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Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique

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ABSTRACT

Many farmers in central Mozambique intercrop maize with grain legumes as a means to improve food security and income. The objective of this study was to understand the farming system, and to evaluate the suitability of maize–legume intercropping to alleviate the biophysical and socio-economic constraints faced by smallholder farmers in Ruaca and Vunduzi villages, central Mozambique. To achieve this we characterised the farming systems and measured grain yields, rainfall infiltration, economic returns and acceptability of maize–legume intercrops under different N and P application rates. Two intercropping strategies were tested: (a) an additive design of within-row intercropping in which legume was intercropped with alternating hills of maize within the same row; maize plant population was the same as sole crop maize, and (b) a substitutive design with distinct alternating rows of maize and legume (local practice). Fertiliser treatments imposed on all treatments were: (i) no fertiliser, (ii) 20 kg P ha^{-1}, (iii) 20 kg P ha^{-1} + 30 kg N ha^{-1}, and (iv) 20 kg P ha^{-1} + 60 kg N ha^{-1}. Intercrops were relatively more productive than the corresponding sole crops; land equivalent ratios (LER) for within-row intercropping ranged between 1.1 and 2.4, and between 1.0 and 1.9 for distinct-row intercropping. Average maize yield penalty for intercropping maize and pigeonpea in the within-row was small (8%) compared with 50% in the distinct-row design; average (season × fertiliser) sole maize yield was 3.2 t ha^{-1}. Intercropping maize and cowpea in within-row led to maize yield loss of only 6%, whereas distinct-row intercropping reduced maize yield by 25% from 2.1 t ha^{-1} of sole maize (season × fertiliser). Cowpea yield was less affected by intercropping: sole cowpea had an average yield of 0.9 t ha^{-1}, distinct-row intercropping (0.8 t ha^{-1}) and the within-row intercropping yielded 0.9 t ha^{-1}. Legumes were comparatively less affected by the long dry spells which were prevalent during the study period. Response to N and P fertiliser was weak due to poor rainfall distribution. In the third season, maize in rotation with pigeonpea and without N fertiliser application yielded 5.6 t ha^{-1}, eight times more than continuous maize which was severely infested by striga (*Striga asiatica*) and yielded only 0.7 t ha^{-1}. Rainfall infiltration increased from 6 mm h^{-1} to 22 mm h^{-1} with long-term maize–legume intercropping due to a combination of good quality biomass production which provided mulch combined with no tillage. Intercropping maize and pigeonpea was profitable with a rate of return of at least 343% over sole maize cropping. Farmers preferred the within-row maize–legume intercropping with an acceptability score of 84% because of good yields for both maize and legume. Intercropping increased the labour required for weeding by 36% compared with the sole crops. Farmers in Ruaca faced labour constraints due to extensification thus maize–pigeonpea intercropping may improve productivity and help reduce the area cultivated. In Vunduzi, land limitation was a major problem and intensification through legumes is amongst the few feasible options to increase both production and productivity. The late maturity of pigeonpea means that free-grazing of cattle has to be delayed, which allows farmers to retain crop residues in the fields as mulch if they choose to; this allows the use of no-tillage practises. We conclude that maize–legume intercropping has potential to: (a) reduce the risk of crop failure, (b) improve productivity and income, and (c) increase food security in vulnerable production systems, and is a feasible entry point to ecological intensification.

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1. Introduction

Legumes provide an important pathway to alleviate the constraints related to nitrogen (N) limitations in the soil and improve crop productivity. They can quickly cover the soil surface and reduce soil erosion (Giller and Cadisch, 1995), suppress weeds (Liebman and Dyck, 1993), fix atmospheric N_2 (Giller et al., 1994), reduce pests and diseases (van der Pol, 1992; Trenbath, 1993), spread labour needs (van der Pol, 1992) and improve the efficiency of land use (Morris and Garrity, 1993a,b). Grain legumes are generally preferred by smallholder farmers in the tropics above green manures and cover crops because they ensure food security, improved diet and income (Giller, 2001). When intercropped with cereals, larger quantities of better quality organic matter inputs are produced leading to greater productivity benefits compared with continuous maize monocrops (Hartwig and Ammon, 2002; Schmidt et al., 2003; Rochester, 2011). Multi-purpose grain legumes such as pigeonpea (*Cajanus cajan* (L.) Millsp.) have shown potential to be included in cereal-legume rotations in the tropics (Giller et al., 2009; Baudron et al., 2011). Due to these attributes, legumes are regarded as a critical component of conservation agriculture (Meyer, 2010), and results of a recent meta-analysis confirmed this suggestion (Rusinamhodzi et al., 2011). The contribution to the soil N-budget through biological N_2-fixation is especially important in low-input farming systems such as those that prevail in central Mozambique. Thus cereal legume intercropping appears to be a useful component of ecological intensification (Doré et al., 2011), an approach to produce more food per unit resource to achieve positive social outcomes without negative effects on the environment (Cassman, 1999; Hochman et al., 2011).

Despite the many benefits, the importance of legumes in the farming systems of the tropics is hampered by lack of information, seed costs, and poor market infrastructure (Graham and Vance, 2003). As a result the contribution of legumes to many smallholder farming systems remains small (Giller, 2001). When legumes are intercropped, the planting of two or more crops either simultaneously or in relay increases the labour requirements compared with cereal monocropping which may limit the widespread use of legumes (Waddington et al., 2007). In the field, deficiencies of phosphorus (P), potassium (K), sulphur (S), and micronutrients such as zinc (Zn), molybdenum (Mo) and boron (B) may limit legume growth and N_2-fixation (O'Hara et al., 1988). Phosphorus availability is often regarded as the most limiting factor (Giller and Cadisch, 1995). At the farm level, it is important that grain legumes provide multiple benefits and are acceptable to farmers; farmer evaluations provides a basis for assessing the suitability of production options to their needs and local environment (Ashby, 1991; Rusinamhodzi and Delve, 2011). Thus we hypothesised that if maize–legume intercropping is more productive, economically viable, and is acceptable to the majority of farmers then it is a low cost pathway to remove the binding constraints of poor soils, unreliable rainfall and drought that are characteristic of central Mozambique.

Central Mozambique is sparsely populated (Folmer et al., 1998) and characterised by extensive farming systems in which slash and burn, limited fertiliser use and continuous monocropping are common, and there is little crop-livestock integration. Soils are infertile (Maria and Yost, 2006) and the poor soil productivity is compounded by limited capital resource endowments, poverty and limited market participation. A major challenge in central Mozambique is to improve soil and crop productivity to meet the food security and cash needs of smallholder farmers without creating new constraints (Mafongoya et al., 2006). Grain legume crops provide a good starting point as intensification and diversification options due to their multi-purpose nature (food, fodder and soil fertility) and the small initial capital investment required. Development agencies in central Mozambique worked with the government extension department to introduce new varieties of grain legumes, particularly improved pigeonpea and cowpea varieties, in the mid-2000s. They encouraged farmers to intercrop these legumes with maize as a way of improving soil productivity, food security and income. The initiative was based on known benefits of introducing legumes in maize-dominated cropping systems of southern Africa (Jeranyama et al., 2000; Giller, 2001; Snapp et al., 2003; Waddington et al., 2007). Although the initiative was targeted at overcoming prevailing soil fertility problems, there were no best practice guidelines and intercropping had not been systematically studied to develop site-specific recommendations for farmers interested in the new cropping systems.

