for that field type.

Economic analysis

Benefit cost ratio (BCR) analysis (CIMMYT 1988) was conducted to assess the profitability of legume-millet rotations. A BCR > 2 is taken to be sufficiently profitable to be of interest to farmers. The benefit of the legume technologies compared with continuous millet cropping was assessed as a ratio between total benefits of the legume treatment to that of continuous millet. Ratios greater than one indicated the legume technology to be superior to continuous millet. Total yields of finger millet for two seasons of 2006 were used to compute year round total benefits. The benefits were discounted by 10% to take into account higher yields normally achieved under researcher management. Production costs for both legumes and millet were included in the calculation of the benefits. No grain was obtained in the season that legumes were grown due to drought late in the season and are thus not included in calculation of benefits. The total variable costs for legume biomass production included; seed, single superphosphate (SSP) fertiliser at the farm gate, labour (cost of ploughing, planting, weeding, chopping and incorporation). For finger millet, the variable cost for each season included seed and labour for land preparation, planting, weeding, harvesting, drying and threshing. The labour costs were obtained from farms within the study sites and for mucuna from two progressive farmers of a project promoting Conservation Agriculture who were producing mucuna seed for sale and practicing fallowing to improve fertility of their farms. Since pigeonpea was not native to this system, production costs could not be obtained. We assumed the costs to be similar to those of mucuna since it also required cutting and chopping biomass before incorporation. The farm gate millet price was 400 Ush kg^{-1} as observed during the experimentation seasons and was used to calculate the gross value of production. The benefit cost ratio (BCR) was calculated as:

$$\text{BCR} = \frac{\text{GVT} - \text{TVCT}}{\text{TVCT}} \tag{6}$$

where GVT = Gross value treatment and TVCT = total variable cost of treatment.

Statistical analysis

Analysis of farmers' acceptance of legume species

Farmers' acceptance of legume species was assessed by quantitative analysis of ranking data of legumes through computation of probabilities and logistic regression analysis (using a Chi squared test at 15% significance) using the logistic preference ranking analysis tool (Hernández-Romero 2000). The analytical approach allows for separation of species to those that are likely to be accepted and has been applied successfully in evaluation of acceptance of legume cover crop technologies (Nyende and Delve 2004). In the regression analysis, the cumulative probabilities and the ranks were the dependent and the independent variables, respectively.

Analysis of legume biomass and millet yield responses

Legume biomass, N accumulation and amounts of N_2-fixed, and millet grain yield data were analysed with the Restricted Maximum Likelihood (RELM) mixed effects model in Genstat 11.1. The fixed model terms included landscape, field type, legume species, phosphorus application and seasons, and their interactions and the random terms included farm, field and plot.

Results

Initial soil conditions of experimental fields

The soils from the experimental fields in Chelekura were weakly acidic to basic, with low organic carbon and CEC. Soils from the fields in Onamudian village were moderately to weakly acidic and with moderate organic carbon and CEC (Table 1). Fields of both sites had small concentrations of extractable P (<10 mg kg^{-1}) with the exception of good fields on the middle landscape position. Exchangeable bases were high but higher in Onamudian than in Chelekura. Though not always significantly different, measured soil properties in a village were in general better in the fields farmers classified as good than the fields they classified as poor. Significantly ($P < 0.01$) better soil properties were found in good than poor fields in the middle landscape position except for the soil particle size fractions and soil pH in Chelekura village. Significantly better soil pH, SOC, exchangeable bases were found in good than poor fields located in the upper landscape position in Onamudian village. Our results agree with findings in central Kenya that farmer's local knowledge can be used to categorise the relative fertility of fields within their farms (Mairura et al. 2008). This farmer categorisation is, however, relative to the specific context: good fields in Chelekura were similar to poor fields in Onamudian (Table 1).

Heterogeneity and P effects on legume productivity

Biomass productivity

Biomass productivity differed strongly ($P < 0.001$) between the study villages, with larger yields generally in Onamudian (Table 2a). Field type, legume species ($P < 0.001$) and phosphorus and landscape position × legume interaction significantly ($P < 0.05$) affected biomass yield in Chelekura village. Biomass yield was generally larger on good compared with poor fields on each of the landscape positions for all the legumes. This effect remained when P was applied although the effect of P was mixed and sometimes negative. Biomass productivity followed the order: mucuna (3.9–6.5 Mg ha^{-1}) > cowpea (3.4–6.1 Mg ha^{-1}) > green gram (2.0–5.3 Mg ha^{-1}) > pigeonpea (1.1–2.6 Mg ha^{-1} > groundnut (1.0–1.8 t ha^{-1}) ≈ soyabean (0.9–1.9 Mg ha^{-1}). The trend in biomass production in Onamudian village was similar to that of Chelekura except that soyabean performed better than groundnuts. The largest biomass (10.9 Mg ha^{-1}) was obtained in this village from mucuna. Application of phosphorus consistently increased biomass yield of cowpea on both good and poor fields on both landscape positions in each study site. This increase in biomass with P application ranged from 3–25% in Chelekura and 21–35% in Onamudian. P increased groundnut biomass on all fields and landscape positions in Onamudian (5–25%) with apparent overall P effects ranging from −18 to 86%. The strongest effects of P application were obtained with soyabean (86%) on good fields in the middle landscape position in Chelekura and with mucuna on poor fields in the middle position (52%) in Onamudian village.

Biomass N accumulation

Legume biomass N accumulation significantly ($P < 0.001$) differed between villages (Table 2b). The effect of landscape position was significant in only Onamudian village. Groundnut and soyabean accumulated comparatively small amounts of N on both good and poor fields and landscape positions in Chelekura and Onamudian villages. The ranges for groundnut were 27–56 kg N ha^{-1} and 43–119 kg N ha^{-1}, and for soyabean 23–48 kg N ha^{-1} and 32–

Table 1 Initial soil characteristics for fields selected for field experimentation on the upper and middle landscape positions in Chelekura and Onamudian village

Village/landscape position	pH (H_2O)	SOC (%)	Tot N (%)	Extr. P (mg kg^{-1})	Exc. K (cmol $_{(c)}$ kg^{-1})	Exc. Ca (cmol $_{(c)}$ kg^{-1})	Exc. Mg (cmol $_{(c)}$ kg^{-1})	CEC (cmol $_{(c)}$ kg^{-1})	Tot P (%)	Sand (%)	Clay (%)	Silt (%)
Chelekura												
Upper												
Good	7.2	0.89	0.09	9.50	0.79	1.81	0.89	6.9	0.03	69	23	8
Poor	6.5	0.67	0.08	4.50	0.55	2.70	0.66	5.4	0.02	68	25	7
SED	0.55	0.20	0.01	5.90	0.16	0.66	0.15	1.1	0.01	3.8	2.4	1.7
Middle												
Good	7.2	0.87	0.10	21.0	0.59	4.5	1.33	7.1	0.03	68	22	10
Poor	6.2	0.63	0.07	9.10	0.34	2.4	0.75	3.8	0.01	67	24	9
SED	0.19	0.09*	0.01**	5.2*	0.07*	0.56**	0.09***	1.1**	0.004**	2.0	1.8	1.0
Onamudian												
Upper												
Good	6.5	1.24	0.13	8.20	0.74	4.80	1.50	9.76	0.04	63	25	12
Poor	5.7	0.95	0.11	5.6	0.58	1.93	0.87	9.05	0.04	60	26	14
SED	0.34*	0.10**	0.01	3.6	0.05**	0.58***	0.16**	0.57	0.003	1.7	1.5	1.4
Middle												
Good	6.4	1.19	0.13	19.0	0.59	4.57	1.44	9.23	0.04	63	23	14
Poor	6.0	1.02	0.11	3.80	0.39	2.95	1.41	8.35	0.03	65	22	13
SED	0.25	0.20	0.01	7.80	0.15	0.98	0.28	1.60	0.01	4.7	3.3	4.6

