Increased productivity through integrated soil fertility management in cassava–legume intercropping systems in the highlands of Sud-Kivu, DR Congo

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ABSTRACT

Smallholder farmers in sub-Saharan Africa are confronted by low productivity and limited investment capacity in nutrient inputs. Integrated soil fertility management (ISFM) aims at increased productivity through the combined use of improved germplasm, judicious fertilizer application and organic matter management, adapted to the local farming conditions. We hypothesize that the application of these different ISFM components can result in significant increases in productivity and economic benefits of cassava–legume intercropping systems. Participatory demonstration trials were conducted in the highlands of Sud-Kivu, DR Congo with 12 farmer groups during 3 seasons. Treatments included the farmers' common practice (local common bean and cassava varieties, seed broadcast and manure addition) and sequentially added ISFM components: improved bean and cassava germplasm, modified crop arrangements, compound NPK fertilizer application and alternative legume species (groundnut or soybean). The use of improved germplasm did not result in yield increases without simultaneous implementation of other ISFM components. Modifying the crop arrangement by planting cassava at 2 m between rows and 0.5 m within the row, intercropped with four legume lines, increased bean yields during the first season and permits a second bean intercrop, which can increase total legume production by up to 1 t ha^{-1} and result in an additional revenue of almost 1000 USD ha^{-1}. Crop arrangement or a second legume intercrop did not affect cassava storage root yields. Fertilizer application increased both legume and cassava yield, and net revenue by 400–700 USD ha^{-1} with a marginal rate of return of 1.6–2.7. Replacing the common bean intercrop by groundnut increased net revenue by 200–400 USD ha^{-1} partly because of the higher market value of the grains, but mostly due to a positive effect on cassava storage root yield. Soybean affected cassava yields negatively because of its high biomass production and long maturity period; modifications are needed to integrate a soybean intercrop into the system. The findings demonstrate the large potential of ISFM to increase productivity in cassava–legume systems in the Central-African highlands. Benefits were, however, not observed in all study sites. In poor soils, productivity increases were variable or absent, and soil amendments are required. A better understanding of the conditions under which positive effects occur can enable better targeting and local adaptation of the technologies.

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1. Introduction

Integrated soil fertility management (ISFM) offers technologies that aim at increased productivity through the use of improved germplasm, fertilizer application, organic matter management, and adaptation to the local conditions of smallholder farmers (Vanlauwe et al., 2010). There is great need for sustainable intensification of small-scale agriculture in sub-Saharan Africa: increasingly larger marginal areas are taken under cultivation, insufficient nutri-

ent inputs are used and traditional management practices relying on recycling of soil nutrients are unable to maintain productivity (Smaling et al., 1997). ISFM recognizes the absolute necessity of mineral fertilizer use, but aims at maximizing the agronomic efficiency of moderate quantities of fertilizer (Vanlauwe et al., 2010), as it is an expensive commodity for most farmers. Improved, disease-resistant germplasm is indispensable to ensure response to fertilizer. Organic matter commonly improves the use efficiency of fertilizer (Vanlauwe et al., 2001), and biomass can be produced *in situ* by integrating dual-purpose grain legumes into cropping systems, which might offer benefits from biological N fixation (BNF) while providing revenue from the crop produce (Carsky et al., 1999; Sanginga et al., 2003). Agronomic practices using modified crop

arrangements can result in significant yield increases with minimal labour investments, as demonstrated for instance by Mucheru-Muna et al. (2010) using a staggered arrangement in legume–cereal intercropping systems.

In a series of on-farm experiments in Kenya and Uganda, Fermont et al. (2010) demonstrated that cassava is highly responsive to fertilizer. Observed fertilizer responses were highly variable and to some extent related with soil fertility levels, but independent of variety, disease incidence or harvest age. Smallholder farmers, however, rarely apply fertilizer to cassava, as they consider the crop suited for poor soils, and not requiring fertilizer. Commonly, only limited amounts of manure or composted crop residues are applied. Cassava is susceptible to diseases such as bacterial blight, viral mosaic disease and brown streak, which can result in severe yield losses, and large efforts have been invested in the development of improved, disease-resistant varieties (Restrepo et al., 2000; Jennings and Iglesias, 2001). Investments in soil fertility are only sensible when disease-resistant varieties are used, as fertilizer application does not control cassava diseases, and may even increase symptom severity (Ogbe et al., 1993; Osiru et al., 1999).

Because of the long period to attain harvest maturity, typically 10–14 months in regions with bimodal rainfall and altitudes ranging between 1400 and 2000 m above sea level, farmers often intercrop cassava with cereals (most often maize) or with grain legumes. Legumes are highly compatible with cassava in terms of growth pattern, canopy development and nutrient demands, as they require mostly P and can satisfy part of their N needs through BNF (Giller, 2001), while cassava requires large amounts of K for storage root formation and N for leaf production (Howeler, 1991, 2002; Carsky and Toukourou, 2005). Intercropping systems have higher yield stability (Dapaah et al., 2003), reduced disease severity (Zinsou et al., 2004), and benefits weed control (Hernández et al., 1999a,b; Amanullah et al., 2007), especially when combined with nutrient addition (Olasantan et al., 1994). Intercropping with grain legumes (common beans, cowpea, groundnut, pigeon pea or soybean) generally increases productivity (land equivalency ratios of 1.2–1.9), with cassava yields either unaffected or decreased and legume yields least affected for species with short maturity periods (Mason et al., 1986; Mutsaers et al., 1993; Ennin and Dapaah, 2008). Mason and Leihner (1988), for example, showed 30–50% increase in land-use efficiency in cassava–cowpea intercropping systems, and highest benefits were obtained if P fertilizer was applied to ensure adequate growth of the legume. Legume intercropping can greatly increase biomass production in the system, without necessarily compromising on cassava biomass yield (Borin and Frankow-Lindberg, 2005). Contributions from BNF by the legumes cannot be expected to meet the N needs of the cassava crop, but may benefit the cassava crop. Makinde et al. (2007) observed 10–23% increase in cassava yield due to soybean residue incorporation, but only after two years of cassava–soybean intercropping.

Agronomic measures, plant densities, crop arrangements and relative planting times can greatly increase productivity of the system. Hernández et al. (1999a,b), for example, found higher land equivalency ratios in a cassava–beans intercrop when beans were sown 3 weeks after planting of cassava in a system with alternate rows of both crops sown at 35 cm, in comparison with mixed rows of both crops planted simultaneously at 70 cm. Although little research has been conducted on the topic, Leihner (2002) advised that the exact arrangement of the cassava crop can be modified to suit production system needs without compromising on storage root yield, provided that a planting density of 10,000 plants ha^{-1} is maintained. Midmore (1993) suggested that an increase in "rectangularity" of the main crop (cassava) tends to enhance transmission of light to the shorter crop (legume) during longer periods before

canopy closure. Olasantan (1988) showed that grain yields of a cowpea intercrop could be increased by using a 2:2 row arrangement instead of a 1:1 arrangement, without much reduction in cassava storage root yield.