Inclusion of legumes as intercrops requires rearrangement of the planting patterns through substitutive or additive designs to maintain the productivity of the main crop (Liebman and Dyck, 1993; Giller, 2001). Competition can also be reduced by staggering the planting dates of the companion crops in the intercropped system (Francis et al., 1982). Staggered planting is also used for reducing risk of total crop failure when expected rainfall is uncertain and within-season fluctuations are common (Cooper et al., 2008). In central Mozambique, the promoted intercropping strategy was a substitutive design where two rows of maize alternate with a row of the legume reducing the plant population for both maize and legume compared with sole crops. Yet in southern Malawi, maize is intercropped with pigeonpea in the same row in an additive design. The space lost to the pigeonpea is compensated by sowing three maize seeds per planting station thus maintaining the plant population of maize which results in no substantial yield loss (Sakala et al., 2000).

Intercropping systems have not been studied in central Mozambique; we studied maize–pigeonpea and maize–cowpea intercropping under farmers' conditions for 3 years from 2008 to 2011 in the Ruaca and Vunduzi communities in central Mozambique. The central objective of this study was to understand the farming system, and to evaluate the suitability of maize–legume intercropping to alleviate the biophysical and socio-economic constraints faced by smallholder farmers in central Mozambique. In Ruaca, grain yields, rainfall infiltration, economic returns and acceptability of maize–pigeonpea intercropping were compared for two intercrop combinations and sole crops under different N and P application levels. In Vunduzi, grain yields of maize–cowpea intercrops were compared for two intercrop combinations and sole crops under different N and P application levels. In addition, we assessed the proportion of farmers practising maize–pigeonpea intercropping each season.

2. Materials and methods

2.1. Study areas

The experiments were conducted in the Ruaca (18°50′S, 33°11′E; 700 masl; mean seasonal rainfall of 900 mm) and Vunduzi (18°46′S, 34°20′E; 300 masl; mean seasonal rainfall of 700 mm) villages in central Mozambique. Rainfall occurs between October and April in a unimodal distribution pattern. Soils in both sites are predominantly sandy of extreme poor fertility (Table 1) classified as Haplic Lixisols (FAO). The extensive farming systems are characterised by slash and burn and no mineral fertilisers are used. Farmers traditionally grow food crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) (Rohrbach and Kiala, 2007). Local varieties of pigeonpea are traditionally grown on the edges of fields, and cowpea (*Vigna unguiculata* (L.) Walp.) in mixtures of more than three crops in fields close to the homestead. Fewer farmers grow

Table 1
Selected top-soil (0–20 cm) properties of representative soil profiles in (a) Ruaca and Vunduzi and (b) fields used in the rainfall simulation experiment in Ruaca village, central Mozambique.

(a)										
Site	Bulk density ($mg\,m^{-3}$)	pH	Organic C (%)	Total N (%)	Available P ($mg\,P\,kg^{-1}$)	Exchangeable K ($cmol_c\,kg^{-1}$)	Exchangeable Ca ($cmol_c\,kg^{-1}$)	Particle size (%)		
								Clay	Silt	Sand
Ruaca	1.5	6.0	0.6	0.04	3.0	0.2	2.2	9	11	80
Vunduzi	1.6	5.9	0.9	0.08	4.0	0.4	2.8	10	13	77
(b) Rainfall simulation experimental fields										
Field										
0 year, continuous maize	1.5	5.9	0.2	0.02	0.7	0.1	0.5	11	9	80
1 year, maize–pigeonpea	1.4	6.0	0.6	0.04	2.8	0.2	2.2	14	12	74
3 years, maize–pigeonpea	1.4	5.9	1.2	0.08	6.9	0.3	3.6	6	5	89
5 years, maize–pigeonpea	1.3	6.0	1.4	0.09	8.4	0.3	3.8	14	11	75

groundnuts (*Arachis hypogaea* L.) as a sole crop often on small pieces of land. Maize is an important food and cash crop which is often intercropped with pigeonpea or cowpea in both sites. Cultivation on mountain slopes is common in Vunduzi whereas fields in Ruaca are fairly level. Labour shortages often lead to severe weed pressure which is only controlled by burning the entire field before seeding of the next crop.

2.2. On-farm trials

Experiments in which maize was intercropped with pigeonpea were established on four farms with four replications per farm in Ruaca, and maize intercropped with cowpea was established on six farms with two replications per farm in Vunduzi. Replications were reduced in Vunduzi due to the relatively smaller fields compared to Ruaca. In Ruaca, pigeonpea was a priority cash crop because of a ready outside market, whereas in Vunduzi farmers preferred cowpea because their primary concern was food security. To reduce variability, all selected experimental fields were previously under continuous maize monocropping for at least 5 years prior to the establishment of the trials. In Ruaca, the treatments tested over three seasons (2008–2011) were: (a) maize sole crop (37,000 plants per ha), (b) pigeonpea sole crop (37,000 plants per ha) for the first two seasons followed by a maize sole crop, (c) within-row intercropping where maize and pigeonpea were planted within the same row (0.9 m between rows and 0.45 m between maize and pigeonpea plants within the row, three plants per station to give a population of 37,000 maize plants and 37,000 pigeonpea plants), and (d) distinct-row intercropping where two maize rows alternated with a single row of pigeonpea (2 m between rows of pigeonpea and 0.9 m between rows of maize to give a population of 24,667 plants of maize and 16,667 pigeonpea plants). The distinct-row intercropping treatment was considered local as farmers were practising it whereas the within-row treatment was adapted from southern Malawi (Sakala, 1994). Due to practical considerations we did not increase the plant population of the distinct-row intercrop option; it would be impossible to get between the rows and weed if normal population density of crops was maintained and the rows were separate.

The experimental design was split-plot; major plots (6 m wide × 80 m long) were for crop arrangement and split into 16 sub-plots (6 m wide × 5 m long) for fertiliser treatments. Fertiliser treatments imposed on all sole and intercrop treatments were: (i) no fertiliser, (ii) $20\,kg\,P\,ha^{-1}$, (iii) $20\,kg\,P\,ha^{-1} + 30\,kg\,N\,ha^{-1}$, and (iv) $20\,kg\,P\,ha^{-1} + 60\,kg\,N\,ha^{-1}$. The plots for distinct-row intercropping treatment were wider (10 m wide × 80 m long) to accommodate more rows of pigeonpea. Maize and pigeonpea were planted simultaneously because pigeonpea grows slowly and offers little competition to maize. In the third season (2010–2011), the residual benefits of pigeonpea were measured by planting maize in plots previously with sole pigeonpea. To maintain a sole crop of pigeonpea in the last season, continuous maize plots were split into two; continuous maize was planted in eight plots and sole pigeonpea was planted in the remaining eight plots.