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 2 Performance of legumes (a) biomass productivity (Mg ha^{-1}), (b) biomass N (kg ha^{-1}) and (c) N_2-fixed (kg ha^{-1}) without or with 30 kg P ha^{-1}, weedy fallow and millet grown on good and poor fields on the upper and middle landscape positions in Chelekura and Onamudian villages (2005B)

Treatment/village	Upper						Middle					
	Good			Poor			Good			Poor		
	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP
(a) Biomass productivity (Mg ha^{-1})												
Chelekura												
Cowpea	4.8	6.0	25	3.4	3.8	13	4.8	6.1	26	3.8	3.9	3
Green gram	3.2	3.7	18	2.0	2.6	30	4.2	5.3	25	2.7	2.7	0
Groundnut	1.8	1.5	−16	1.0	1.4	37	1.5	1.4	0	1.2	1.3	8
Mucuna	6.5	5.3	−18	3.9	4.1	4	6.1	6.0	−2	5.3	4.7	−11
Pigeonpea	2.2	2.1	−1	1.2	1.1	−9	2.5	2.6	6	1.8	1.8	0
Soyabean	1.1	1.2	7	0.9	0.9	7	1.0	1.9	86	0.9	1.3	45
Weedy fallow	2.2	–		1.7	–		1.9	–		1.3	–	
Continuous millet	1.1	–		1.0	–		1.9	–		1.1	–	
Onamudian												
Cowpea	4.3	5.2	21	3.2	4.1	28	5.6	7.6	35	3.7	4.9	30
Green gram	3.3	4.3	32	2.6	3.3	27	4.3	4.2	−3	3.1	3.9	24
Groundnut	1.2	1.5	17	1.2	1.3	6	2.7	3.4	25	2.5	2.6	5
Mucuna	5.1	4.8	−6	4.2	3.8	−10	7.6	10.9	44	5.9	8.9	52
Pigeonpea	2.2	2.4	9	1.6	1.8	13	4.9	4.0	−19	3.6	3.9	10
Soyabean	1.8	1.9	10	1.0	1.3	32	3.7	4.2	15	2.9	2.7	−8
Weedy fallow	1.8	–		1.5	–		3.2	–		1.7	–	
Continuous millet	2.0	–		1.8	–		2.8	–		3.4	–	
SED villages = 0.090***												
SED Chelekura village: LP = 0.093 ns; FT = 0.101***; Legume = 0.104***; Phosphorus = 0.103*; LP × legume = 0.06*												
SED Onamudian village: LP = 0.078***; FT = 0.076**; Legume = 0.078***; Phosphorus = 0.078***; LP × Legume = 0.054***; FT × Legume = 0.050*												
(b) Biomass N (kg ha^{-1})												
Chelekura												
Cowpea	136	204	50	108	109	1	128	141	10	97	111	14
Green gram	100	114	14	58	73	26	115	174	51	74	86	16
Groundnut	56	42	−25	27	45	62	44	40	−11	36	40	13
Mucuna	148	180	22	92	95	4	177	175	−1	144	104	−28
Pigeonpea	72	73	1	41	35	−15	79	89	13	57	54	−6
Soyabean	32	39	21	23	26	11	26	48	82	25	35	42

Table 2 continued

Treatment/village	Upper						Middle					
	Good			Poor			Good			Poor		
	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP
Weedy fallow	22	–		15	–		20	–		11	–	
Continuous millet	13	–		11	–		21	–		14	–	
Onamudian												
Cowpea	133	167	26	96	134	39	165	296	79	121	147	22
Green gram	99	117	17	80	91	13	153	151	−2	78	132	70
Groundnut	45	53	18	43	48	11	108	119	9	87	92	6
Mucuna	119	140	17	127	103	−19	217	281	29	191	216	14
Pigeonpea	80	73	−9	57	72	26	173	143	−18	115	121	5
Soyabean	56	56	−1	32	51	58	129	134	4	95	80	−16
Weedy fallow	17	–		14	–		33	–		15	–	
Continuous millet	23	–		29	–		33	–		47	–	
SED villages = 0.094***												
SED Chelekura village: LP = 0.093 ns; FT = 0.102***; Legume = 0.103***; Phosphorus = 0.103*; LP × legume = 0.08*												
SED Onamudian village: LP = 0.076***; FT = 0.076**; Legume = 0.079***; Phosphorus = 0.078***; LP × Legume = 0.048***; FT × Legume = 0.064*												
(c) N_2-fixed (kg ha^{-1})												
Chelekura												
Cowpea	119	185	55	95	95	0	105	113	7	83	97	17
Green gram	77	97	26	45	57	27	88	144	64	58	70	21
Groundnut	41	24	−40	14	31	126	23	19	−18	18	25	39
Mucuna	127	173	36	78	81	4	147	146	−1	126	91	−27
Pigeonpea	53	50	−6	26	21	−21	54	63	18	41	37	−9
Soyabean	18	24	30	14	10	−26	7	24	235	11	10	−13
Weedy fallow	–	–		–	–		–	–		–	–	
Continuous millet	–	–		–	–		–	–		–	–	
Onamudian												
Cowpea	108	137	27	54	81	51	138	266	93	70	94	34
Green gram	72	91	26	51	44	−12	117	116	−1	41	77	88
Groundnut	19	23	21	10	11	7	71	81	13	21	42	97
Mucuna	95	110	16	90	68	−24	179	253	41	145	165	14
Pigeonpea	54	46	−15	21	31	44	141	110	−22	64	52	−19

Table 2 continued

Treatment/village	Upper						Middle					
	Good			Poor			Good			Poor		
	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP
Soyabean	30	30	2	10	12	12	92	97	5	50	36	−29
Weedy fallow	–	–		–	–		–	–		–	–	
Continuous millet	–	–		–	–		–	–		–	–	

SED villages = 0.16 ns

SED Chelekura village: LP = 0.156 ns; FT = 0.152**; Legume = 0.154***; Phosphorus = 0.153[a]; LP × Legume = 0.09[a]

SED Onamudian village: LP = 0.14**; FT = 0.141**; Legume = 0.153***; Phosphorus = 0.150*; LP × Legume = 0.08**; FT × Legume = 0.077*

Statistical analysis done on log transformed data

P_0 and P_{30} are 0 and 30 kg P ha^{-1} respectively; ΔP = respectively percentage apparent P effects on biomass production, N accumulation and N_2-fixed calculated as (P30−P0)/P0 × 100

SED standard error of difference of the means; *LP* landscape position (Upper and Middle); *FT* field type (Good and Poor)

P significance: *ns* not significant; ** $P < 0.01$; *** $P < 0.001$; $^a P < 0.1$

126 kg N ha^{-1} in Chelekura and Onamudian villages, respectively. Cowpea and mucuna accumulated the largest amounts of N in good fields on the middle landscape positions in both villages.