In the highlands of Sud-Kivu, cassava–legume intercropping is a common practice by smallholder farmers, but productivity is low. We hypothesize that productivity can be increased by incrementally applying different ISFM components, namely (i) proper agronomic practices (planting in lines), (ii) use of improved legume and cassava germplasm, (iii) a modified crop arrangement that favours the legume intercrop, and (iv) fertilizer application. Participatory demonstration trials were conducted with farmer groups to assess improvements in system productivity and profitability. A financial analysis was done to evaluate benefits obtained against input and labour costs, and marginal rates of return were calculated for each system component. The farmer groups evaluated the trial at crucial stages and scored the different ISFM components.

2. Materials and methods

2.1. The study area

In the highlands of Sud-Kivu, cassava and common beans are amongst the main food crops, next to banana, sweet potatoes, maize and sorghum, traditionally cultivated in mixed cropping systems. In a survey of farmers' fields, more than half of the cassava fields were intercropped with a legume, or with a legume and a cereal crop. Cassava monocropping is only done in marginal fields, where other crops fail to yield (CIALCA, 2010). Common beans are the predominant legume intercrop, but to a lesser extent, also soybean and groundnut are grown. In the traditional practice, farmers do not plant in lines but grow their crops without a specific arrangement. Farmers generally allocate about 0.2–0.3 ha (30–45% of their farm area) to cassava–legume intercropping, and obtain average yields of 400–800 kg ha^{-1} legume grains and 10–15 t ha^{-1} cassava fresh storage roots (CIALCA, 2010). The region has long been deprived from new research and development initiatives due to civil strife. Most farmers have no access to improved varieties, and are very limited in their possibilities to improve soil fertility. Manure is only available in limited quantities and mineral fertilizer is practically absent. Pressure on land is very high due to high population density (estimated at 300–350 inhabitants per km^2 in the "territoires" near Bukavu; DSRP, 2005), and justifies agricultural intensification and investment in soil productivity.

The rainfall in Sud-Kivu is bimodal and allows crop cultivation during two subsequent seasons: the "A" season starts mid-September and ends mid-January, while the "B" season lasts from mid-February to mid-June, followed by a short dry period, often referred to as the "C" season, when farmers cultivate in valleys and drained marshlands. The area receives on average 1500–1800 mm per year, and the growing period extends to over 325 days per year (Hijmans et al., 2005). The study was conducted in the "territoire de Kabare", "groupement" of Kabamba (2.184°S, 28.852°E, 1600 m above sea level), and in the "territoire de Walungu", "groupements" of Burhale (2.692°S, 28.647°E, 1700 m above sea level) and Lurhala (2.625°S, 28.758°E, 2000 m above sea level). Soils in Lurhala and Burhale are rather infertile Dystric or Humic Nitisols or Humic Ferralsols (FAO/UNESCO, 1998), developed on eruptive formations from the Pliocene or Pleistocene and characterized by a heavy clay texture, low soil pH, low base saturations and high organic C contents (Hecq, 1961). In Kabamba, more fertile Humic Nitisols and Ferralsols are found because of recent rejuvenation by volcanic ashes or mudflow deposits; these soils have high organic matter content, favourable pH and larger nutrient reserves (Lunze, 2000).

Table 1
Selected physico-chemical soil properties of the trial sites.

Property	Units	Kabamba 2008 A ($n = 6$)		Lurhala–Burhale 2008 B ($n = 6$)		Kabamba 2009 A ($n = 6$)	
		Mean	Range	Mean	Range	Mean	Range
pH (H$_2$O)		5.67	5.04–6.24	5.31	4.62–5.86	5.59	5.14–6.01
Organic C	(%)	2.19	1.83–2.56	2.48	1.23–4.24	2.14	1.75–2.48
Total N	(%)	0.19	0.16–0.21	0.22	0.10–0.41	0.19	0.17–0.23
Olsen-P	(mg P kg^{-1})	15.6	6.36–31.8	8.20	3.59–21.7	18.7	11.7–34.5
Exchangeable K	(cmol$_c$ kg^{-1})	1.08	0.48–1.96	0.91	0.24–2.47	0.83	0.50–1.77
Exchangeable Mg	(cmol$_c$ kg^{-1})	2.08	1.52–2.82	1.22	0.15–1.90	2.19	1.57–3.06
Exchangeable Ca	(cmol$_c$ kg^{-1})	5.29	4.35–6.30	3.80	0.97–6.50	5.85	4.34–7.32
Exchangeable acidity	(cmol$_c$ kg^{-1})	0.21	0.00–0.64	0.68	0.00–2.46	0.26	0.00–0.60
ECEC	(cmol$_c$ kg^{-1})	8.66	7.30–9.65	6.60	3.06–9.85	9.18	7.51–10.6
Clay	(%)	43	25–71	32	17–58	38	21–57
Silt	(%)	20	18–22	17	14–24	19	17–22
Sand	(%)	37	12–57	51	28–64	43	25–59

2.2. Trial establishment and management

In October 2007 (season 2008 A), six demonstration trials were installed with three farmer groups in Kabamba. Each farmer group presented two separate fields. All fields were located either on the plateau or on the upper end of the slope. Fields on strong slopes (>10%) were avoided. In February 2008 (season 2008 B), six demonstration trials were conducted with six farmer groups in Burhale and Lurhala. Each farmer group presented a field for the experiment. In September 2008 (season 2009 A), demonstration trials were repeated in Kabamba on demand of the farmer groups because of the moderate performance of the legumes during the first set of trials. Three trials were installed with the same three farmer groups in three new fields, and three additional trials were installed with new groups. The farmer groups performed all field operations, and installed and harvested the trials under the supervision of a team of agronomists. Data collection and sampling was done by the agronomist teams, who visited the groups regularly and ensured that farmers weeded all plots timely and concurrently. Prior to trial installation, composite soil samples were collected from the 0–15 cm soil layer, air-dried, sieved to pass 2 mm and analyzed for standard physico-chemical properties (Table 1).