In Vunduzi, the treatments tested for the same period were: (a) maize sole crop (37,000 plants per ha), (b) cowpea sole crop (111,000 plants per ha), (c) within-row intercropping where maize and cowpea were intercropped within the same row (0.9 m between rows and 0.45 m between maize and cowpea plants within the row, three plants per station to give a population of 37,000 maize plants and 37,000 cowpea plants), and (d) distinct-row, intercropping with two maize rows alternated with a single row of cowpea (0.9 m between rows of maize to give a population of 24,690 plants of maize and 18,500 cowpea plants). The experimental design was split-plot with the major plots (6 m wide × 40 m long) being for crop arrangement were split into 8 sub-plots of 6 m width × 5 m length for fertiliser treatments. The plots for distinct-row intercropping treatment were wider (10 m wide × 40 m long) to accommodate more rows of cowpea. Cowpea was planted 6 weeks after maize to reduce competition to maize (Shumba et al., 1990), and was the standard local practice. Fertiliser treatments in Vunduzi were the same as in Ruaca. Phosphorus was applied in the planting holes for both maize and legumes but N was spot applied as a top dressing on maize at four and eight weeks after planting. It was not possible to quantify the residual benefits of cowpea in Vunduzi because maize failed totally the preceding season.

The experiments were established without tillage in both sites: planting and weeding was done with minimal soil disturbance using hand hoes. In Ruaca, fewer than 20% of the farmers own livestock and tillage implements, and the majority use hand hoes for land preparation and planting. In Vunduzi, farmers do not own cattle and use hand hoes for land preparation and planting. Cattle were decimated in this area due to a combination of the long civil war and livestock diseases, and tsetse fly (*Glossina* spp.) is still prevalent in the area. Previous crop residues were retained *in situ* but soil cover at planting was less than 10% in all seasons mainly due to termite attacks. The seeds of maize hybrid SC513 (137 days to maturity), improved pigeonpea ICEAP00040 and cowpea (erect type short season, 75 days to maturity variety derived from IT18) were planted into moist soil.

2.3. Soil sampling and analysis

In 2008, soil was sampled in experimental fields from 0 to 20 cm depth, air-dried, sieved and stored prior to analysis. Bulk density was calculated as mass of oven dry soil core divided by volume of the core; undisturbed soil cores were taken using metal rings of 8 cm internal diameter and height of 5 cm. Soil texture analysis was done through the hydrometer method, pH was measured with a digital pH metre in a 1:2.5 (w/v) soil: deionised water suspension. Total C and N were analysed through dry combustion using a Carbon/Hydrogen/Nitrogen Analyzer (Leco-CNS2000). The K and Ca concentrations were determined by flame photometry, and plant available P using the Bray method (Anderson and Ingram, 1993). Data from a selected soil profile most representative of the soil in each site is presented in Table 1.

2.4. Crop yield and rainfall measurements

Daily rainfall was measured with a rainfall gauge in the experimental fields. Grain and above-ground biomass yield measurements were estimated from 3 rows × 2 m sub-plots in the centre of each plot after physiological maturity. Pigeonpea and cowpea pods were harvested when they turned brown, dried and shelled by hand. Maize and legume grain yield was calculated at 12% moisture content and stover on dry weight basis. Sub-samples for stover were taken and dried at 70 °C for moisture correction. Maize was harvested in mid-April and pigeonpea in mid-August. Cowpea was harvested three weeks after maize harvest.

2.5. Infiltration measurements

In 2010, water infiltration measurements were carried out in selected farmers' fields using a portable rainfall simulator described by Amezquita et al. (1999). A chronosequence of continuous maize–pigeonpea intercropping was established through farmer interviews and soil sampling; fields for the rainfall simulation experiment were selected based on similarity in soil properties (Table 1b). Durations of intercropping compared were: 0, 1, 3 and 5 years; zero duration corresponded to continuous maize monocropping. Simulated rainfall with intensity of 70 mm h^{-1} was applied for 2 h on an area measuring 0.13 m^2 (0.325 m × 0.4 m) surrounded by a 4 cm buffer zone (Thierfelder and Wall, 2009). An intensity of 70 mm h^{-1} was chosen because it is a typical intensity for tropical and semi-arid rainfall (Hudson, 1993), and ensured uniformity of raindrop size. The small plots were confined using metal sheets leaving a single outlet leading into a small gutter where runoff was collected. Rainfall simulations were performed when the soil was close to field capacity (we allowed 2 days after rainfall events) in February 2010 when maize was at grain filling and pigeonpea was still in vegetative growth. Horton's equation, which describes water infiltration as a continuous function in which infiltration rate decreases asymptotically from an initial value, was fitted to the infiltration data for the short duration fields (<3 years of intercropping): $f = f_c + (f_0 - f_c)e^{-kt}$, where f is the maximum infiltration rate (mm h^{-1}) at time t, f_c is the saturated soil infiltration rate (mm h^{-1}), f_0 is the initial infiltration rate (mm h^{-1}) at time zero, k is a constant that defines function f, and t is time (Horton, 1940). Infiltration characteristics in the longer duration fields (3 and 5 years of continuous intercropping) were well described by a sigmoidal decay curve characterised by a lag-phase of decrease of initial infiltration with four parameters: $i_t = i_f + \frac{i_i - i_f}{1-(t/t_0)^K}$ where t_0 is time at $i_i/2$, i_i is initial infiltration, and i_f is infiltration at saturation.

2.6. Farm surveys

Focus group discussions were conducted in the study sites to identify local criteria used by farmers to categorise themselves into different resource groups (RG). The indicators of resource ownership were prioritised, and based on these; all farmers in the village were allocated to one of the identified resource groups. A total of 52 and 42 farmers were interviewed in Ruaca and Vunduzi, respectively. Initial selection of farmers was random but some of the selected farmers were not willing to be interviewed and we had to select from those initially omitted. The interviews were conducted at the farmer's homestead with the assistance of local extension officers to understand landholdings, crop types, typical crop rotations, nutrient inputs, and tillage and crop residue management. Socio-economic characteristics included family size, labour availability, months of food security, sources of income, proportion of off-farm income and production orientation. Land to labour ratio was calculated by dividing the land size and available labour per farm. Comparing households, small values of land:labour ratio indicate land limitation, larger values suggest labour limitation. A specific question was asked to ascertain the number of farmers who had planted the intercrops, this data was verified through transect walks and fields visits.

A matrix scoring method on a scale of 1–20 was used to evaluate the maize–pigeonpea intercrops and the corresponding sole crops treatments in the 2009/2010 season using the criteria of food security, cash income, input costs, ease of weeding and time to maturity. A group of 23 farmers (14 women and 9 men) participated in the evaluation using a combination of visual assessments, ranking and scoring procedures. Final scores were obtained by multiplying the scores given by farmers and the appropriate weight of each criterion (Pimbert, 1991), assigned through pairwise ranking. Acceptability of a treatment was calculated as the percentage of total score to the maximum possible score for each treatment. The full scoring procedure is described by Rusinamhodzi and Delve (2011).

2.7. Labour data collection

We estimated labour requirements by direct observation for each treatment from the experimental plots (480 and 800 m^2). A regular team of farmers performed required activities on each plot at similar times of the day; the farmers were not informed that their activities were being timed. Important recordings were: activity, start time, number of people, treatment, plot size and end time. The average labour times for each task for each treatment were calculated and converted to man-days units (8 h) per hectare. Weeding was done three times at three, six and nine weeks after crop emergence; reported data is total time for the three weeding stages. Data from "farmers' recall" were not used because there were many confounding factors mainly related to planting densities, not having all treatments and the irregular nature at which farmers carried out their activities.