The apparent effects of P on biomass N accumulation varied with legume species, field type, landscape position and P application. The strongest increase was obtained with cowpea on good fields (79%) and green gram on poor fields (70%) both on middle landscape position in Onamudian village. In Chelekura village, the strongest apparent effects of P were from soyabean (82%) and green gram (51%) on good fields and poor fields, respectively on the middle landscape position and from groundnut (62%) on poor fields in the upper landscape position.

Nitrogen fixation

In Chelekura village, the majority of the legumes fixed more than 50% of their N with or without P application in both landscape positions (Fig. 2a). Soyabean derived the smallest %N from N_2-fixation on the good fields in the middle landscape position and on poor fields on the upper landscape position even when P was applied, probably because of soyabean rust. The highest increase in the proportion of N_2-fixed when P was applied was obtained with groundnut on the good fields (38%) followed by soyabean (16%) on the poor fields of the middle landscape position (Fig. 2a, c). Application of P increased N_2-fixed by groundnuts by 19% on the poor fields on upper landscape position and 10% by soyabean on the good fields on the middle landscape position. The proportions of N_2-fixed from the atmosphere were generally higher in Chelekura (Fig. 2a) than in Onamudian village (Fig. 2b). In the latter village, only mucuna, cowpea and pigeonpea fixed more than 50% of their N when combined with P on the poor fields on the middle landscape position (Fig. 2b, d). The largest increments in N_2-fixed were obtained with groundnut (40%) and mucuna (42%) grown on poor fields with P at the upper landscape position. On poor fields at the middle landscape position, increases of 15, 26 and 20% with P application were obtained for cowpea, pigeonpea and soyabean, respectively. Without P, no N_2-fixation by soyabean was detected on the good fields of the middle landscape positions but there was a 50% increase in N_2-fixation when P was applied.

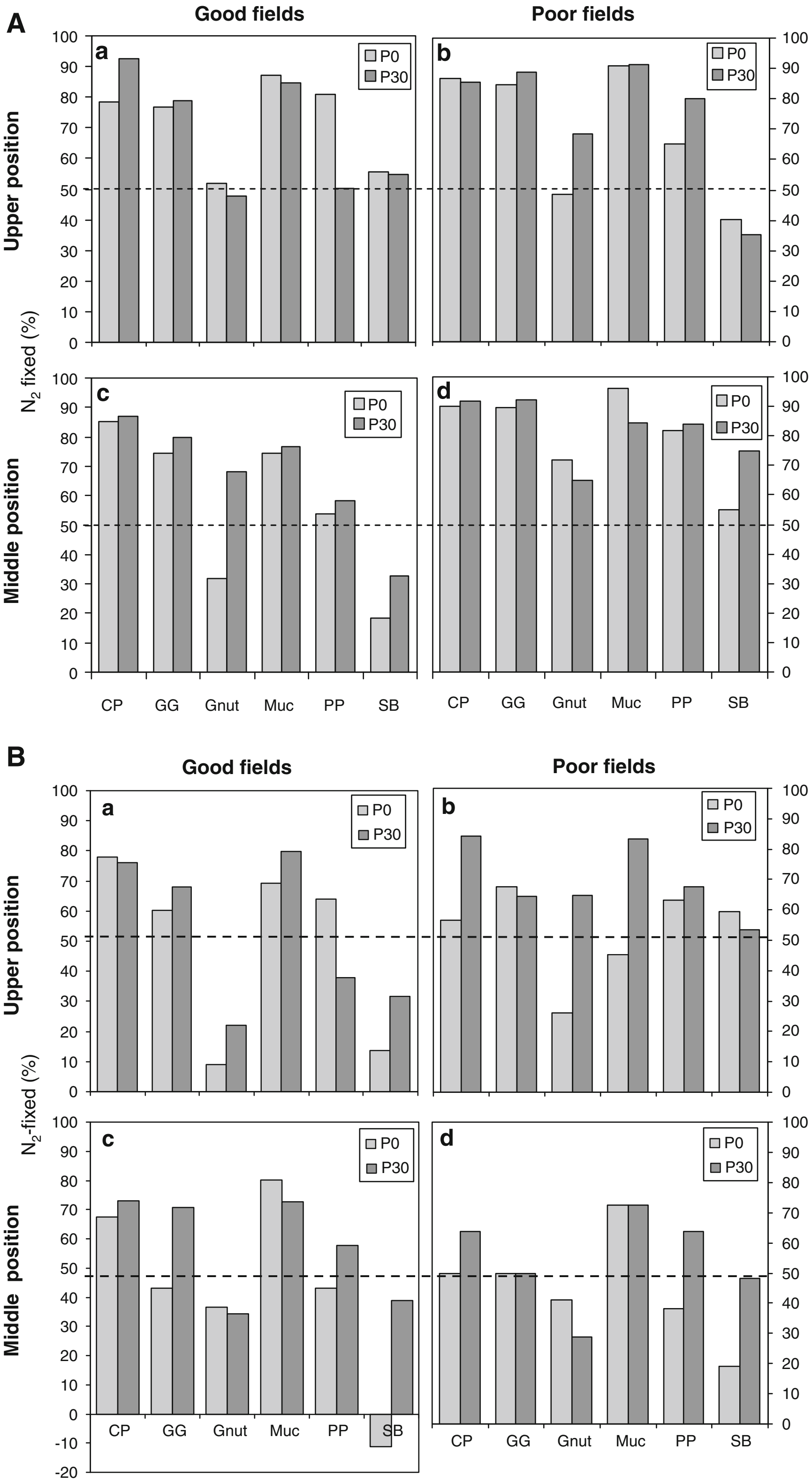

Fig. 2 **A** Percentage of N_2-fixed from the atmosphere by legume species without (P0) and with 30 kg P ha^{-1} (P30) on good and poor fields in Chelekura village during the short rainy season (2005B). *a* and *b* are respectively good and poor fields on *upper landscape position*. *c* and *d* are good and poor fields respectively on the *middle landscape position*. *CP* cowpea; *GG* greengram; *Gnut* groundnut; *Muc* mucuna; *PP* pigeonpea and *SB* soyabean. **B** Percentage of N_2-fixed from the atmosphere by legume species without (P0) and with 30 kg P ha^{-1} (P30) on good and poor fields in Onamudian village during the short rainy season (2005B). *a* and *b* are respectively good and poor fields on *upper landscape position*. *c* and *d* are good and poor fields respectively on the *middle landscape position*. *CP* cowpea; *GG* greengram; *Gnut* groundnut; *Muc* mucuna; *PP* pigeonpea and *SB* soyabean

Application of P resulted in a 26% increase in N_2-fixation by green gram on the good fields on the middle landscape position.