The design of the demonstration trials was based on experiences from preceding legume and cassava germplasm evaluation trials, and discussions with farmers, extension agents and agronomists from research institutes active in the region. Each trial contained eight treatments following a cumulative design, sequentially adding on ISFM components with increasing complexity or cost. This design was considered most suitable as it does not entail a large number of experimental plots, while it allows demonstrating the added benefit of each component of the technology (in that particular order). Treatments were not replicated within each field; instead, farmer groups per site and season were considered as replicates. Plots measured 36 m^2. In the first treatment, local planting material was used, and cassava (*Manihot esculenta* Crantz) and common beans (*Phaseolus vulgaris* L.) were grown following farmers' common practice. Cassava cuttings were planted randomly, and bean seed was broadcast. A crop density of 10,000 cassava and 100,000 bean plants ha^{-1} was imposed to allow comparison with subsequent treatments (although farmers commonly plant at slightly higher plant densities). Also, farmers were not allowed to pick leaves (although this is common practice), since this may negatively affect storage root yields (Lockard et al., 1985). Local farm yard manure (FYM), containing on average 20% C, 2.4% N, 0.2% P and 2.3% K, was broadcast and incorporated at a rate of 2.5 t dry matter (DM) ha^{-1} prior to planting. All subsequent treatments received FYM at the same rate as in farmers' common practice. In the second treatment, the crop arrangement was modified and cassava was planted at 1 m by 1 m, intercropped with two

lines of legumes at distances of 33 cm between lines and 20 cm within the line. In the third treatment, improved varieties were used. In season 2008 A in Kabamba, cassava variety 'Sawasawa' and bean variety 'CODMLB001' were used, and in season 2009 A, cassava variety 'Liyayi' was used. In Lurhala and Burhale, cassava variety 'Sawasawa' and bean variety 'MLB49' were used. Varieties were chosen based on their performance and adaptation to both agro-ecologies. Crop arrangement was identical to the second treatment. In the fourth treatment, the crop arrangement was modified: cassava was planted at distances of 2 m between lines and 0.5 m within the line, intercropped with 4 legume lines at distances of 40 cm between lines and 20 cm in the line. Crop densities remained unchanged at 10,000 cassava plants and 100,000 bean plants ha^{-1}. In the fifth treatment, fertilizer (NPK 17:17:17) was applied at a rate of 150 kg ha^{-1}, equally distributed to the cassava and the first bean crop. Fertilizer was administered at planting using a bottle cap in the cassava planting hole or in the bean line, and covered with some soil. In the sixth treatment, the possibility of intercropping a second legume was evaluated. After harvest of the first bean crop, a second bean crop was planted at a reduced density of 50,000 plants ha^{-1} (two bean lines between the cassava lines at distances of 67 cm between lines and 20 cm in the line). In the seventh and eighth treatment, the first bean crop was replaced by groundnut (*Arachis hypogaea* L., variety ICGV-SM99545) and soybean (*Glycine max* L. Merril, variety TGx1835-10E, a promiscuous variety from the IITA breeding program with a low harvest index, also known as Maksoy), planted at distances of 20 and 10 cm in the line, respectively, and 40 cm between lines (corresponding to 100,000 groundnut plants and 200,000 soybean plants ha^{-1}). Similarly as in the sixth treatment, a second bean crop was planted after harvest of the first legume.

At 50% podding, aboveground legume biomass was collected from a 1 m strip within the net plot. Legumes were harvested at full maturity, when pods had dried in the field, and grains were collected. Biomass and grains were oven-dried (65 °C) and weighed. Cassava was harvested between 11 and 12 months after planting. Prior to harvest, the height of the canopy, number of primary branches and the diameter of the stem at 1 cm above the soil surface were determined for 5 random stands in the plot. Subsequently, stem yield and storage root yield were determined. Storage roots were divided in large tradable and small non-tradable storage roots, counted, and sub-sampled for determination of the DM content of the flesh (parenchyma) and peelings. Farmers commonly peel the entire storage root, without cutting the tip or tail.

2.3. Economic analysis

A financial analysis was conducted to evaluate the profitability of the various ISFM components. Gross benefits were estimated

using the unit prices for the grains of the three legumes and dried cassava cubes obtained at the local markets in Kabamba, Lurhala and Burhale (1.1 and 1.0, 1.8 and 2.1, 0.84 and 1.2, and 0.44 and 0.61 USD kg^{-1} of bean grains, groundnuts, soybean grains and dried cassava cubes in Kabamba, and Lurhala–Burhale, respectively). An exchange rate of 900 Congolese francs to 1 USD (December 2009) was used. Cassava fresh storage root yields were converted using the proportion of tradable storage roots (relative to the total yield), and the flesh and DM content of the tradable roots. Total costs were separated in input costs (seed, fertilizer and FYM) and labour costs. The cost of the fertilizer was obtained from a local stockist in Bukavu (75 USD per 50 kg bag). For seed, grain prices were used since most farmers recycle seed. Labour was not directly quantified, but two male and female participants of each farmer group were asked to estimate the labour time required for land preparation, planting, weeding and harvesting in the different treatments. These estimations were calibrated against actual measurements in fields of individual farmer households and confirmed by key informants before use in economic analysis. Labour was valued at a wage of 1500 FRC for a 6-h working day. Marginal rates of return (MRR) were calculated as the additional net benefits over the additional total costs, relative to the corresponding preceding non-dominated treatment. Dominated treatments, i.e. treatments with smaller net benefits and higher costs than a preceding treatment, were excluded. The MRR of the fifth treatment (with fertilizer application), for example, was calculated relative to the fourth treatment with the same legume intercrop, germplasm and crop arrangement, but without fertilizer addition (if not dominated by a preceding treatment). This allows evaluating the profitability by sequentially adding on ISFM components, which was considered adequate if the MRR exceeded 118% (CIMMYT, 1998).

2.4. Participatory farmer evaluations

Evaluations were organized at harvest of the first legume crop and at harvest of the cassava crop. During each evaluation, farmers were divided in groups of 5–15 men or women. Each group was then asked to define criteria for evaluating crop performance, and to include 'legume grain yield' and 'cassava storage root yield' for evaluation. Farmers then discussed performance of each treatment based on these criteria. Subsequently, farmers' preferences for the various treatments were assessed using a participatory method modified from the indigenous 'bao' board game (Franzel et al., 1995). Each group member was given eight marbles, and asked to allot the marbles as 'marks' to the different plots, according to his or her preference. A preference score (%) was then calculated as the sum of the marbles assigned, divided by the number of treatments and participants, multiplied by 100 and rounded to the nearest integer, separately for male and female group members.

