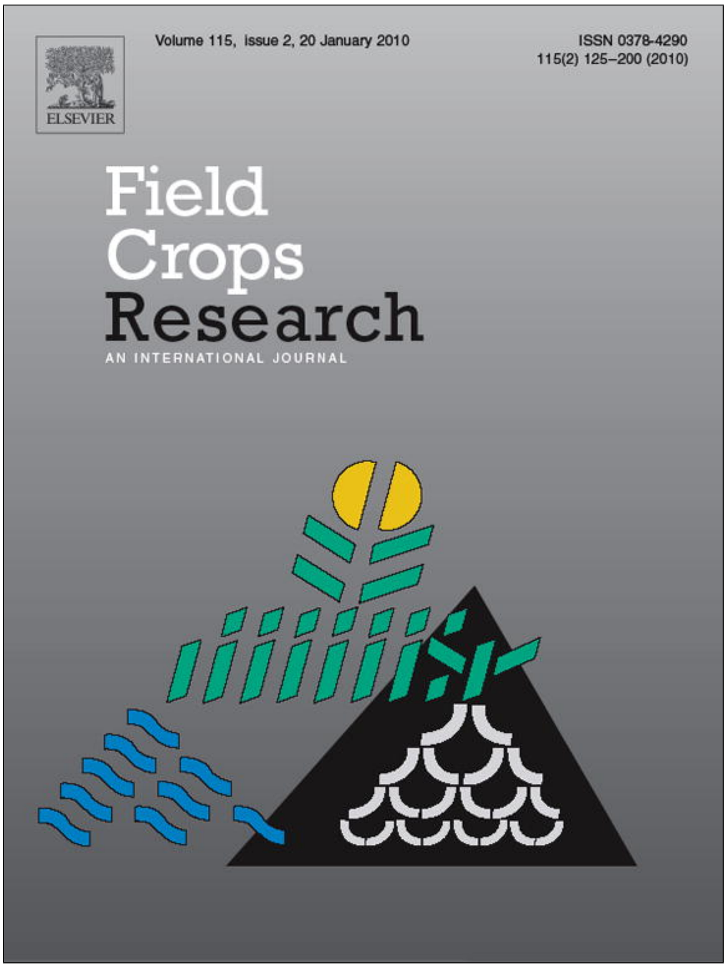
ELSEVIER
Volume 115, issue 2, 20 January 2010
ISSN 0378-4290
115(2) 125–200 (2010)
Field
Crops
Research
AN INTERNATIONAL JOURNAL

Field Crops Research 115 (2010) 132–139

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya

Monicah Mucheru-Muna[a,*], Pieter Pypers[b], Daniel Mugendi[a], James Kung'u[a], Jayne Mugwe[c], Roel Merckx[d], Bernard Vanlauwe[b]

[a] *Kenyatta University, Department of Environmental Sciences, P.O. Box 43844, 00100 Nairobi, Kenya*
[b] *TSBF-CIAT, Tropical Soil Biology and Fertility Institute of CIAT, P.O. Box 30677, 00100 Nairobi, Kenya*
[c] *Kenyatta University, Department of Agricultural Resource Management, P.O. Box 43844, 00100 Nairobi, Kenya*
[d] *K.U.Leuven, Department of Earth and Environmental Sciences, Division Soil and Water Management, Kasteelpark Arenberg 20, 3001 Heverlee, Belgium*

ARTICLE INFO

Article history:
Received 16 July 2009
Received in revised form 9 October 2009
Accepted 10 October 2009

Keywords:
Cereal–legume intercropping
MBILI system
Fertilizer
Economic analysis
N fixation
^{13}C isotope discrimination