The amounts of N_2-fixed by legume species, by field types and by landscape position were generally larger for each legume species when established with P (Table 2c). Field type and legume effects were significant ($P < 0.001$) in Chelekura village. In Onamudian, landscape position × legume and field type × legume interactions were also significant in addition to the main effects of landscape position, field type, legume and phosphorus. Considering both villages, cowpea and mucuna, respectively fixed 83–266 and 68–253 kg ha^{-1} which were the highest amounts in both field types in the upper and middle landscape positions. The amounts fixed were usually larger in the middle compared with the upper landscape positions in both villages. The range of N_2-fixed by soyabean was small (7–97 kg ha^{-1}) because of the generally small amounts of biomass accumulated.

Finger millet grain yield performance after legumes

In Chelekura village, millet grain yield significantly differed between seasons ($P < 0.001$), field type ($P < 0.01$) and legume species ($P < 0.05$) (Table 3a). The yield was greater in 2006A compared with 2006B due to the immediate beneficial effects of biomass incorporation. In 2006A, legume biomass without P increased millet yield from −0.12 to 1.02 Mg ha^{-1} (good fields) and 0.14–0.85 Mg ha^{-1} (poor fields) on the upper landscape position. Yield increases ranged from 0.42 to 0.78 Mg ha^{-1} (good fields) and from −0.05 to 0.23 Mg ha^{-1} (poor fields) in the middle landscape position. The residual effect of the legume in season 2006B was small, resulting in yield increases above the continuous millet treatment of −0.14–0.39 Mg ha^{-1} in both good and poor fields in the upper landscape position and from −0.02 to 0.31 Mg ha^{-1} in the middle landscape position.

Yield responses were consistent with inherent variability in soil fertility. Usually stronger responses were found in the good compared with the poor fertility fields in both seasons. On average, yields on the good fields were higher than those on poor fields in 2006A and the difference was even larger in the 2006B season as a result of decline in residual effectiveness of legumes biomass. Millet grain yields did not differ significantly on establishment of legumes with P.

The general trends in millet grain responses to legume biomass incorporation in Onamudian village were similar to those in Chelekura village except that responses to landscape positions ($P < 0.05$) and P ($P < 0.001$) were also significant (Table 3b). In addition, the apparent effects of P were stronger in the good fields than the poor fields and millet yielded more in the middle landscape position for both field types and seasons.

Average additional grain yield of finger millet above continuous millet for the two seasons showed a positive contribution of the legumes to millet production (Fig. 3). The added yields only significantly ($P < 0.001$) differed between legumes species in Chelekura village. In Onamudian village, the added yields significantly ($P < 0.001$) differed with legumes and application of phosphorus and interaction between landscape position × legume ($P < 0.05$). Amounts of added grain yield were on average 0.2–0.3 Mg ha^{-1} in poor and good fields located on the upper landscape position in Chelekura and 0.15–0.2 Mg ha^{-1} in Onamudian village. Millet responses were larger for all legumes with P except for cowpea and green gram in good fields (upper landscape position) in Chelekura village. Generally P applied to the legumes benefited millet more in the poor fields than in the good fields.

Biomass NUE by finger millet

NUE was in general low and only in few cases approached 25 kg grain kg^{-1} N taken up. P application gave increased NUE in each of the field types and landscape positions in both Chelekura and Onamudian village (Table 4). NUEs were higher on poor than on good fields in the upper landscape position with the largest NUE obtained with groundnut residues (18.2 kg grain kg^{-1} N). With P, the NUE after pigeonpea doubled from 7.1 to 14.3 kg grain kg^{-1} N. In Onamudian village higher NUE's were found on the good fields ranging from 0.87 to almost 25 kg grain kg^{-1} N.

Grain yield and N uptake

Overall relationships between grain yield with N uptake following biomass incorporation across the

Table 3 Grain yield of finger millet (Mg ha^{-1}) following incorporation of biomass of legumes established with or without P, weedy fallow and continuous millet treatments on good and poor fertility fields located on the upper and middle landscape positions (LP) in (a) Chelekura village and (b) Onamudian meaned across the 2006A and 2006B seasons

Season/treatment	Upper						Middle					
	Good			Poor			Good			Poor		
	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP
(a) Chelekura village												
2006A												
Cowpea	1.47	1.30	−12	1.29	1.31	2	1.74	1.66	−5	1.08	1.23	14
Green gram	2.04	1.36	−33	1.33	1.53	15	1.81	1.79	−1	0.92	1.16	26
Groundnut	1.28	1.40	9	1.45	1.5	3	1.45	1.63	12	0.87	0.77	−11
Mucuna	1.28	1.48	16	1.23	1.19	−3	1.76	1.74	−1	0.85	1.03	21
Pigeonpea	0.80	1.25	56	1.02	1.31	28	1.58	1.39	−12	0.80	0.94	18
Soyabean	1.13	1.12	−1	0.74	1.15	55	1.58	1.57	−1	0.86	0.95	10
Weedy fallow	0.91	–		0.79	–		1.04	–		0.59	–	
Continuous millet	1.02	–		0.60	–		1.03	–		0.85	–	
2006B												
Cowpea	0.71	0.94	32	0.53	0.67	26	0.80	0.78	−3	0.78	0.85	9
Green gram	0.70	0.83	19	0.38	0.60	58	0.77	0.79	3	0.76	0.60	−21
Groundnut	0.65	0.96	48	0.50	0.51	2	0.81	0.79	−2	0.45	0.58	29
Mucuna	0.79	0.77	−3	0.82	0.55	−33	0.64	0.77	20	0.74	0.79	7
Pigeonpea	0.73	0.85	16	0.68	0.76	12	0.77	0.89	16	0.59	0.69	17
Soyabean	0.63	0.73	16	0.29	0.25	−14	0.76	0.71	−7	0.59	0.57	−3
Weedy fallow	0.78	–		0.39	–		0.62	–		0.43	–	
Continuous millet	0.69	–		0.43	–		0.63	–		0.47	–	
SED season	0.269***											
SED LP	0.261 ns											
SED field type	0.265**											
SED legume	0.271***											
SED phosphorus	0.270 ns											
(b) Onamudian village												
2006A												
Cowpea	1.87	2.01	7	1.09	0.88	−19	1.83	1.73	−5	1.29	1.18	-9
Green gram	1.81	2.10	16	0.88	0.68	−23	2.15	1.88	−13	0.89	1.00	12
Groundnut	1.54	1.74	13	0.68	0.91	34	1.63	1.95	20	0.96	1.08	13