2.8. Calculations and statistical analysis

Intercrop productivity was analysed using the land equivalency ratio (LER) method (de Wit and van Den Bergh, 1965), computed using the following formula: LER = [intercrop maize yield/sole maize yield] + [intercrop legume yield/sole maize yield] where all yields are expressed in t ha^{-1}. LER is relative land requirements for intercrops compared to monocrops. LER values greater than 1.0 show that intercropping is more productive and those less than 1.0 show that monocropping is more efficient. Competition was evaluated by computing the competitive ratio (CR) using the formula described by Willey and Rao (1980):

$$CR_{\text{crop}\,x} = \left(\frac{LER_{\text{crop}\,x}}{LER_{\text{crop}\,y}}\right) \times \left(\frac{Z_x}{Z_y}\right)$$

where Z_x and Z_y are the sown proportion of each crop in the mixture. Yield penalty was calculated as the percentage difference in yield between sole crop maize and intercropped maize; data reported for each intercrop treatment was calculated as an average for three seasons across fertiliser treatments.

A principal components analysis was performed to determine the household characteristics that were most important for explaining variability between the identified farmer resource groups (McLachlan, 2005) in both Ruaca and Vunduzi. A partial budget analysis was done at farm level to understand the impact of moving from maize monocropping to maize–pigeonpea intercropping in Ruaca. The marginal rate of return (MRR) was calculated by expressing the difference between the net benefit of the treatments under comparison as a percentage of the difference of the total variable costs (Evans, 2005). Different price scenarios were used for both crops as significant price changes were observed; prices were often subdued soon after harvest but rose sharply as supply of produce diminishes especially in November and December.

The generalised linear model (GLM) in SAS 9.2 (TS2MO) of the SAS System for Windows © 2002–2008 was used to test the individual and interactive effects of intercropping treatment, fertiliser application and season on crop yield. The interactions tested were intercrop treatment × fertiliser, and season × arrangement × fertiliser. In the analysis, intercropping treatments and fertiliser application were considered fixed factors whilst season was considered as a random factor. The standard error of difference between means was calculated using the procedure described by Saville (2003).

3. Results

3.1. Rainfall distribution

More rainfall was received in Vunduzi (mean of 947 mm and coefficient of variation of 15%) than in Ruaca (mean of 729 mm and coefficient of variation of 9%). Rainfall distribution was erratic and variable between sites and seasons (Fig. 1). Severe mid-season drought spells were common with only the 2008/2009 season having well-distributed rainfall. There was a severe dry spell in the first half of the 2009/2010 season followed by excessive rainfall. By contrast there was heavy rainfall early in the 2010/2011 season until January and then a severe long dry spell in February and March.

3.2. Grain yields and intercrop productivity in Ruaca

Season (through rainfall distribution) and crop arrangement had a significant effect ($p < 0.001$) on maize and pigeonpea grain yield, and intercrop productivity in Ruaca (Table 2 and Fig. 2); the interactions between fertiliser and intercrop treatments were weak. Maize yield in the within-row intercropping treatments was larger than in sole crop in both the 2009/2010 and 2010/2011 seasons whereas the distinct-row intercropping resulted in significantly less yield than the sole crop in both the 2008/2009 and 2009/2010 seasons. The largest yield in sole maize was 2.3, 2.6 and 0.8 t ha^{-1} for 2008/2009, 2009/2010 and 2010/2011, respectively; in the distinct-row intercropping treatment it was 0.8, 1.6 and 2.8 t ha^{-1} and in the within-row intercropping treatment 1.6, 2.8 and 5.8 t ha^{-1} (Fig. 2). In the 2008/2009 season, the response of maize to N and P fertilisation was significant; 20 kg ha^{-1} P and 60 kg ha^{-1} N increased maize yields in the sole crop by 1.4 t ha^{-1}, in the within-row intercrop by 0.4 t ha^{-1}, and by 0.3 t ha^{-1} in the distinct-row intercropping treatment compared to no fertiliser application. Pigeonpea responded better to fertiliser application in the second and third season but not in all treatments (Fig. 2b). Pigeonpea grain yield was 1.2 t ha^{-1} in sole crop, 0.8 t ha^{-1} in distinct-row intercrop and 1.0 t ha^{-1} in within-row intercrop in 2008/2009 season and there was no response to fertiliser application (Fig. 2b). In 2009/2010, intercropping reduced significantly the yield of pigeonpea, the largest yield was 1.5 t ha^{-1} in sole crop, 0.7 t ha^{-1} in distinct-row and 0.9 t ha^{-1} in within-row intercropping. The yield penalty of intercropping maize was compensated for by yield of the companion pigeonpea crop leading to LERs of at least one for all treatments across all seasons (Table 2). The yield penalty for intercropping maize and pigeonpea within the same row was small (8%) compared with the distinct-row option (50%). LERs for within-row intercropping were significantly larger than for distinct-rows in all years. In the third year, sole maize yields in Ruaca were strongly suppressed (<0.8 t ha^{-1}) by heavy infestation with striga (*S. asiatica* (L.) Kuntze) that was not observed in the intercrops or the sole pigeonpea plots. Yields of maize grown as a sole crop after two previous years of sole pigeonpea yielded 4.8 t ha^{-1} without fertiliser and 5.9 t ha^{-1} with addition of only 20 kg P ha^{-1} (Fig. 3) and there was no response to N fertiliser application. Competitive ratios (CR) were larger for maize (0.9–1.4) than for pigeonpea (0.7–1.1) in maize–pigeonpea intercropping.

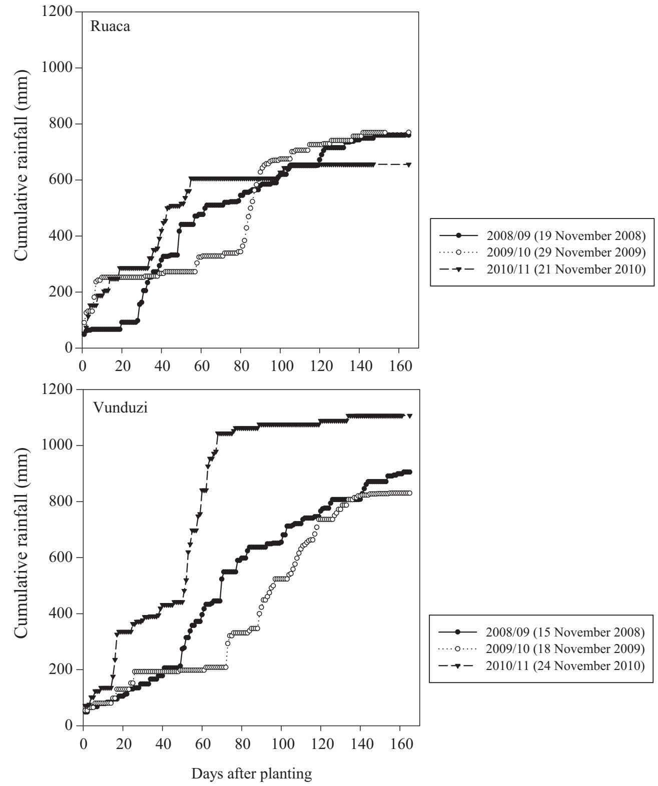

Fig. 1. Cumulative rainfall distribution at the two experimental sites (Ruaca and Vunduzi) for three consecutive seasons. The rainfall pattern is unimodal and occurs between October and April, dates in parenthesis are the maize planting dates for each season.