2.5. Statistical analysis

An analysis of variance was conducted to determine the effects of the different treatments in the two sites, and in the two seasons in Kabamba using a mixed linear model (MIXED procedure, SAS Institute Inc., 2003). The effects of the different treatments were compared by computing least square means and standard errors of difference (SED); significance of difference was evaluated at $P < 0.05$. In the mixed model analysis, 'farmer group' within 'site and season' were considered as random factors. Regression analysis was done using the REG procedure and the stepwise selection option to predict storage root yields based on plant height and stem diameter, including the second and third power of both parameters. Observed yields were plotted against predicted yields, and the goodness-of-fit was evaluated by comparison against the 1:1 line (Piñeiro et al., 2008). Farmer preferences were analysed using
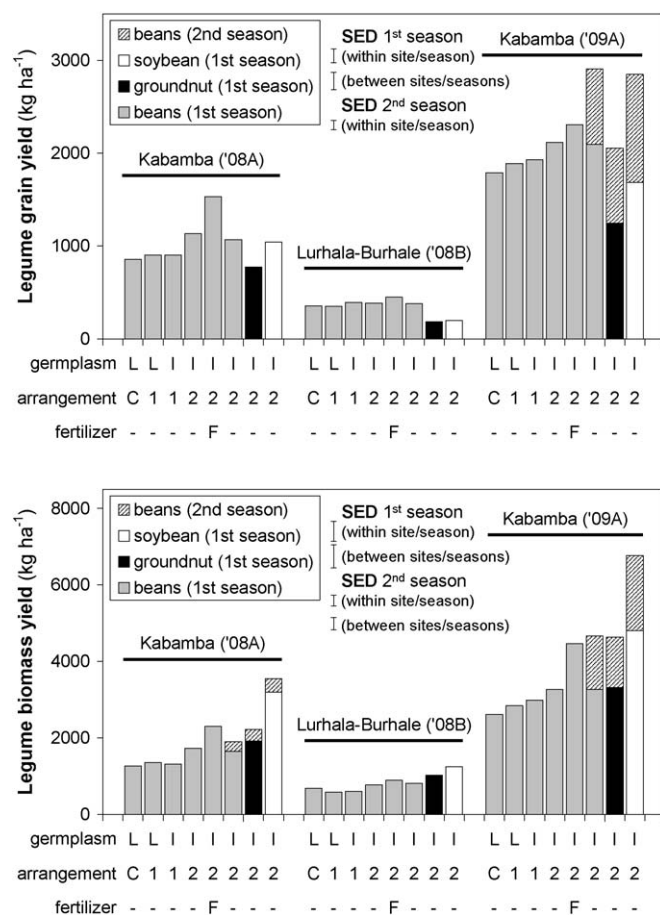

Fig. 1. Grain and biomass DM yield of the first legume crop (beans, soybean or groundnut) and the second bean crop as affected by germplasm (L = local, I = improved), cassava crop arrangement (C = common practice, 1 = 1 m × 1 m, 2 = 2 m × 0.5 m) and fertilizer application (– = without, F = with fertilizer). Trials were installed in seasons 2008 A and 2009 A in Kabamba, and in 2008 B in Lurhala and Burhale. Error bars represent standard errors of difference for the site × treatment interaction.

a multinomial logistic regression model (LOGIST procedure, SAS Institute Inc., 2003) with treatment as the outcome, the farmers' practice as the baseline category, and farmer group, 'site and season', and sex of the participants as covariates.

3. Results

3.1. Grain and biomass yield of the legume crops

In Kabamba, average bean yields in the farmers' practice were higher in the 2009 A season (1800 kg ha^{-1}) than in the 2008 A season (850 kg ha^{-1}) due to more favourable rainfall (Fig. 1). In 2008 A, a significant ($P < 0.05$) but relatively small (200 kg ha^{-1}) yield increase was observed when cassava was planted at 2 m × 0.5 m. Use of improved germplasm did not affect bean yields, and no differences were observed between the farmers' practice and the crop arrangement with cassava planted at 1 m × 1 m. In the 2009 A season, combined use of improved germplasm and crop arrangement with cassava planted at 2 m × 0.5 m resulted in a bean grain yield increase of 320 kg ha^{-1}, relative to the farmers' practice. In the arrangement with cassava planted at 2 m × 0.5 m, legume yields for the lines adjacent to the cassava corresponded with yields for the interior pair of lines (slope = 0.98 ± 0.1, R^2 = 0.87). In both seasons, a significant ($P < 0.01$) response to fertilizer was observed; fertilizer application increased bean yields by 200–430 kg ha^{-1}. Groundnut

yields (800–1250 kg ha^{-1}) were smaller than bean yields in the corresponding treatments in both seasons, while soybean yields (1000–1700 kg ha^{-1}) were comparable with bean yields in the first season, and slightly smaller than bean yields in the second season. In Lurhala and Burhale, grain yields of the first legume crop were generally poor (less than 400 kg ha^{-1} for beans, and less than 200 kg ha^{-1} for soybean and groundnut), and bean yields were not affected by treatments. The poor yields are primarily due to the low fertility of the soils (lower pH, lower available P content and lower contents of exchangeable cations) relative to soils in Kabamba (Table 1). Maturity periods for beans (92–97 days) were shorter than for groundnut (123–135 days) and soybean (133–143 days). Maturity periods for groundnut and soybean were about one week longer in Lurhala and Burhale than in Kabamba due to the higher altitude but similar in both sites for beans because MLB49 matures faster than CODMLB001.

In Kabamba, bean biomass yields in the farmers' practice were smaller during the 2008 A season (1.6 t ha^{-1}) than during the 2009 A season (3.2 t ha^{-1}). During the first season, biomass yields were not affected by variety or crop arrangement. Fertilizer application, however, increased biomass yields by 80% ($P < 0.05$). During the second season, combined use of improved germplasm and crop arrangement with cassava planted at 2 m × 0.5 m resulted in a significant ($P < 0.05$) increase in biomass yield of 0.65 t ha^{-1}, relative to the farmers' practice. Fertilizer application increased biomass yields by 1.2 t ha^{-1}, relative to the corresponding treatment without fertilizer addition ($P < 0.001$). Highest biomass yields were observed for soybean, producing 3.2 t ha^{-1} in the first season, and almost 5 t ha^{-1} in the second season. Groundnut produced similar quantities of biomass as beans in the corresponding treatment without fertilizer application. In Lurhala and Burhale, legume biomass yield was generally poor. Common beans produced on average 0.7 t biomass ha^{-1}, independent of variety, crop arrangement or fertilizer application. Soybean produced 1.2 t biomass ha^{-1}, but this was not significantly ($P = 0.13$) larger than bean biomass yields.