ABSTRACT

Smallholder farmers in East-Africa commonly intercrop maize (*Zea mays* L.) with grain legumes to maximize utilisation of land and labour, and attain larger crop yields. Conventionally, one legume line is intercropped between each pair of maize lines. This study evaluated the potential of a modified two-by-two staggered arrangement (MBILI) to increase crop yields and economic benefits in two sites in Central Kenya with contrasting soil fertility levels during 7 consecutive seasons. Common beans (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and groundnut (*Arachis hypogaea* L.) were grown as legume intercrops. The MBILI system resulted in increased maize yields in both sites, and increased cowpea yields in the poor site. In the fertile site, using beans as an intercrop was most profitable, and the MBILI system increased net benefits by 40%, relative to the conventional system. In the poor site, groundnut and cowpea were better adapted, and the MBILI system increased net benefit by 12–37%. Positive effects of the MBILI system were most pronounced in the poor site, but occurred independent of soil fertility level. Rainfall amounts and distribution varied widely, but the MBILI system increased yields both under conditions of ample and inadequate rainfall. N balances were negative with beans and groundnut, but neutral with cowpea as the intercrop. A modest N fertilizer application is therefore essential to sustain yields in the long term, especially when beans or groundnuts are intercropped. In conclusion, the MBILI system, when combined with adjusted nutrient inputs, resulted in superior and robust improvements in crop yields and economic benefits, relative to the conventional intercropping system.

1. Introduction

Low soil fertility, limited availability of resources to farmers, nutrient mining, and drought are the main causes for low agricultural productivity in Sub-Saharan Africa (McCann, 2005). Suitable technologies that are accessible to resource-poor farmers must be affordable in terms of labour, land and capital investments (Barrett et al., 2002). This is, however, often not the case (Sanchez and Jama, 2002). Fertilizers are essential to improve agricultural production in densely populated regions, and this was acknowledged during the Africa Fertilizer Summit held in Abuja, Nigeria in 2006. Mineral fertilizer prices continue to increase. Integrated soil fertility management (ISFM) options therefore aim at optimizing the agronomic efficiency of applied inputs (Vanlauwe et al., in press). Major components include improved germplasm, mineral fertilizer application and organic matter management. By making effective use of resources, ISFM options maximize the profitability of investments in soil fertility.

Legume integration is an important component of ISFM technologies. Legume–cereal intercropping, especially maize-beans intercropping, is common throughout East and Southern Africa (Giller, 2001). In drier areas, common beans are often replaced by cowpea or groundnut. Farmers commonly intercrop to secure food production by averting risk, and to maximize utilisation of land and labour. When crops are complimentary in terms of growth pattern, aboveground canopy, rooting system, and their water and nutrient demand, intercropping effectively enables a more efficient utilisation of available resources (sunlight, moisture and soil nutrients), and can result in relatively higher yields than when crops are grown separately, as pure stands

* Corresponding author. Tel.: +254 0733915165.
E-mail address: moniquechiku@yahoo.com (M. Mucheru-Muna).

0378-4290/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2009.10.013

(Willey, 1979). Other benefits of intercropping are related to the better soil cover, which has advantages for weed control, and leads to reduced erosion and nutrient leaching. Because legumes can rely on atmospheric N, they are less likely to compete for N with the cereal (Fujita et al., 1992; Fan et al., 2006). The presence of a cereal, exploiting the soil mineral N, may even stimulate legumes to fix N (Marschner, 1995), although most often shading significantly reduces N fixation (Nambiar et al., 1983). The integration of legumes in maize-based systems can partially counter N losses through atmospheric N fixation, but basal N application remains indispensable (Jerenyama et al., 2000; Giller, 2001). Legume species and varieties differ in their N fixation potential. Common beans are unlikely to contribute much N to the system. Other legumes, such as pigeonpea or cowpea have a higher potential to supply N to the cereal. Especially the N benefits of pigeonpea in intercropping systems have been demonstrated (Myaka et al., 2006). A more efficient use of soil nutrients in intercropping systems may accelerate soil nutrient depletion, particularly for P, because of higher removal through the produce (Anders et al., 1996). Rhodes et al. (1996) and Bationo and Mokwunye (1991) indicated that the continual removal of harvest residues leads to reduction in total nutrient balance and further depletion. However, contributions from the fallen leaves during legume senescence are likely more important than retaining the haulm residues at harvest (Ncube et al., 2007).