3.3. Grain yields and intercrop productivity in Vunduzi

Season (through rainfall distribution) and crop arrangement had a significant effect ($p < 0.001$) on maize and cowpea grain yield in Vunduzi; fertiliser application had a significant effect on cowpea and not maize yield (Table 2 and Fig. 2). In Vunduzi, the within-row intercropping strategy was more productive than the farmers' two rows of maize alternating with a row of cowpea in 2010/2011 when both crops yielded (Table 2). In the maize–cowpea intercrops, the poor productivity of maize due to long dry spells reduced competition, which led to relatively greater cowpea productivity. The intercropping treatments were at least equal to or more productive

Table 2
Effect of intercropping, fertiliser application and season on the land equivalence ratios (LER) of maize–legume intercropping in Ruaca and Vunduzi.

Treatment	Fertiliser	Maize–pigeonpea intercropping (Ruaca)			Maize–cowpea intercropping (Vunduzi)		
		2008/2009	2009/2010	2010/2011	2008/2009[a]	2009/2010[b]	2010/2011
Distinct-row	No fertiliser	1.1	1.1	1.4	–	–	1.4
	20 kg P ha^{-1}	1.0	1.1	1.2	–	–	1.8
	30 kg N + 20 kg P ha^{-1}	1.1	1.0	1.2	–	–	1.7
	60 kg N + 20 kg P ha^{-1}	1.0	1.2	1.3	–	–	1.9
Within-row	No fertiliser	2.2	1.7	2.0	–	–	2.4
	20 kg P ha^{-1}	1.4	1.7	2.4	–	–	2.0
	30 kg N + 20 kg P ha^{-1}	1.4	2.0	2.0	–	–	2.2
	60 kg N + 20 kg P ha^{-1}	1.5	1.9	2.1	–	–	2.0
[c]SED		0.1	0.1	0.2	–	–	0.2

[a] In the 2008/2009 season, farmers consumed the cowpea before the experiment could be harvested, LER not calculated.
[b] In the 2009/2010 season, the maize crop failed completely due to a prolonged mid-season dry spell, LER not calculated.
[c] Combined SED for treatment means.

than the sole crop, as shown by the LERs (Table 2). In the first year (2008/2009), no cowpea yields were recorded in Vunduzi because farmers started consuming it due to their severe food insecurity before measurements could be made. In the 2009/2010 season, maize completely failed due to a prolonged dry spell lasting more than 55 days, yet cowpea survived and gave a significant harvest especially in plots where N and P fertiliser was applied (Fig. 2a). We also observed that maize was affected more by the dry spells in plots that received N than plots that received only P fertiliser. Cowpea yield responded better to fertiliser application than maize. In Vunduzi, the yield penalty of intercropping maize and cowpea was 6% in the within-row treatment and 25% with distinct-rows. In the maize–cowpea intercrop, the CRs for maize ranged from 1.2 to 1.8 and for cowpea 0.6 to 0.8.

3.4. *Rainfall infiltration*

Intercropping maize and pigeonpea continuously for 5 years increased steady state rainfall infiltration from 6 mm h^{-1} to 22 mm h^{-1} compared with continuous maize monocropping (Fig. 4). There was more surface water run-off (94%) on plots that were under continuous maize than on plots that were intercropped since 1 year (88%), or 3 years (68%), and least (42%) run-off was recorded on plots that were since 5 years under intercropping. Infiltration characteristics in the sole maize field and the field that was intercropped since only 1 year, followed an exponential decrease whereas in the fields that had been intercropped since 3–5 years, the pattern followed a sigmoidal decay curve characterised by a lag-phase in decrease of infiltration.

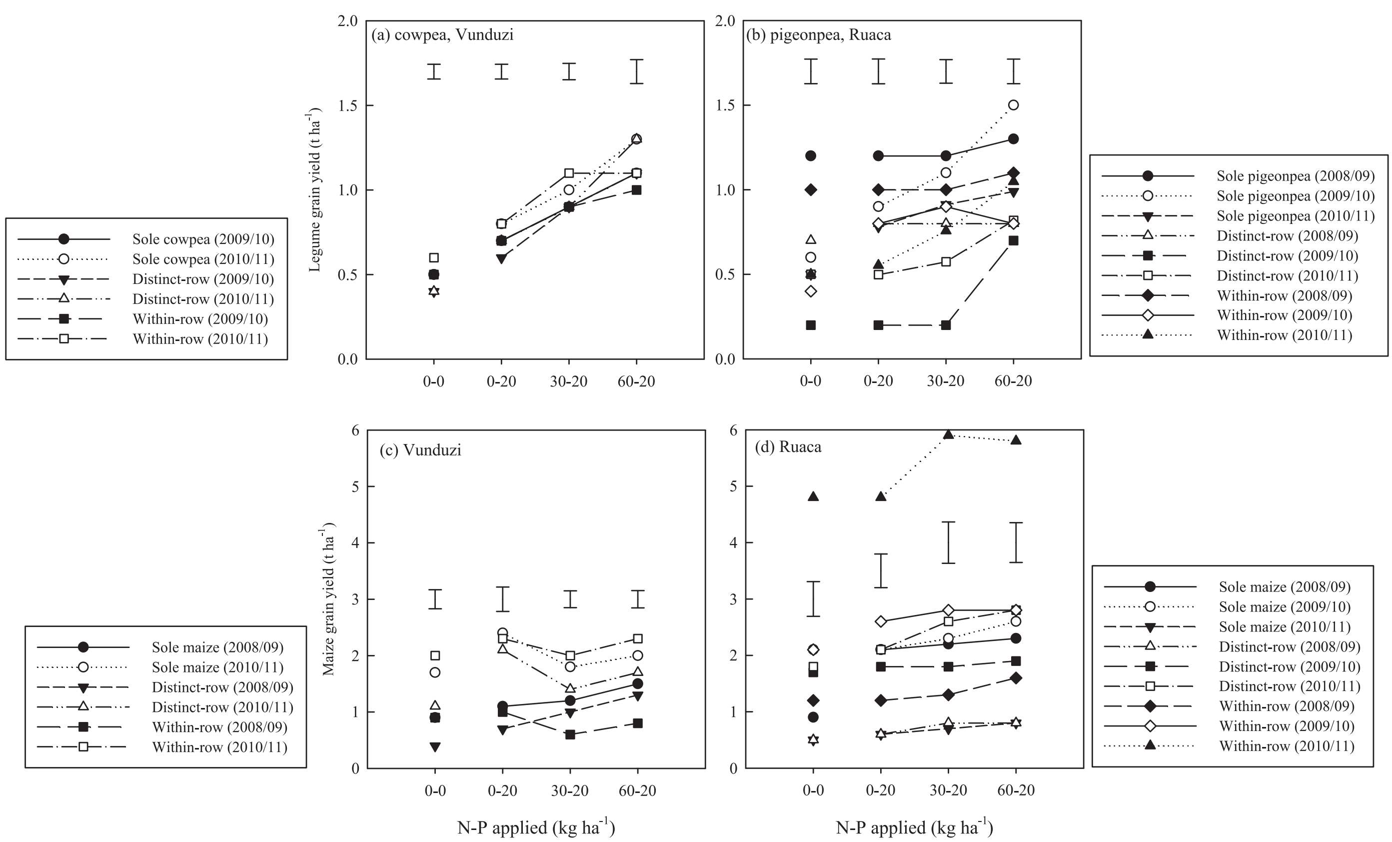

Fig. 2. Effect of intercropping, N and P fertilisation, and season on grain yield of (a) cowpea, (b) pigeonpea, (c) maize in Vunduzi, and (d) maize in Ruaca. Maize and legume yields plotted at different scales to allow easier visualisation of effects. Error bars indicate the standard error of difference between means (SED).