In season 2008 A in Kabamba, the second bean crop was planted late and rains ceased early, resulting in crop failure. Biomass yields were smaller than 500 kg ha^{-1}, and pods did not form or fill. In the 2009 A season, the second bean crop was planted early, immediately after the first rains, and relatively good yields were obtained (on average 930 kg ha^{-1}). The yield of the second bean crop was significantly ($P < 0.05$) higher when it followed soybean (almost 1200 kg ha) than when it followed beans or groundnuts (about 800 kg ha). Biomass yields of the second bean crop were almost 1 t ha^{-1} larger in plots where previously soybean was grown, relative to plots where previously beans or groundnut was grown. In Burhale and Lurhala, heavy rainfall during the first month after planting resulted in high prevalence of root rot disease and the bean crop was lost. This is a frequent phenomenon during the A season in these sites.

3.2. Cassava storage root and stem yields

In season 2008 A in Kabamba, an average storage root yield of 15 t ha^{-1} was observed in the farmers' practice (Fig. 2). Storage root yield was not affected by the variety used (local or improved), the arrangement (local practice, 1 m × 1 m or 2 m × 0.5 m), or by intercropping with a second bean crop. Fertilizer application, however, significantly ($P < 0.01$) increased storage root yield by 40% (5.8 t ha^{-1}). Growing soybean as the first legume intercrop resulted in a significant ($P < 0.05$) loss in cassava storage root yields of 6–8 t ha^{-1}, in comparison with beans or groundnut grown as the first intercrop. These findings were confirmed during season 2009 A in Kabamba. In Lurhala and Burhale, on the contrary, cassava
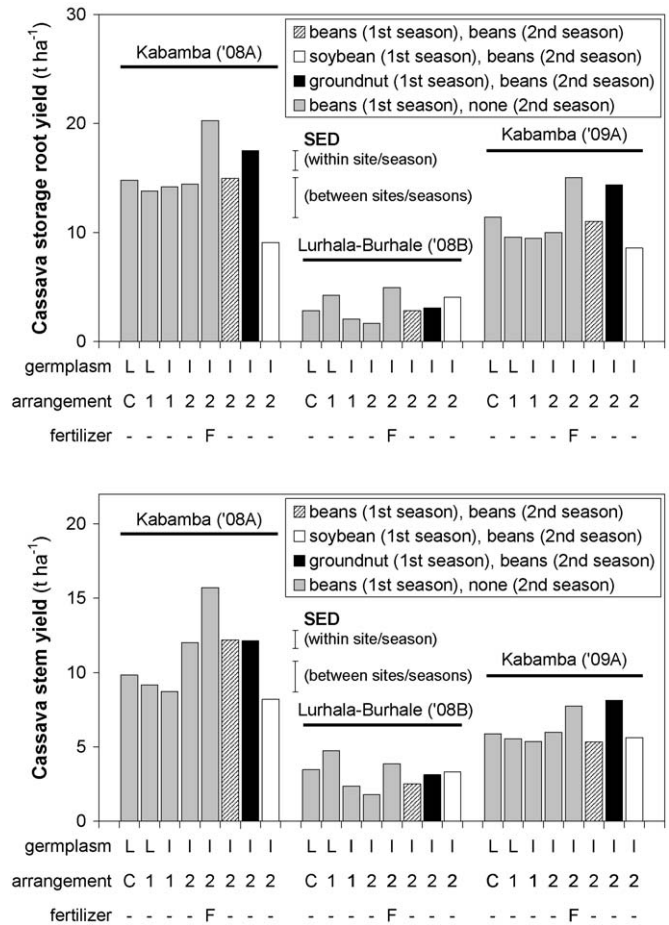

Fig. 2. Cassava FM storage root and stem yields as affected by intercropping with a first legume (beans, soybean or groundnut) and a second bean crop, germplasm used (L = local, I = improved), cassava crop arrangement (C = common practice, 1 = 1 m × 1 m, 2 = 2 m × 0.5 m) and fertilizer application (– = without, F = with fertilizer). Trials were installed in seasons 2008 A and 2009 A in Kabamba, and in 2008 B in Lurhala and Burhale. Error bars represent standard errors of difference for the site × treatment interaction.

storage root yields were poor (2–5 t ha^{-1}) and not affected by treatments. Fertilizer application did not significantly ($P = 0.33$) increase cassava yields, probably because of low soil fertility (Table 1) and consequent inefficient use of the fertilizer nutrients applied.

Farmers distinguish tradable and non-tradable storage roots based on their weight or size. In Kabamba (both seasons), tradable storage roots weighed on average 400 g per piece, while non-tradable roots weighed just over 100 g (data not shown). In Lurhala and Burhale, storage roots were significantly smaller: 270 g for tradable storage roots and 80 g for non-tradable roots. The proportion of tradable roots was larger in Kabamba (80%) than in Lurhala and Burhale (62%). The proportion of tradable roots or the storage root weights were not affected by the crop arrangement or the germplasm used. Fertilizer application increased the number of storage roots per stand ($P < 0.05$) and only slightly increased the size of the tradable storage roots ($P = 0.11$). Growing soybean as the first intercrop reduced the proportion and the average size of the tradable roots. In Kabamba, the average flesh content of the tradable storage roots (79%) was larger than in Lurhala and Burhale (63%). The average DM content of the flesh equalled 34%.

Cassava stem yields were not affected by the germplasm used, the crop arrangement or intercropping with a second bean crop. However, in season 2008 A in Kabamba, stem yields tended ($P = 0.12$) to be higher when cassava was planted at 2 m × 0.5 m. Fertilizer application only increased ($P < 0.01$) cassava stem yields
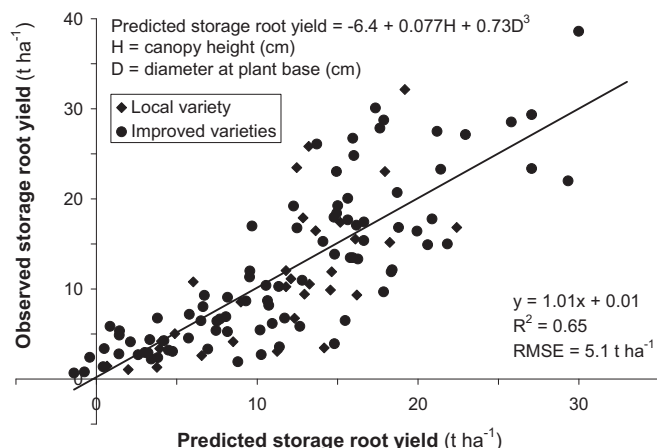
Fig. 3. Observed versus predicted cassava storage root yields based on canopy parameters (canopy height and stem diameter at base) determined between 11 and 12 months after planting. Observations were lumped for the different sites, seasons, varieties and treatments.

in season 2008 A in Kabamba. Growing soybean as the first legume intercrop only significantly reduced cassava stem yields in season 2008 A in Kabamba, relatively to when beans or groundnut were grown. Storage root yields were well-correlated with stem yields ($P < 0.001$, $R^2 = 0.65$, slope = 1.01). Storage root yields could therefore be predicted based on canopy parameters. Regression analysis revealed that storage root yields could be predicted based on the height of the canopy and the diameter at the plant basis, measured between 11 and 12 months after planting (Fig. 3). This relationship was similar for the local variety and the two improved varieties (Liyayi and Sawasawa). Storage root yields were best predicted in the range of 0–15 t ha^{-1}; at larger values, the relationship tended to underestimate root yields.