Table 3 continued

Season/treatment	Upper						Middle					
	Good			Poor			Good			Poor		
	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP	P_0	P_{30}	ΔP
Mucuna	1.98	1.90	−4	0.92	0.93	1	1.88	1.76	−6	1.16	1.25	8
Pigeon pea	1.90	1.89	−1	0.99	0.87	−12	1.70	1.87	10	0.87	1.18	36
Soyabean	1.76	2.03	15	0.61	0.74	21	1.70	2.08	22	1.05	1.12	7
Weedy fallow	1.69	–		0.84	–		1.85	–		0.65	–	
Continuous millet	1.67	–		0.98	–		1.63	–		0.58	–	
2006B												
Cowpea	0.72	1.21	68	0.63	0.67	6	1.06	1.23	16	0.75	0.74	−1
Green gram	0.65	0.83	28	0.51	0.59	16	1.18	1.34	14	0.74	0.90	22
Groundnut	0.62	1.13	82	0.55	0.5	−9	0.77	0.74	−4	0.57	0.76	33
Mucuna	0.80	0.93	16	0.76	0.71	−7	0.76	0.92	21	0.76	0.90	18
Pigeonpea	0.80	1.07	34	0.69	0.71	3	0.70	0.77	10	0.92	0.93	1
Soyabean	0.81	0.92	14	0.46	0.37	−20	0.69	0.81	17	0.59	0.68	15
Weedy fallow	0.69	–		0.52	–		0.71	–		0.76	–	
Continuous millet	0.52	–		0.48	–		0.74	–		0.57	–	
SED season	0.212***											
SED LP	0.209*											
SED field type	0.208***											
SED legume	0.213***											
SED phosphorus	0.212***											

SED standard error of difference; Significance, * $P < 0.05$; *** $P < 0.001$; ΔP Apparent effect of phosphorus = (P30 − P0)/P0 × 100

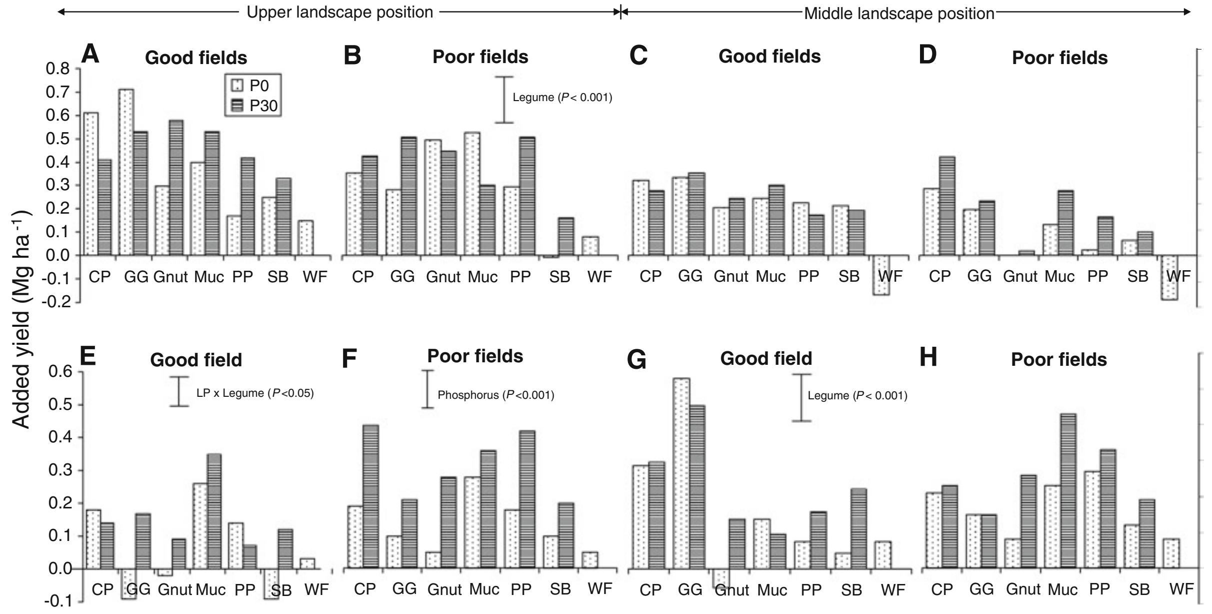

Fig. 3 Average additional grain yield of finger millet (Mg ha^{-1}) above continuous millet following legumes grown with or without P fertiliser and weedy fallow on good and poor fields located on the *upper* and *middle landscape positions* in Chelekura (*upper*) and Onamudian (*below*) for 2 seasons. Respective grain yields for continuous millet treatment in Chelekura village, **a**–**d** 0.85, 0.47, 1.00 and 0.76 Mg ha^{-1}; and for Onamudian village, **e**–**h** 1.22, 0.51, 1.23 and 0.54 Mg ha^{-1}. *CP* cowpea; *GG* green gram; *Gnut* groundnut; *Muc* mucuna; *PP* pigeonpea; *SB* soyabean and *WF* weedy fallow

treatments in each village were relatively weaker in Chelekura ($R^2 = 0.52$) than in Onamudian ($R^2 = 0.85$) and slopes of the lines are lower in the first village compared with the latter. The relationship was also weaker when P was applied in Chelekura ($R^2 = 0.40$) but not different between with and without P in Onamudian village (Fig. 4). The latter could be due to the somewhat higher extractable P in the soils in Chelekura (Table 1). In both villages, increasing grain yield with N-uptake were low perhaps because other nutrients were limiting response. This was more distinct in Chelekura (lower R^2) than in Onamudian (higher R^2) which is supported by the fact that soil fertility in the latter village was somewhat better, in particular in CEC (Table 1).

Socio-economic evaluation

Legume acceptance and preferential targeting by farmers

Groundnut had the highest probabilities of being ranked first in Chelekura (60%) and Onamudian (75%) villages (Fig. 5). It was followed by cowpea and green gram in Chelekura and Onamudian, respectively. The slopes of regression lines of cumulative frequencies of farmers ranking of groundnut were 0.07 and 0.04, with positive and significant probabilities of being greater than zero of 0.59 and 0.80 in Chelekura and Onamudian, respectively indicating a strong likelihood of acceptance by farmers. In both sites, probabilities were not significantly different for mucuna and the intercepts were negative. In the case of pigeonpea, the intercepts were negative although the probabilities were significant. The results indicated that mucuna and pigeonpea are unlikely to be accepted by farmers. For a majority (90%) of the farmers, preference of a legume species was driven by whether it provided food and income.

Farmers preferred to target grain legumes with or without P application to fields of good fertility as indicated by 35–96% of the respondents and pigeonpea and mucuna to fields of poor fertility (70–100%) in both villages. The farmers indicated that they would grow cowpea in both good (35–38%) and poor (45–63%) fertility field types which tallies with the good agronomic performance of cowpea across field

Table 4 Nitrogen use efficiencies (kg grain kg^{-1} N uptake) in finger millet following incorporation of biomass of legumes grown with or without P fertiliser, weedy fallow on good and poor fertility fields located on the upper and middle landscape positions in Chelekura and Onamudian villages (averaged across 2 seasons)