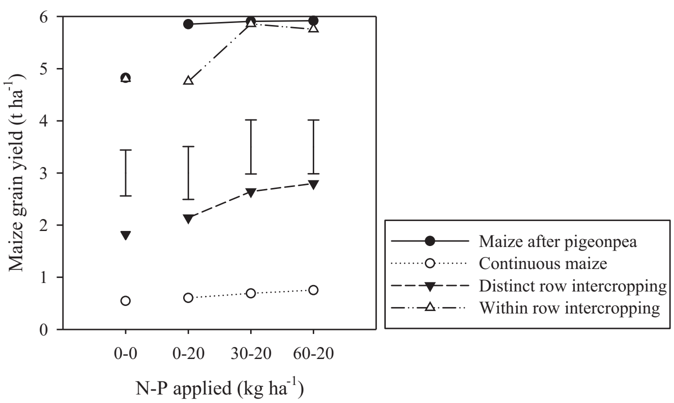

Fig. 3. Effect of intercropping, rotation, and N and P fertilisation on maize–grain yield in Ruaca in the third (2010/2011) season.

3.5. Economic analysis

Weeding in sole maize required a total of 17.6 man days per hectare, in sole pigeonpea it increased to 18.2, to 22.3 in within-row intercrops, and to 26.4 man days per hectare in the distinct-row intercrops. On average, intercropping maize and pigeonpea increased weeding time by 36%. The analysis of benefits *versus* variable costs showed that integrating legumes into maize-based cropping systems increased profitability at all price scenarios for the crop grain sales with a minimum of 343% MRR (Table 3a). The MRR was greater without than with fertiliser mainly because the sole maize crop responded better to fertiliser than when intercropped. Farmers generally sold their produce immediately after harvest when prices were low; later in the year, maize prices increased by up to 140% and pigeonpea prices by up to 50% of the initial prices. Under these price scenarios, farmers' earnings increase by 67% without fertiliser and 35% with fertiliser for the within-row intercropping treatment and, 36% without fertiliser and 61% with fertiliser for the distinct-row treatment (Table 3a).

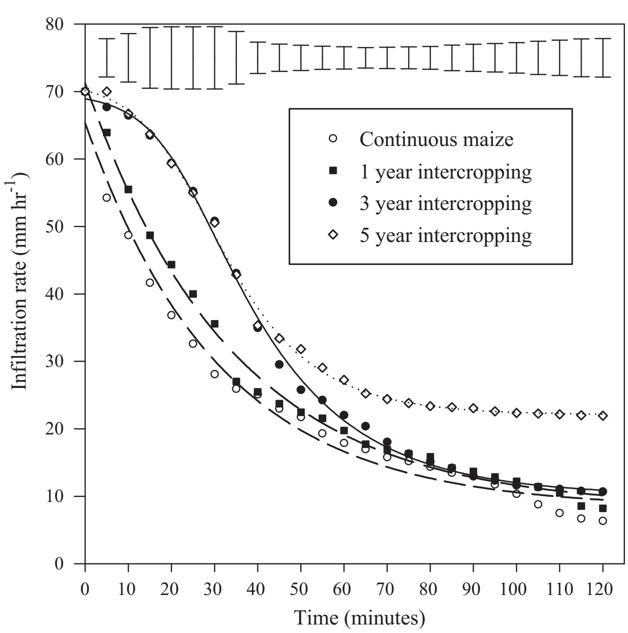

Fig. 4. Simulated rainfall infiltration as affected by duration of intercropping in a sandy soil in Ruaca village, central Mozambique. Error bars indicate the standard error of difference between means (SED). Lines show fitted data according to equations described in Section 2.5.

3.6. Farmer evaluation of maize–pigeonpea intercrops in Ruaca

Food security and cash income were identified by farmers as priority production objectives. Input costs, ease of weeding and time to maturity, in that order, were also important for evaluating maize–pigeonpea intercrops. Overall, farmers preferred intercrops over sole crops; although not currently practised, the within-row intercropping strategy was found to be the most acceptable to farmers (84%) followed by distinct-row intercropping, and sole maize was more acceptable than sole pigeonpea (Table 3b). Farmers in the richest and poorest resource group (see Section 3.6) did not attend these evaluation meetings as a result the acceptability scores were for the middle resource group. Scores did not differ between men and women.

3.7. Diversity of farmers in the study areas in relation to the practise of maize–legume intercropping

Four resource groups were identified in Ruaca using the size of cropped land, the number of cattle owned, the farmers' production orientation and the characteristics of the main house (Table 4). Farmers in category RG4 were under-resourced and frequently worked as casual labourers for wealthier farmers in the village. Farmers in category RG1 depended on off-farm activities for most their livelihoods, provided an important link with traders and employed labourers. Only farmers in RG2 and RG3 were already practising maize–pigeonpea intercropping. In Vunduzi, field size and household characteristics were important as indicators of wealth status and three resource group categories were identified. Farmers in the best resourced group (RG1) regularly hired casual labourers because they cropped large areas and used the produce to pay for the labour. Only better-resourced farmers in RG1 and RG2 practised maize–legume intercropping. Principal components analysis showed that more than 97% of the variability in households in Ruaca was explained by the first three principal components, PC1 (89%), PC2 (6.7%) and PC3 (1.9%). In Ruaca, PC1 was strongly related to livestock ownership and PC2 was related to land size owned and area of land cropped. The variability in households in Vunduzi was explained by more factors as compared with Ruaca, the first three principal components accounted for only 74% of the variability, PC1 (42.3%), PC2 (20.3%) and PC3 (11.7%). In Vunduzi, PC1 was related to the area of land cropped and PC2 to the number of goats and pigs.

The land:labour ratio was greater in Ruaca (1.6 ha person^{-1}) than Vunduzi (0.6 ha person^{-1}), however land utilisation was greater in Ruaca (76%) than in Vunduzi (62%). In Vunduzi only 2% of the farms were self-sufficient in food for 12 months whereas in Ruaca, 46% of the farmers were self-sufficient in food for 12 months. The proportion of farmers practicing maize–pigeonpea in Ruaca decreased from 85% in the 2007/2008 season to 78% in 2008/2009, 52% in 2009/2010 and finally to 37% in the 2010/2011 season. In Vunduzi, the proportion increased from 25% in 2007/2008 to 32% in 2008/2009, it was 34% in 2009/2010 and finally to 66% in the 2010/2011 season.