Intercrops can be arranged in different ways. In the conventional 1:1 intercropping system, recommended in Kenya by the Ministry of Agriculture, one row of maize is alternated by one legume row. In an innovative, improved intercropping system, named MBILI (*kiswahili* for “two”, and an acronym for “Managing Beneficial Interactions in Legume Intercrops”), two maize rows are alternated by two legume rows, also known as a two-by-two staggered arrangement (Tungani et al., 2002). The MBILI system allows more light penetration for the under-storey legume component, without changing the plant densities. The system has proven to be very successful in western Kenya (Woomer et al., 2004; Woomer, 2007). Woomer et al. (2004) demonstrated more than 50% higher light penetration, but also suggested that superior crop yields in the MBILI system were related to additional advantages in root distribution and reduced belowground competition. Recently, the use of ^{13}C isotope discrimination has been demonstrated as a valuable tool for evaluating the impact of water stress on crop performance (Yu et al., 2004; Dercon et al., 2006). This tool can be used to compare water stress levels in maize in both intercropping systems.

In the Meru South district in Central Kenya, farmers predominantly grow maize, the major staple food, in rotation or intercropped with beans (Government of Kenya, 2001). Population pressure (800 inhabitants km^{-2}) pushed people from this high-potential area to more marginal areas such as the Mbeere District (400 inhabitants km^{-2}). Average farm sizes in both districts vary between 0.5–3 ha and 1–10 ha, respectively. Cropping systems in Mbeere remained predominantly maize-based, with beans as the preferred legume intercrop, although cowpea, groundnut and green grams gained importance. Further population growth resulted in the expansion of the area of fragile and low-potential lands taken under cultivation, reduced fallow periods and systematic degradation. Maize yields drastically reduced from 3.3 to 0.7 t ha^{-1} during the past three decades (Jaetzold et al., 2006). Fertilizer trials showed that N and P are the two most widespread limiting nutrients in the area are N and P, reported in 57% and 26% of the cases, respectively (KARI, 1994). Only 25% of the maize growers in the central highlands of Kenya use mineral fertilizers. The majority moreover apply fertilizer at inadequate rates, less than 20 kg N ha^{-1} and 10 kg P ha^{-1} (Adiel and Kihanda, unpublished data). In this context, improved intercropping systems as part of ISFM technologies have large scope for increasing crop yields.

The primary objective of this study was to evaluate the robustness of the MBILI intercropping system in two sites in the Central highlands of Kenya with contrasting soil fertility and highly variable rainfall patterns. Grain yields and economic returns for the MBILI system and the conventional intercropping system were compared for different legume intercrops and P application levels. In addition, the contribution from N fixation by the legumes and N balances were assessed in the two contrasting intercropping systems.

2. Materials and methods

2.1. The study area

The study was conducted in the Meru South and Mbeere Districts of Kenya. In Meru South, the experiment was conducted in Mukuuni (00°23′30.3″S; 37°39′33.7″E, 1287 m above sea level). The soil was classified as a Humic Nitisol (FAO, 1991), a typical deep and weathered soil with moderate to high inherent fertility (Jaetzold et al., 2006). In the Mbeere District, the trial was conducted in Machang’a (00°47′26.8″S; 37°39′45.3″E, 1028 m above sea level). The soil was sandy loam, yellowish red, classified as a Xanthic Ferralsol (FAO, 1991). Soils in Mbeere are typically poor and require intensive fertilisation (Jaetzold et al., 2006). Selected soil characteristics are presented in Table 1.