Village/legume	Upper				Middle			
	Good		Poor		Good		Poor	
	P_0	P_{30}	P_0	P_{30}	P_0	P_{30}	P_0	P_{30}
Chelekura								
Cowpea	2.57	0.77	3.25	3.84	2.35	1.81	2.71	3.42
Green gram	4.55	2.37	4.82	6.89	2.69	1.87	2.42	2.51
Groundnut	0.76	7.75	18.28	9.75	4.20	5.71	0.09	0.48
Mucuna	0.98	1.49	5.63	3.43	1.29	1.60	0.87	2.42
Pigeonpea	−1.23	2.29	7.10	14.34	2.56	1.76	0.34	2.76
Soyabean	−0.12	1.79	−0.33	6.01	7.63	3.75	2.48	2.78
Weedy fallow	−4.85		5.19		−8.23		−15.26	
Millet	–	–	–	–	–	–	–	–
Onamudian								
Cowpea	1.38	0.87	2.02	3.31	1.64	0.94	1.70	1.54
Green gram	−0.87	11.84	1.26	2.34	3.29	2.86	1.86	1.08
Groundnut	−0.51	24.79	1.33	5.92	−0.44	1.13	0.86	2.88
Mucuna	2.21	11.24	2.21	3.53	0.61	0.32	1.18	1.99
Pigeonpea	1.81	17.73	3.14	5.89	0.40	1.08	2.33	2.72
Soyabean	−1.52	23.89	3.22	4.04	0.29	1.57	1.27	2.50
Weedy fallow	1.94		3.64		2.12		4.93	
Millet	–	–	–	–	–	–	–	–

types (Table 2), and the response to P fertiliser. Farmers targeted grain legumes more to the good (26–93%) than poor fields mainly to avoid yield losses. Pigeonpea and mucuna were targeted to fields of poor fertility because of their biomass production potential and accompanying benefits of weed suppression and tolerance to poor soil fertility (63–92%).

Economic benefits

Benefits from millet following legumes were greater than from continuous millet treatment in both field types and landscape positions in the study villages as shown by the ratios of total benefits legumes to total benefits continuous millet which were generally >1 (Table 5). Legumes without P application achieved a BCR > 2 only on good fields in both villages. In Chelekura, discounted benefits (10%) showed that the most profitable legumes (BCRs > 2) were green gram and cowpea on good fields in the upper position and all the legumes except groundnut on good fields in the middle position. On the poor fields, none of the legumes achieved a BCR of 2 on either landscape position. With the exception of groundnut, all the legumes without P application and weedy fallow and continuous millet cropping had BCRs > 2 on good fields on both upper and middle landscape positions in Onamudian village but, as in Chelekura village, none achieved a BCR of 2 on poor fields on either of the landscape positions.

Discussion

Heterogeneity in soil fertility influenced productivity of legumes established without and with P (Table 2) and the response of yield of the subsequent millet crop to the incorporation of the legume biomass (Table 3). Biomass production, N accumulation and N_2-fixation of the legumes were within ranges reported elsewhere in sub-Saharan Africa (Hauser and Nolte 2002; Baijukya 2004; Kaizzi et al. 2006; Ncube 2007; Ojiem et al. 2007). Greater N availability in soils is known to inhibit N_2-fixation (Giller 2001) which explains why the proportions of N_2-fixed were larger in Chelekura village with fields of lower total N than in Onamudian village (Table 1). Application of P increased the amounts of N_2-fixed

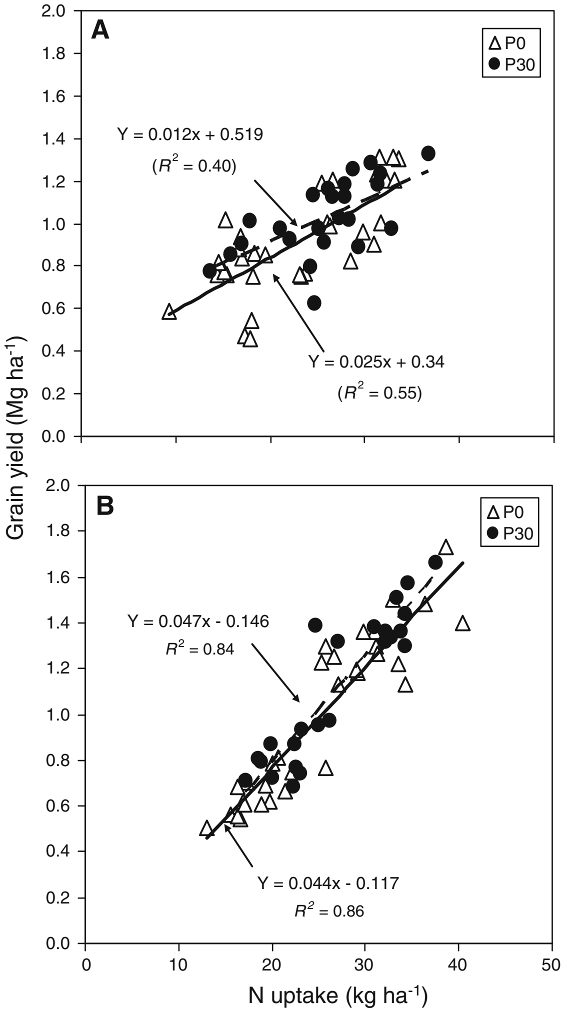

Fig. 4 Finger millet grain yield relationships with total N uptake (kg ha^{-1}) in Pallisa district, 2006. **a** Chelekura and **b** Onamudian village. *Open triangles* are treatments without P and *filled circles* are treatments with 30 kg P ha^{-1} on preceding legume crops

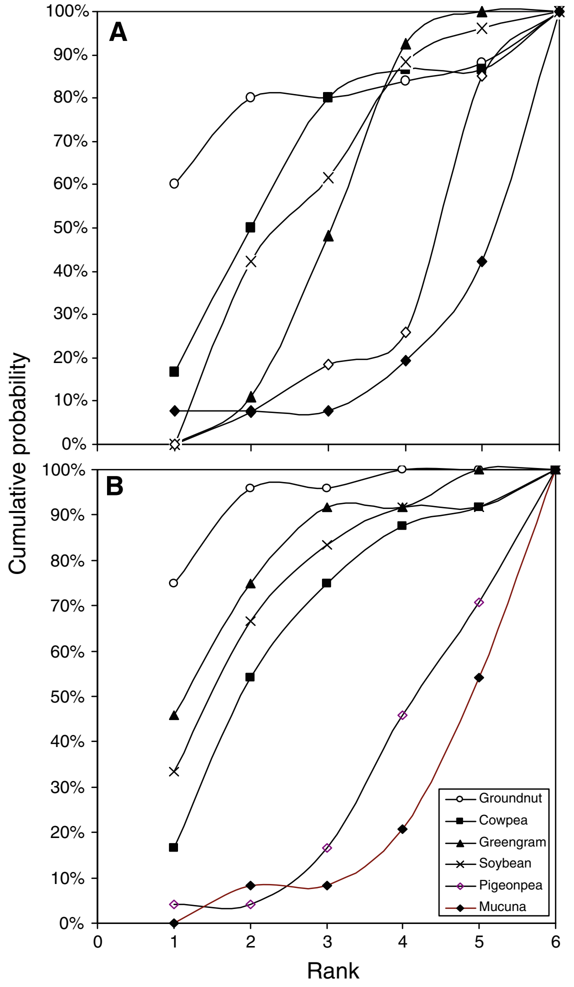

Fig. 5 Comparison of acceptance of legume species by participants in the farmer field schools in **a** Chelekura (n = 27) and **b** Onamudian (n = 24) villages, Pallisa District

(Table 2b) rather than the proportion fixed (Fig. 2) and had stronger effects in the poor fertility fields which were often P deficient (Table 1).