3.3. Economic analysis

The use of improved germplasm or the modified crop arrangements with cassava planted at 1 m × 1 m or 2 m × 0.5 m (without the second legume) did not increase gross or net benefits of the system (Table 2). The total labour cost was very little affected by the crop arrangement but labour requirements for the different operations differed. The traditional arrangement required about 30% less labour for planting, but 20% more labour for weeding (data not shown). In season 2009 A in Kabamba, the system with the second legume crop was highly profitable, as it resulted in a significant ($P < 0.01$) increase in net benefits of 800 USD ha^{-1} with a MRR of 4.5 (relative to the corresponding treatment without the second legume). Fertilizer application significantly ($P < 0.05$) increased gross benefits in both seasons in Kabamba by 700–1000 USD ha^{-1}, but MRR's were moderate (1.6–2.7) due to the high costs of fertilizer use (almost 270 USD ha^{-1}). The use of groundnuts as the first intercrop was more profitable than beans or soybean because of the high market value of groundnut grains relative to the other legumes, and because of the higher cassava storage root yields when intercropped with groundnuts. Replacing the first common bean intercrop by groundnut resulted in favourable MRR's. In season 2008 A in Kabamba, lowest gross and net benefits were recorded when soybean was grown as the first intercrop, partly because of the lower market value of soybean but mostly because of the negative effect on cassava storage root yields. In season 2009 A, benefits were higher because of the revenue obtained from the second bean crop, but remained inferior relative to when beans or groundnut were grown. In Lurhala and Burhale, none of the treatments resulted in significant increases in gross or net benefits.
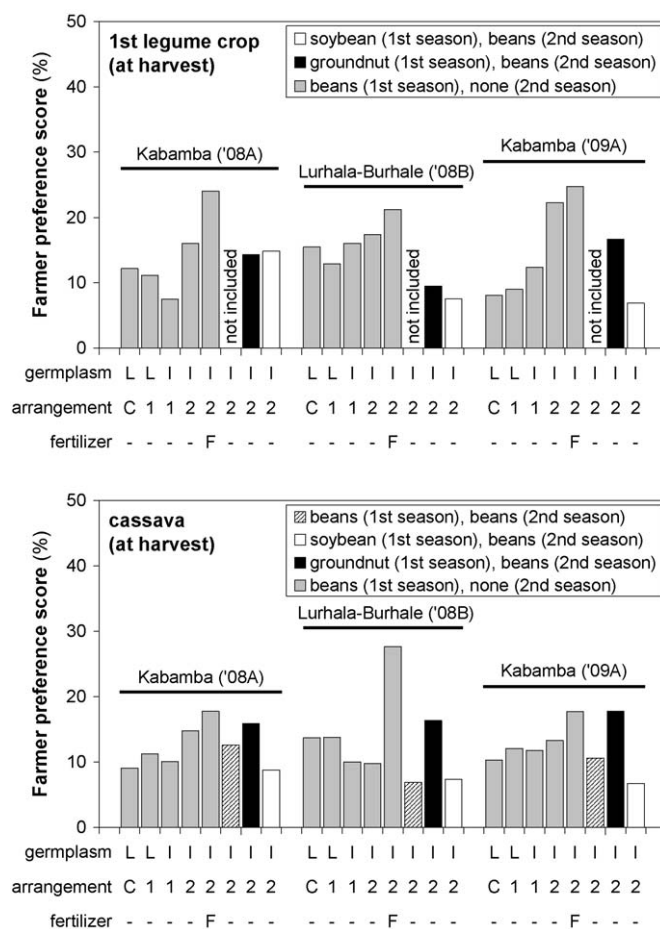

Fig. 4. Farmer preference scores from participatory evaluations conducted at harvest of the first legume and the cassava crop for treatments with different first legumes (beans, soybean or groundnut), cultivation of a second bean crop, germplasm used (L = local, I = improved), cassava crop arrangement (C = common practice, 1 = 1 m × 1 m, 2 = 2 m × 0.5 m) and fertilizer application (– = without, F = with fertilizer). Trials were installed in seasons 2008 A and 2009 A in Kabamba, and in 2008 B in Lurhala and Burhale. At harvest of the first legume, the sixth treatment was excluded from the evaluation since the 2nd bean crop had not been sown yet.

3.4. Participatory farmer evaluations

At harvest, farmers evaluated the legume and cassava crop based on yield and quality of the produce (size, shape, colour, luminosity, and absence of impurities or insect damage, etc.) and then scored the different treatments. The multinomial logistic regression model revealed a highly significant ($P < 0.001$) effect of the 'site and season' covariate at both harvest events. In Kabamba, the majority of the farmers preferred their common practice over the 1 m × 1 m arrangement because it was less complex to plant, although they recognized that planting in lines facilitated weeding (Fig. 4). The 2 m × 0.5 m arrangement, however, was highly favoured over the other arrangements (and more so during the 2009 A season). Farmers generally preferred improved legume and cassava varieties over their local germplasm, mostly because of superior quality of the produce rather than yield. Highest preference scores were noted in the treatment with fertilizer application in both seasons for both crops. Lowest scores were recorded in the treatment with the soybean intercrop because farmers realized the negative effect on cassava storage root yield. The groundnut intercrop was only favoured at harvest of the cassava crop, as farmers recognized that intercropping with groundnut resulted in higher cassava yields. In Lurhala and Burhale, farmers only considered the use of fertilizer advantageous in comparison with the local practice.

Table 2

Economic analysis of cassava–legume intercropping for treatments with cumulatively added ISFM components (improved germplasm, crop arrangement, integration of a 2nd legume intercrop, fertilizer application and alternative first legume intercrops).