The rainfall is bimodal, divided into two distinct seasons: the ‘long rains’ (LR) lasting from March to June, and the ‘short rains’ (SR) lasting from October to December. Mean annual rainfall averages 1200 and 900 mm in the Meru South and Mbeere districts, respectively (Government of Kenya, 1997). In both districts, rainfall is often unreliable, and mid-season drought spells are frequent, although less in Meru South than in Mbeere. Daily rainfall at the trial sites was determined using a rain gauge.

2.2. Trial establishment and management

The experiment was established in October 2004 (SR04) and ran for 7 consecutive seasons (SR04–SR07). In Mukuuni, land was obtained from a farmer, on behalf of the community for experimental purposes. In Machang’a, the trial was established on land belonging to a school. Trials were researcher-managed, but local farmers were involved to stimulate learning and exposure to the technology. The trial was laid out as a randomized complete block design (RCBD) with 3 replicate blocks and plot sizes measuring 6 m × 4.5 m. The trial was arranged in a complete factorial design with 3 factors (i) legume intercrop, (ii) row arrangement, and (iii) P application. Maize (*Zea mays* L.), was intercropped with different legumes: common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and groundnut (*Arachis hypogaea* L.). Maize varieties H513 and Katumani were

Table 1
Selected topsoil (0–15 cm) characteristics at the two trial sites.

Soil parameter	Mukuuni	Machang’a
pH (1:2.5 in H_2O)	5.9	6.4
Total N (%)	0.24	0.09
Total organic C (%)	2.72	1.05
Bicarbonate-extractable P (mg P kg^{-1})	20.9	12.9
Exchangeable K ($cmol_c$ kg^{-1})	2.65	0.35
Exchangeable Ca ($cmol_c$ kg^{-1})	4.44	1.0
Exchangeable Mg ($cmol_c$ kg^{-1})	1.44	0.14
ECEC ($cmol_c$ kg^{-1})	8.53	1.49
Clay (%)	37	22
Sand (%)	38	67
Silt (%)	25	11

planted in Mukuuni and Machang'a, respectively, following the recommendations of the Kenya Agricultural Research Institute (KARI) for the two areas. Katumani is a short-duration variety (85–100 days) recommended for the drylands, while H513 has a longer growing period (120–150 days) for high-potential areas. Legume varieties were CAL143 for beans, CP21 for cowpea and ICGV12991 for groundnuts, with growing periods of 70–80 days, 75–90 days and 100–110 days.

The maize and legumes were intercropped either following the conventional or the MBILI arrangement. In the conventional intercropping system, each maize line is alternated by a legume line. The spacing recommended by the Kenyan Ministry of Agriculture differs for both sites because of the difference in agro-ecology. In Mukuuni, maize was planted at an inter- and intra-row spacing of 0.75 and 0.5 m, respectively, with two plants per stand (=53,333 plants ha^{-1}) while in Machang'a, maize was planted at an inter- and intra-row spacing of 0.90 and 0.6 m, respectively, with two plants per stand (=37,037 plants ha^{-1}). Beans and cowpea were planted at intra-row distances of 20 cm in Mukuuni (=66,666 plants ha^{-1}) and in Machang'a (55,555 plants ha^{-1}). Groundnut was planted at an intra-row distance of 10 cm in Mukuuni (133,333 plants ha^{-1}) and at 30 cm in Machang'a (=37,037 plants ha^{-1}). In the MBILI intercropping system, the two neighbouring maize lines were planted at a 50 cm inter-row distance and between each pair of maize rows, two legume rows were planted at 33 cm inter-row distances. The maize and legumes are planted at the same intra-row distances as in the conventional intercropping system. In Mukuuni, maize and legume populations were identical for both intercropping systems. In Machang'a, however, maize and legume populations were 20% higher in the MBILI system, compared to the conventional intercropping system, because of the lower planting density in the recommended conventional system. We did not modify the planting density in the MBILI system to allow comparison between sites. In both systems, plots were continuously cropped, but the position of the legume and maize lines was rotated with seasons.