4. Discussion

4.1. Maize–legume intercrop productivity

Our results suggest that maize–legume intercropping fits well within the biophysical and socio-economic conditions of smallholder farmers in central Mozambique and is a suitable starting point for ecological intensification. The maize–legume intercrop options studied were relatively more productive than the corresponding sole crops despite a strong response to seasonal variation in rainfall. Thus, grain yield results across seasons suggest that crop

Table 3
(a) The marginal rate of return of sole pigeonpea and maize–pigeonpea intercropping compared with sole maize cropping with and without fertiliser at variable prices of both maize and pigeonpea and (b) acceptability of maize–pigeonpea intercrops to farmers' production orientation and objectives in Ruaca village, numbers in parenthesis are the weighted scores (score × weight).

(a)

Fertiliser	Production option	MRR (%) at given price condition			
		Normal price	Peak maize price (+140%)	Peak pigeonpea price (+50%)	Peak price for both crops
No fertiliser	Sole pigeonpea	3729	437	6819	3528
	Within-row	667	1361	1112	1639
	Distinct-row	343	621	465	743
Fertiliser (20 kg P and 30 kg N ha^{-1})	Sole pigeonpea	759	93	1326	660
	Within-row	500	791	673	963
	Distinct-row	472	472	758	758

(b)

Evaluation criteria	Treatment (scoring scale 1–20)			
	Sole maize	Sole pigeonpea	Distinct row intercrop	Within row intercrop
Food security (weight = 5)	14 (70)	8 (40)	19 (95)	20 (100)
Cash income (weight = 4)	6 (24)	18 (72)	16 (64)	20 (80)
Input costs (weight = 3)	15 (45)	9 (27)	12 (36)	10 (30)
Ease of mechanical weeding (weight = 2)	15 (30)	14 (28)	6 (12)	15 (30)
Time to maturity (weight = 1)	14 (14)	4 (4)	12 (12)	12 (12)
Total score	183	171	219	252
Acceptability (%)	61	57	73	84

production in the two sites was water-limited (Harmsen, 2000). In a similar study spanning over 12 years in a loamy sand soil under sub-humid conditions in Zimbabwe, Waddington et al. (2007) reported that yield variations between seasons was mainly caused by rainfall fluctuations; maize yield was reduced when rainfall was below 600 mm with or without fertiliser application.

Well-designed maize–legume intercrops in both time and space have been found to be highly productive (LER ≥ 1) and efficient in resource utilisation under sub-humid conditions resulting in maintenance or improvement of the yield of the main crop (Baldé et al., 2011). The small yield penalty in within-row maize–pigeonpea intercropping showed that pigeonpea can provide an additional yield benefit without negatively affecting maize as has been reported previously (Sakala, 1994; Waddington et al., 2007). Intercropping cowpea with a non-legume has also been shown to increase the efficiency of the biological N fixation process and reduces the reliance of the legume on applied N (Rusinamhodzi et al., 2006). Cowpea was harvested when maize totally failed in Vunduzi in 2009/2010 season suggesting that relay planted intercropping with short duration crops such as cowpea can reduce risk of crop failure under erratic rainfall. Other authors have demonstrated that intercropping can reduce the risk of low yields or crop failure associated with drought or unpredictable rainfall (*e.g.* Ghosh et al., 2006). On the other hand, the failure of maize crop was beneficial to cowpea as there was no shading; Ofori and Stern (1987) suggested that cowpea yields are likely to be depressed due to shading by the companion maize crop. In 2010/2011 season, cowpea yields were not reduced even though maize yields were large (Table 3) suggesting reduced competition for resources. Jeranyama et al. (2000) reported that companion maize–grain yields were not reduced when cowpea was relay planted because peak nutrient demands where temporally different.

Effect of fertiliser application on maize yield was poor in both sites due the effects of dry spells which coincided with critical

Table 4
Perception of wealth and the resource groups identified by farmers in Ruaca and Vunduzi villages in central Mozambique. Numbers in parentheses are the farmers in that particular resource group.

Ruaca				Vunduzi		
RG4 (14)	RG3 (19)	RG2 (13)	RG1 (6)	RG3 (5)	RG2 (33)	RG1 (5)
Land size: 0.5–1 ha, small compound, sells labour, and consistently food insecure. They are mostly heavy drinkers and children do not go to school. Lack of blankets, utensils and clothes.	Land size: 2–5 ha, cattle owned: <5, goats: <3, medium compound, occasionally sell labour, production is just enough to feed the family, Own a vegetable garden.	Land size: ≥10 ha, cattle: 5–10, goats: >10, permanent house and farm workers, transport: ox-cart and bicycle. Consistently food secure, more off-farm activities and income. Access to clean water and good sanitation. Children go to school.	Land size: ≥10 ha, cattle: >10, goats: >10, permanent house and farm workers, transport: car, bicycle, ox-cart. Have jobs in the city. Main house has bricks walls and iron sheets. Own a car, clean water and good sanitation. Access to credit and loans.	Land size: <0.5 ha, one small house in the compound. Food insecure, sell labour, heavy beer drinkers. Always have many children.	Land size: 0.5–1 ha, small and few houses. Goats: <5, chickens: <10. Food production is slightly below consumption. Own a bicycle for transport, and a radio.	Land size: ≥5 ha. Main houses with iron sheets in a large. Goats ≥ 20 compound. Hire farm labourers. Own at least 1 bicycles for transport, at least 4 radios. Produce a variety of crops (beans, pigeonpea, groundnuts). Sell crop produce.

crop growth stages such as tasseling and silking. Pigeonpea yield responded significantly to the largest N input of 60 kg ha^{-1}. Ghosh et al. (2006) reported that N is a limiting factor for growth of pigeonpea intercrop during the first half of the season, thus N fertiliser is necessary to improve productivity. Cowpea responded significantly to the application of N and P fertiliser in the seasons when it was harvested. The good response to fertiliser in cowpea was due to staggered planting; its maturity coincided with favourable moisture conditions later in the season. However, Ofori and Stern (1987) reported larger yield loss of cowpea with addition of N fertiliser in a silt loam soil under Mediterranean-type climate.

Rotational effects of pigeonpea in sole and in intercrop were significant; the initial effect was through the reduction of Striga infestation. Continuous maize was heavily infested with Striga in the third season of the experiment leading to yield loss of up to 88% compared to maize after pigeonpea. Other studies have reported that Striga infestations can reduce maize yields by up to 80% (*e.g.* Ransom et al., 1990); both rotation and maize–legume intercropping are effective to overcome this challenge (Oswald and Ransom, 2001; Oswald et al., 2002). A second effect was the residual N effect from pigeon pea. In our experiments, maize after pigeonpea did not respond to added N but only to P because pigeonpea has been found to contribute as much as 90 kg N ha^{-1} to the N nutrition of the next maize crop (Sakala et al., 2000), which might have been sufficient under the conditions of our study.