Legume intercrop	Germplasm	Crop arrangement	Second intercrop	Fertilizer application	Gross benefits	Labour costs	Input costs	Net benefits	MRR[a]
					(USD ha^{-1})				
Kabamba, 2008 A									
Beans	Local	Traditional	–	–	2311	629	67	1615	
Beans	Local	1 m × 1 m	–	–	2268	653	67	1549	D
Beans	Improved	1 m × 1 m	–	–	2302	653	67	1583	D
Beans	Improved	2 m × 0.5 m	–	–	2583	674	67	1842	5.0
Beans	Improved	2 m × 0.5 m	–	F	3557	709	292	2556	2.7
Beans	Improved	2 m × 0.5 m	Beans	–	2560	740	84	1736	D
Groundnut	Improved	2 m × 0.5 m	Beans	–	3011	746	120	2145	2.4
Soybean	Improved	2 m × 0.5 m	Beans	–	1718	751	73	894	D
Lurhala – Burhale, 2008 B									
Beans	Local	Traditional	–	–	581	491	65	25	
Beans	Local	1 m × 1 m	–	–	689	506	65	118	6.2
Beans	Improved	1 m × 1 m	–	–	555	506	65	−16	D
Beans	Improved	2 m × 0.5 m	–	–	520	505	65	−50	D
Beans	Improved	2 m × 0.5 m	–	F	841	555	290	−4	D
Beans	Improved	2 m × 0.5 m	Beans	–	607	550	81	−24	D
Groundnut	Improved	2 m × 0.5 m	beans	–	632	551	132	−51	D
Soybean	Improved	2 m × 0.5 m	Beans	–	562	554	82	−74	D
Kabamba, 2009 A									
Beans	Local	Traditional	–	–	3023	774	67	2182	
Beans	Local	1 m × 1 m	–	–	2961	794	67	2100	D
Beans	Improved	1 m × 1 m	–	–	3001	794	67	2140	D
Beans	Improved	2 m × 0.5 m	–	–	3254	808	67	2380	5.8
Beans	Improved	2 m × 0.5 m	–	F	3931	845	292	2794	1.6
Beans	Improved	2 m × 0.5 m	Beans	–	4216	966	84	3166	4.5
Groundnut	Improved	2 m × 0.5 m	Beans	–	4460	978	120	3363	4.2
Soybean	Improved	2 m × 0.5 m	Beans	–	3488	975	73	2440	D
SED (site/season × treatment) within site					415			272	
SED (site/season × treatment) between sites					482			319	

[a] MRR's were not determined for dominated treatments (i.e. treatments with lower net benefits and higher total costs, relative to a preceding treatment; D = dominated). MRR's were calculated as the additional net benefits over the additional total costs for the corresponding preceding non-dominated treatment (or the local practice).

4. Discussion

4.1. Use of improved germplasm

Cassava yields observed under farmers' practice in the demonstration trials in Kabamba were generally higher than yields observed by Fermont et al. (2009) under farmers' practice in Kenya and Uganda (6–12 t ha^{-1}), probably because soils are inherently more fertile. In the acid and poor soils of Lurhala–Burhale, however, yields were much lower. Fermont et al. (2009) observed yield increases of 3.5 t ha^{-1} through use of improved cassava germplasm. We, on the contrary, did not observe differences in cassava yields for local and improved varieties. The improved varieties were resistant to mosaic disease, but the local varieties only sporadically showed disease symptoms, which may explain the lack of yield improvement. The improved bean varieties did neither outyield local varieties; therefore, the sole use of improved germplasm is insufficient to increase system productivity.

The growth habit of the cassava variety had an important effect on the land use efficiency in intercropping systems. Cenpukdee and Fukai (1992a,b) and Dapaah et al. (2003) showed that short-statured, small and less-branching cassava varieties have least negative effects on a legume intercrop. In our trials, both the local and improved varieties had an erect growth habit, but the local variety generally remained smaller, and Liyayi exhibited higher branching and vigour in comparison with Sawasawa and the local variety. However, according to Mutsaers et al. (1993), competition is limited if the growth duration of the legume intercrop does not exceed 90 days. Hence, the local and improved bean crop likely matured early enough not to be affected by the cassava, regardless of its growth habit.

4.2. Fertilizer application

Our findings demonstrate that fertilizer use at small rates is profitable in cassava–legume intercropping systems, but only in the relatively more fertile soils in the Kabamba site. Marginal rates of return of fertilizer use met the minimum value of 118% (CIMMYT, 1998) in the two seasons. Generally 60–70% of these returns resulted from the increase in cassava storage root yields. Profitable returns to the investment can thus be obtained despite the high fertilizer price in the area, which is more than twice as high as in Kenya and Uganda, mostly due to lack of adequate infrastructure, knowledge and extension, low demand and offer, and a poorly developed agro-input market. If prices were to be levelled with other countries in East-Africa, fertilizer use would be highly profitable. Fermont et al. (2009) found higher value-to-cost ratios of 1.8–5.2 for fertilizer use on a cassava monocrop applied at 3–4 times higher rates (but broadcast rather than spot-applied) in farmers' fields in Kenya and Uganda, and similarly showed that fertilizer application increases the number of storage roots per plant, rather than the size of the roots, or the proportion of tradable roots. Makinde et al. (2007) also demonstrated that fertilizer use is highly profitable in cassava–legume intercropping systems, increasing net benefits by on average 700 USD ha^{-1} (value-to-cost ratio of fertilizer use = 6.7).

Given that K concentrations in the storage roots vary between 0.7% and 1.0% (Howeler, 2002), storage root yield increases due to fertilizer application represent estimated K removals of 12–19 kg ha^{-1}, which are comparable with the 21 kg K ha^{-1} applied as fertilizer. Since K was also removed through the aboveground biomass of the cassava and the legume, addition of fertilizer application likely stimulated uptake of soil K. Soil K contents are generally above the critical threshold of 0.18 cmol$_c$ K kg^{-1} (Howeler, 2002) but continuous cropping may deplete the soil K reserves. Especially the soils in the "territoire de Walungu" are prone to K deficiency (Lunze, 2000). These soils are also highly P-fixing (Lunze, 2000) with low Olsen-P values (Table 1), and the applied rate of P (11 kg P ha^{-1}) may be insufficient to overcome P deficiency. In addition, soils are acid with aluminium saturation levels up to 70% (Table 1). Under these conditions, fertilizer nutrients are likely utilized inefficiently, which may explain the lack of crop response. Other trials in the Walungu territory have shown that soil amendments combining strategic placement of manure with fertilizer application result in largest yield increases, probably because of an effective aleviation of nutrient and acidity limitations. Long-term monitoring of nutrient balances and a more detailed evaluation of fertilizer response is needed to formulate fertilizer recommendations, especially since intercropping systems may not respond to fertilizer in the same way as the component crops planted solely (Leihner, 1983).