Millet yields increased following legumes, as is commonly found in legume cereal cropping systems (Osunde et al. 2003; Ncube 2007; Franke et al. 2008). The yield responses were larger when larger amounts of legume biomass were incorporated. Residual effectiveness of the legumes was however short lived as the yields in season 2006B were significantly less than those of 2006A season due to a decrease in N availability. Legume residues release large amounts of N rapidly once incorporated in soil rendering it susceptible to leaching losses (Dawson et al. 2008). This could have been more likely as more than normal rainfall was received in 2006B season (Fig. 1). Millet straw has high C: N ratio and because the straw of the previous season was incorporated into the plots, N immobilisation could have also compounded the low yields in 2006B season.

Heterogeneity in soil fertility mediated the millet yield responses. The larger millet yield responses observed in good than poor fields following legumes imply that other factors than N restricted millet growth. Larger relative responses of millet to P applied to the previous legume crop on poor fields showed a residual benefit of P application as reported earlier from legume-cereal rotations (Kihara et al.

Table 5 Total millet grain yield (Mg ha^{-1}), gross value and total variable costs (both in Ush ha^{-1}) and benefit cost ratios (in bold BCR > 2.0) following rotations with legumes grown with or without P fertiliser, weedy fallow and continuous millet cropping systems grown on good and poor fields located on upper and middle landscape positions in (a) Chelekura village and (b) Onamudian village

Position/Treatment	Good fields										Poor fields									
	P_0					P_{30}					P_0					P_{30}				
	TGY	GV	TVC	BCR	GVt/GVc	TGY	GV	TVC	BCR	GVt/GVc	TGY	GV	TVC	BCR	GVt/GVc	TGY	GV	TVC	BCR	GVt/GVc
(a) Chelekura village																				
Upper																				
Cowpea	2.2	785	395	**2.0**	1.3	2.2	806	746	1.1	1.3	1.9	670	395	1.7	1.4	2.1	749	746	1.0	1.6
Green gram	2.7	986	363	**2.7**	1.6	2.2	788	714	1.1	1.3	1.7	605	363	1.7	1.3	1.8	634	714	0.9	1.3
Groundnut	1.9	695	590	1.2	1.1	2.4	850	941	0.9	1.4	1.3	475	590	0.8	1.0	1.4	486	941	0.5	1.0
Mucuna	2.1	745	398	1.9	1.2	2.3	810	749	1.1	1.3	1.6	572	398	1.4	1.2	1.8	655	749	0.9	1.4
Pigeon pea	1.5	551	412	1.3	0.9	2.1	756	763	1.0	1.2	1.4	500	412	1.2	1.1	1.6	587	763	0.8	1.2
Soyabean	1.8	634	410	1.5	1.0	1.9	666	761	0.9	1.1	1.5	522	410	1.3	1.1	1.5	547	761	0.7	1.2
Weedy fallow	1.7	608	330	1.8	1.0						1.0	367	330	1.1	0.8					
Continuous millet	1.7	616	373	1.7	1.0						1.3	475	373	1.3	1.0					
Middle																				
Cowpea	2.5	914	395	**2.3**	1.5	2.4	878	746	1.2	1.5	1.8	655	395	1.7	1.8	2.0	878	746	1.2	2.4
Green gram	2.6	929	363	**2.6**	1.6	2.6	929	714	1.3	1.6	1.7	616	363	1.7	1.7	2.1	929	714	1.3	2.5
Groundnut	2.3	814	590	1.4	1.4	2.4	871	941	0.9	1.5	2.0	702	590	1.2	1.9	2.0	871	941	0.9	2.3
Mucuna	2.4	864	398	**2.2**	1.4	2.5	904	749	1.2	1.5	2.1	738	398	1.9	2.0	1.7	904	749	1.2	2.4
Pigeon pea	2.4	846	412	**2.1**	1.4	2.3	821	763	1.1	1.4	1.7	612	412	1.5	1.7	2.1	821	763	1.1	2.2
Soyabean	2.3	842	410	**2.1**	1.4	2.3	821	761	1.1	1.4	1.0	371	410	0.9	1.0	1.4	821	761	1.1	2.2
Weedy fallow	1.7	598	330	1.8	1.0						1.2	425	330	1.3	1.1					
Continuous millet	1.7	598	373	1.6	1.0						1.0	371	373	1.0	1.0					
(b) Onamudian village																				
Upper																				
Cowpea	2.9	1040	395	**2.6**	1.2	3.0	1066	746	1.4	1.2	2.0	734	395	1.9	1.8	1.9	691	746	0.9	1.7
Green gram	3.3	1199	363	**3.3**	1.4	3.2	1159	714	1.6	1.4	1.6	587	363	1.6	1.4	1.9	684	714	1.0	1.7
Groundnut	2.4	864	590	1.5	1.0	2.7	968	941	1.0	1.1	1.5	551	590	0.9	1.3	1.8	662	941	0.7	1.6
Mucuna	2.6	950	398	**2.4**	1.1	2.7	965	749	1.3	1.1	1.9	691	398	1.7	1.7	2.2	774	749	1.0	1.9
Pigeon pea	2.4	864	412	**2.1**	1.0	2.6	950	763	1.2	1.1	1.8	644	412	1.6	1.6	2.1	760	763	1.0	1.8
Soyabean	2.4	860	410	**2.1**	1.0	2.9	1040	761	1.4	1.2	1.6	590	410	1.4	1.4	1.8	648	761	0.9	1.6
Weedy fallow	2.6	922	330	**2.8**	1.1						1.4	508	330	1.5	1.2					
Continuous millet	2.4	853	373	2.3	1.0						1.2	414	373	1.1	1.0					

Table 5 continued

Position/Treatment	Good fields										Poor fields									
	P_0					P_{30}					P_0					P_{30}				
	TGY	GV	TVC	BCR	GVt/GVc	TGY	GV	TVC	BCR	GVt/GVc	TGY	GV	TVC	BCR	GVt/GVc	TGY	GV	TVC	BCR	GVt/GVc
Middle																				
Cowpea	2.6	932	395	**2.4**	1.2	3.2	878	746	1.2	1.1	1.39	500	395	1.3	1.0	1.3	878	746	1.2	1.8
Green gram	2.5	886	363	**2.4**	1.1	2.9	929	714	1.3	1.2	1.23	443	363	1.2	0.9	1.4	929	714	1.3	1.9
Groundnut	2.2	778	590	1.3	1.0	2.9	871	941	0.9	1.1	1.68	605	590	1.0	1.2	1.6	871	941	0.9	1.7
Mucuna	2.8	1001	398	**2.5**	1.3	2.8	904	749	1.2	1.1	1.68	605	398	1.5	1.2	1.6	904	749	1.2	1.8
Pigeon pea	2.7	972	412	**2.4**	1.2	3.0	821	763	1.1	1.0	1.07	385	412	0.9	0.8	1.1	821	763	1.1	1.6
Soyabean	2.6	925	410	**2.3**	1.2	3.0	821	761	1.1	1.0	1.36	490	410	1.2	1.0	1.3	821	761	1.1	1.6
Weedy fallow	2.4	857	330	**2.6**	1.1						1.46	526	330	1.6	1.1					
Continuous millet	2.2	788	373	2.1	1.0						1.39	500	373	1.3	1.0					

TGY total grain yield (Mg ha^{-1}) for 2 seasons; *GV* gross value in '000 Ush (GY × price of millet) after discounting TGY by 10%; *TVC* total variable costs in '000 s Ush; *BCR* benefit cost ratio computed from (GV–TVC)/TVC; *GVt* gross value treatment; *GVc* gross value millet; price of finger millet = 400 Ush kg^{-1}; Conversion 1730 Ush = 1US$

2007). This is advantageous as it could cut costs of P application and also has cumulative benefits to all the crops in the rotation sequence because of increasing P recovery with time (Janssen and Wolf 1988).