4.2. Rainfall infiltration

Rainfall infiltration improved significantly with duration of maize–pigeonpea intercropping. The infiltration curves were also different with long-term intercropping causing a lag-phase in infiltration rate, which was attributed to the high accumulation of biomass covering the soil surface and the concomitant increase in soil carbon (C) (Roth et al., 1988). Vachon and Oelbermann (2011) observed that the integration of N-rich legumes in maize-based systems leads to sequestration of C compared with sole crops. Pigeonpea was harvested two months before the start of the succeeding season which ensured crop residues retention and substantial soil C input. Myaka et al. (2006) reported that increased circulation of organic matter due to pigeonpea had a likely long-term effect on soil quality. The undisturbed continuous pore system and the absence of a hardpan due to no-till also contributed to the observed high infiltration (Thierfelder and Wall, 2009). The deep-rooting characteristic of pigeonpea is also thought to contribute significantly to improved infiltration (Godoy et al., 2009). Our results suggest that maize–pigeonpea intercropping in the long-term may lead to greater rainfall infiltration resulting in more water being available for crop growth and offset the effects of dry spells.

4.3. Labour demand, profitability and acceptability

Weeding time was increased by 36% in intercrops although the increase was not related to weed intensity but to the need to take care of pigeonpea which grows slowly compared to maize as well as difficulty in navigating through the crop mixtures. Our results are similar to those of Mucheru-Muna et al. (2009) who reported an increase in requirement for careful weeding operations in intercropping compared with sole cropping. However, other authors have reported lower weeding requirements in maize–legume intercropping systems due to weed suppression (Banik et al., 2006) caused by more crop biomass and better soil cover (Chamango, 2001). Given that in the study sites labour is normally priced on the basis of area worked than the amount of time spent weeding, it is likely that the variation in weeding costs is small between the treatments tested.

The MRR showed that legume monocropping or intercropping with maize was far much more profitable than maize monocropping; profitability was directly related to the proportion of pigeonpea in the intercrop. However, Waddington et al. (2007) reported that low input sole maize was more profitable than when intercropped with pigeonpea or cowpea; low input sole maize was more attractive due to low costs and the a higher selling price than the legumes between 1994 and 2006 in Zimbabwe. In our study area, although maize was commonly sold, it was often sold only when the household food requirements have been achieved whilst pigeonpea could be sold immediately after harvest. Although farmers can increase their earnings if they delay selling their produce at harvest, investments in post-harvest storage and pest control strategies are required. Shifting from sole maize to maize–pigeonpea intercropping can achieve the objectives of improved cash income.

Farmers' evaluation of the intercrops was primarily based on the ability of the options to achieve food security and cash income whilst reducing input costs. Food security was related to yield of maize and cash income to the yield of pigeonpea. On input costs, sole maize scored more than sole pigeonpea and the intercrops. Time to maturity was important because crops should mature early and close the food insecurity gap. Pigeonpea matures late thus the sole pigeonpea crop was scored below maize. This also means that cultivars of pigeonpea that mature early are most suitable for the farmers. Overall, the within-row intercropping strategy was preferred and farmers were willing to shift from the commonly practiced distinct-row intercrop due to its ability to maintain the yield of maize and the relatively high yield of the legume. In general, matching technological performance to farmers' preferences is critical for widespread adoption as farmers prefer technologies that fit within their resources such as labour, capital and management demands (Fujisaka, 1989; Chianu et al., 2006).

4.4. The socio-ecological environment and potential for maize–legume intercropping

Our results suggest that erratic rainfall distribution limited crop responses to added fertiliser despite the low fertility status of the soils (Maria and Yost, 2006). The low N status of the soils is favourable to stimulate legume N_2-fixation but deficiencies of P and K potentially limit the process. Crops such as pigeonpea increase recycling of organic matter, N and other nutrients which is likely to have a long-term beneficial effect on soil fertility (Myaka et al., 2006). The relatively high biomass productivity and late maturity of pigeonpea may delay free-grazing and enable *in situ* crop residue retention and combined with the weed-suppression ability (Gooding, 1962) may facilitate integration with no-tillage practises. Cowpea can also access sparingly soluble P and make it available for uptake by companion or succeeding crop (Vanlauwe et al., 2000). The deep rooted and long duration nature of pigeonpea means that it is suitable for anchoring the soil and preventing soil loss on the steep slopes that are found in Vunduzi and some parts of Ruaca. It may also induce a hydraulic lift, a redistribution of soil water from deeper in the soil profile to dry surface horizons by the root system (Sekiya and Yano, 2004), which may make more moisture available for the companion crop.

Cowpea matures early which is critical to alleviate the food security constraints but had a significantly lower price because it was only sold locally to fellow villagers compared to maize and pigeonpea which had external markets. The high selling price for pigeonpea was particularly attractive to farmers as it was four times that of maize; pigeonpea grain prices ranged between 0.6 and 1.0 US$ per kg whilst that of maize ranged between 0.14 and 0.3 US$ per kg. The attractive market price for pigeonpea in Ruaca was similar to that in Ntcheu district, Malawi as reported by Ngwira et al.

(2012). The number of farmers practicing intercropping in a season in Ruaca suggested that market opportunities for crops were important. Late maturity of pigeonpea coincided with free roaming livestock that destroyed fields in Ruaca and often caused a significant drop in number of farmers growing it the following season. On the other hand, the absence of cattle alone was not enough in Vunduzi to stimulate widespread production of pigeonpea; the sudden rise in proportion of farmers practicing intercropping in 2009/2010 was explained by the emergence of a market for pigeonpea.

Although farmers were diverse and distinct resource groups were identified, they all had similar expectations from their field crop production activities. Farming systems analysis suggested that labour shortage was a greater constraint in Ruaca than in Vunduzi. Land limitation in Vunduzi is an increasing problem because expansion of cropped area is limited by the neighbouring Gorongosa National Park. Despite a larger land:labour ratio in Ruaca, there was significantly greater land utilisation compared with Vunduzi which contributed to more farmers being food self-sufficient. Land utilisation in Vunduzi was limited by the steep slopes and rugged terrain which is less common in Ruaca. Our results showed that maize–legume intercropping required extra labour compared with sole crops; in Vunduzi land sizes were small and farmers were more likely to meet the labour requirements of intercropping than farmers in Ruaca. In Ruaca, farmers needed to reduce the land cultivated per season to be able to manage the intercropping systems or to hire extra labour. However, the loss in production due to reduction in land area could be compensated by the greater productivity of the intercrops.

5. Conclusion

The relatively high crop productivity and economic benefits of the maize–legume intercropping systems were attractive to farmers to address their critical objectives of food security and cash income although intercropping required 36% more labour compared with the monocrops. The within-row intercropping strategy maintained the yield of the main maize crop and was a more acceptable crop production option for farmers. Maize–legume intercropping could be more profitable if farmers can delay selling their produce immediately after harvest. In situations of land limitation and insufficient fertiliser inputs, legume intercropping may provide a pathway for ecological intensification. In extensive farming systems, labour saved by reducing land area may offset the increased labour demand for intercropping. Maize–pigeonpea intercropping significantly increased rainfall infiltration in the long-term due to a better soil cover with residues, more C inputs and no-tillage, and possibly improved soil structure. The relatively high biomass productivity and late maturity of pigeonpea delays free-grazing and enables *in situ* crop harvest residue retention which matches well with no-tillage practises. Maize–legume intercropping reduces the risk of crop failure, improves productivity per unit area, improves profitability and can provide a pathway to food security in vulnerable production systems.

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