4.3. Crop arrangement (improved agronomy)

Fermont et al. (2009) observed that improved crop establishment (early planting of cassava at 1 m × 1 m) had minimal and variable benefits on cassava storage root yields, relative to the local practice. Our findings confirm that the common practice is not inferior in comparison with the recommended 1 m × 1 m arrangement and the legumes planted in lines. Rather, the common practice is advantageous in terms of labour requirement at the onset of the season, when labour demand is highest. However, the 2 m × 0.5 m has a great advantage because it results in higher legume production during the first season and permits a second bean intercrop, resulting in an added economic benefit of almost 1000 USD ha^{-1}. Leihner (2002) also suggests that beans are a suitable second intercrop because cassava intercepts less light during the last months of its cycle. Although the 1 m × 1 m arrangement does not necessarily exclude a second legume crop, it is likely to be less productive because of the higher light competition. Cassava yield, however, is unaffected by the specific arrangement. Other studies confirm this. Findings by CIAT (1977) as reported by Leihner (2002) show that root yields of three cassava cultivars do not differ for a 1 m × 1 m or a 2 m × 0.5 m arrangement (and other arrangements with equal crop density). Tsay et al. (1987) found that cassava planted in paired rows at 90 cm, with 270 cm between the paired rows produced similar storage root yields as cassava planted at 180 cm between rows, but allowed light penetration during a longer period in the inter-row space for the intercrop. Olasantan (1988) showed that a 2:2 row arrangement in a cassava:cowpea intercropping system resulted in increased cowpea yields, without much reduction in cassava storage root yield.

4.4. Choice of the legume intercrop

The cassava–groundnut intercropping system performed superiorly in comparison with the cassava–soybean intercrop. At harvest of the soybean crop, cassava plants were elongated and showed poor vegetative development in comparison with cassava associated with groundnut or beans. This suggests that the cassava crop suffered from shading. Other studies came to similar conclusions. Eke-Okoro et al. (1999) observed highest cassava stor-

age root yields and land equivalency ratios when intercropped with groundnut, relative to other legume intercrops (soybean, cowpea and bambara). Cowpea and beans are more suitable legume intercrops than soybean because of their shorter maturity period (Leihner, 1983). Ennin and Dapaah (2008) demonstrated that cassava yield penalties can be reduced by delaying soybean planting or reducing the soybean crop density. Tsay et al. (1988) showed that cassava intercropped with early-maturing soybean varieties recovered quickly, producing storage root yields similar to sole cassava, while with late-maturing varieties, yield reductions of 40–50% were observed. Studies using artificial shading (Fukai et al., 1984; Aresta and Fukai, 1984) provided evidence that cassava plants were more susceptible to shading during early stages (esp. in the storage root initiation stage) than during the bulking stage.

Despite its negative effect on cassava growth and production, intercropping with soybean has benefits for soil fertility and long-term productivity (Makinde et al., 2007). Soybean produced higher quantities of biomass, and likely made highest contributions from N fixation. Based on proportions of N derived from the atmosphere and N harvest indices reported by Sanginga et al. (1997) and Ojiem et al. (2007), net N benefits of soybean in our study were in the order of 30–60 kg N ha^{-1}, while for beans at best neutral net N inputs could be obtained. N benefits from a legume are important because other work has shown that N deficiency limits crop production, and because cassava N recycling and associated benefits for soil fertility are likely limited. Farmers pick cassava leaves for human consumption and lack sufficient amounts of stems as planting material; therefore little cassava biomass is returned to the soil.

4.5. Farmers' preference of the various technologies

Farmer preferences generally corresponded with economic benefits. Treatments with fertilizer application or with groundnut or beans as the first intercrop, followed by a second bean crop were generally most preferred. Farmers expressed strong discontent towards the soybean intercrop. They proposed to increase the interline distance between the soybean and cassava lines and reduce the soybean crop density, to use an early-maturing variety, or to only grow beans or groundnut as first intercrops, and plant soybean during the second season.

Farmers were convinced that the crop arrangement with cassava planted at 2 m × 0.5 m resulted in superior productivity, but expressed difficulties with the correct implementation of the system as they do not have experience with planting in lines. Agricultural tools that facilitate tracing of the planting lines at the correct interline distance may enhance uptake of the technology. Similar observations were made in alternative arrangements in legume-maize intercropping systems (Woomer, 2007). Although farmers were impressed by the effects of fertilizer application, they expressed worries for accessing fertilizer; agro-dealers selling fertilizer are only present in Bukavu, not in rural areas. Adjei-Nsiah et al. (2007) advised that technologies should suit the needs and resources available to the target farmer groups. The demonstration trials were set up and managed by the farmer groups, but the input costs were supported by the researchers, and farmers may not be sufficiently aware of the costs associated with fertilizer use. Additional efforts are needed to facilitate access to fertilizer and expose farmers to correct fertilizer use, as well as to strengthen access to markets. Sustainable cropping systems must enable farmers to gain money in order to allow investment in fertilizer.

5. Conclusions

Our results demonstrate that integrated soil fertility management can significantly increase productivity and net economic returns in cassava–legume intercropping systems in the Central-

African highlands. A modified crop arrangement with cassava planted at $2\,m \times 0.5\,m$ potentially increases legume production without negatively affecting cassava yield. Fertilizer use at a moderate rate of $150\,kg\,ha^{-1}$ can be highly profitable despite the high price of the commodity, and increases both the legume and the cassava yield. Our results suggest that the sole use of improved legume and cassava germplasm is insufficient to increase system productivity. The integration of dual-purpose soybean as an alternative legume intercrop may have benefits for soil fertility, but cannot simply replace the common beans intercrop, because its longer growth duration and higher biomass production have a negative effect on cassava yield. Modifications are needed to stimulate acceptance by farmers, and may include reduced plant population, delayed planting, or limiting soybean cultivation to the second season.

Although the ISFM components resulted in significant productivity increases, responses were variable, especially for fertilizer use. A better understanding of the conditions under which positive effects are obtained can enable better targeting and local adaptation of the technology. By conducting a high number of small, farmer-managed trials, the extent and frequency of yield increases obtained through the modified crop arrangement and fertilizer use can be evaluated in more detail. At the same time, farmer experimentation can successfully promote the technology and greatly increase acceptance and early adoption.

Acknowledgements

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