Yield responses are also influenced by nutrient recoveries and use efficiencies as modified by heterogeneity in soil fertility. The agronomic N use efficiencies of legume biomass N in this study were stronger when P was applied to both good and poor fields (Table 4) a similar response to that observed with maize across different field types (Tittonell et al. 2007b; Zingore et al. 2007a). The N use efficiencies were however smaller on less fertile fields. Zingore et al. (2007b) demonstrated that poor N use efficiencies on infertile fields were due to multiple nutrient limitations including deficiencies of micronutrients. To realise improved N use efficiencies and benefit from use of legumes, a better understanding of factors influencing N dynamics after legumes is needed, especially after straw incorporation. Other factors that interact to limit millet production in poor fertility fields need to be explored, such as deficiencies of other nutrients.

Although mucuna and pigeonpea resulted in significantly higher millet yield increases compared with continuous millet, farmers indicated that they would not plant them on good fertility fields demonstrating a mismatch between agronomic performance and farmers preferences. Farmers were unfamiliar with pigeonpea which is a crop of the northern farming system in Uganda. They knew the crop neither as a food crop nor the potential marketability of its grain. For the case of mucuna, it was not popular with farmers because it has no direct food benefit to the farmers, although it produced large amounts of N-rich biomass, demonstrating that improving soil fertility is a secondary goal of farmers. Lack of acceptance of mucuna is also linked to substantial amounts of labour required for incorporation, and the fact that land is used without producing food (Nyende and Delve 2004). In Chelekura, soyabean did not establish well and was attacked by rust, which influenced the farmers ranking (Fig. 5). Onamudian is close to the main market in Pallisa and green gram and soyabean are marketable and used in making snacks, and farmers preferred growing them. Their biomass performance also was better in this village. Overall, farmers' evaluation could have been infuenced by the lack of grain yield due to the poor rainfall received during the 2005B season (Fig. 1). Groundnut was highly preferred by farmers' because it contributes to household food needs and is highly marketable despite its poorest economic performance on good fields where almost all legumes had potential to be targeted (Table 5).

Farmers targeting of legumes to field types often did not reflect the agronomic or economic performance of the legumes. For example, farmers do not grow groundnut on high fertility fields as it produces a lot of biomass but the haulm yields are poor. Unpublished survey data from the same villages showed that groundnut was grown on fields of poor to moderate fertility yet farmers said they would target it to good fertility fields. Furthermore, our experimental results showed that in general all of the legumes produced more biomass on good fields than poor fertility fields (Table 2a). Economic analysis indicated high returns on incorporation of legume biomass with or without P application because of the increased yield of the subsequent millet crop (Table 5a, b). However, growing legumes without P was most profitable (BCR > 2) on good fertility fields in both landscape positions in the study villages. With the current yields and prices, use of P fertilisers is not attractive for farmers. At current yields a 15–20% increase in the value of the produce or a 30–40% reduction in the price of P fertiliser would be needed to make all of the legume technologies profitable. It should be noted that since no legume grains were obtained, the residual benefits from the subsequent millet crop may have been larger than obtained if legume grain is harvested as in a normal year. We assume that the larger benefits may have compensated for no grain obtained from legumes. Integration of agronomic performance and farmer's production objectives and economic benefits is needed to best fit legumes to socio-ecological environments (Ojiem et al. 2006).

From agronomic and profitability viewpoint, only green gram and cowpea established without P could be targeted to good fields (upper landscape position) and all the legumes except groundnuts (middle position) in Chelekura village. In Onamudian village, all the legumes without P application (except groundnuts) could be targeted to good fields on both landscape positions. None of the legumes grown with or without P was profitable on poor fields. A BCR > 2 is often used as an economic threshold to identify soil fertility management technologies that can attract reinvestment and in turn may lead to their sustainable use. Millet however is grown for other social benefits (e.g. social functions and ceremonies like marriages) to which it is difficult to attach a direct economic value. Therefore all the legumes (especially without P application) whose benefits were higher than 1 compared with continuous millet could be attractive to farmers for growing in both good and poor fields for social sustainability. In fact the benefit cost ratios of legume millet rotations were double those of continuous millet when P fertiliser was used on poor fields in the middle landscape position in Chelekura village. The wider perceptions of multiple benefits that farmers attach to a technology explain why groundnut was prioritised in both sites although it did not contribute significantly to higher yields of the subsequent millet. The high cost of the seed for the variety used and weak residual effect on millet yield explained its lack of profitability. Due to the poor rainfall, no grain of the legumes was produced, but in better seasons all the legumes including groundnuts may be profitable. Although the economic analysis indicated that pigeonpea and mucuna were profitable on the good fields, the opportunity cost of missing out on food production means they are unlikely to be accepted by farmers, except for growing in the poor fields where their use was not profitable. Integrating the agronomic, social and economics in the targeting of legume species therefore leads us to suggest that green gram and cowpea, and green gram, cowpea and soyabean should be targeted to good fields in the upper positions and middle positions, respectively in Chelekura village. Green gram, cowpea and soyabean should be targeted to good fields in both landscape positions in Onamudian village. All the grain legumes can be grown on poor fields in both villages but more benefits could be obtained if they are established with P fertiliser in both villages.

Although legumes are recommended for smallholder systems (Giller 2001), their production is not suitable everywhere. Site specific management is needed for their efficient production to improve productivity of smallholder systems.

Conclusions

Variability in soil fertility strongly influenced the productivity of legumes and their contribution to subsequent crops of finger millet. Legumes increased millet productivity on both good and poor fields. P is necessary for establishment of legumes and accumulation of N in poor fertility fields. Farmers preferred targeting legumes with perceived multiple benefits to good fertility fields and legumes with no immediate contribution to household food requirement to poor fields but not because of a greater impact on fertility. Economic benefits were affected by heterogeneity between field types and, with current millet yields and prices, legume-millet rotations without P fertiliser were more profitable on good fields. Our results challenge the generalised recommendation that legumes are suitable for improving the productivity of low input farming systems. From our experiments, we suggest that green gram and cowpea without P be targeted to good fields on both upper and middle landscape positions in both villages, mucuna without P to poor fields in the middle landscape position in Chelekura village, and cowpea to poor fields on upper position in Onamudian village. Thus, we demonstrate that site-specific niches can be identified for different legume species in low input farming systems that allow maximum benefit to be derived from the legumes. These niches are readily identified by the farmers. Benefit from targeting of technologies can only be realised if seed of improved varieties and fertilisers are readily accessible and if the prevailing socio-economic environment is sufficiently favourable to make farming with nutrient inputs profitable.

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