Land preparation was done manually, and weeds were regularly controlled using a hand hoe. Two P treatments were included: a control (without P application) and a treatment with *triple super phosphate* (TSP) fertilizer application at a high rate (60 kg P ha^{-1}) to eliminate P deficiency and evaluate the performance of the system under conditions where P is not limiting. TSP was applied in the planting lines; no N fertilizer was applied. Stemborers in maize and aphids in cowpea were controlled by preventive spraying with Buldock pesticide. No diseases were observed on the maize or the legumes. Legume aboveground biomass was determined at 50% podding in Mukuuni only, by sampling 5 random plants. Dry matter yields were extrapolated to a hectare basis using plant populations corrected for the emergence rate. Emergence rates were not affected by treatments. Maize and legumes grain yields, and maize stover yields were determined at maturity. The outer plant lines of the plot were disregarded for taking yield measurements. Maize stover was removed after harvest. Legume leaf and haulm residues were retained and incorporated into the soil at the onset of the next season. All dry matter yields are expressed on an oven-dry (60 °C) weight basis.

2.3. ^{13}C isotopic discrimination

Detailed measurements on ^{13}C isotopic discrimination were only conducted in Mukuuni because in this site, maize yields were likely more limited by rainfall than soil fertility. The $\delta^{13}C$ value was determined as a measure for water stress during seasons LR05, LR06, SR06, LR07 and SR07. At harvest, the stover of five random maize plants was sampled. After drying, grinding and ball-milling, ^{13}C content was determined using a stable isotope mass spectrometer (Europa Scientific ANCA 20-20/GSL). The $\delta^{13}C$ isotope discrimination ratio was calculated using the international PBD standard.

2.4. N fixation

N fixation was determined for the legumes grown during the LR06 season in Mukuuni, using the ^{15}N natural abundance method (Peoples et al., 1991). Legume biomass was collected at the podding stage. At the same time, 3 random maize plants were cut as a reference. After drying and grinding, ^{15}N content was determined using a stable isotope mass spectrometer (Europa Scientific ANCA 20-20/GSL), and the $\delta^{15}N$ value and proportion of N fixed from the atmosphere (%Ndfa) were calculated. *B*-Values used for beans, cowpea and groundnut were −0.482‰ (Kimura et al., 2004), −1.48‰ (Nguluu et al., 2002) and −1.40‰ (Boddey et al., 2000), respectively. These proportions were then used to estimate N balances (N remaining after removal of N through the maize and legume grains and through the maize stover) in the different intercropping systems. We assumed the belowground N contribution to be one third of the aboveground N content of the legume (Choi et al., 2008).

2.5. Economic analysis

Detailed data on labour requirements were collected every season for each of the field operations (land preparation, planting, fertilizer application, thinning, weeding, pest control and harvest). The time taken to perform every activity was recorded and the labour was valued at the local wage of KShs. 100 (USD 1.47) per day (8 h). Maize stover is commonly used as cattle feed in the area (with a market value of USD 22.1 t^{-1}) and thus accounted for as an additional benefit. Other input and output prices, derived from the farm gate prices in the area, and values used in the economic analysis are presented in Table 2. The economic analysis was performed on cumulated costs and benefits over the 7 seasons.

2.6. Statistical analysis

An analysis of variance was conducted to determine the effects of site, season, intercropping system, legume intercrop and P application using a mixed linear model (MIXED procedure, SAS Institute Inc., 2003). Repeated measures were used to analyse seasonal effects, using a first-order autoregressive covariance structure, which was only slightly less conservative but gave better model fits than a covariance structure with standard variance components. The effects of the various factors and their interactions were compared by computing least square means and standard errors of difference (SED); significance of difference was evaluated at $P < 0.05$.

Table 2
Parameters used in the economic analysis of the different intercropping systems.

Parameter	Actual values
Price of maize seed (USD kg^{-1})	2.35
Price of TSP (USD $(kg\ P)^{-1}$)	2.42
Labour cost (USD day^{-1})	1.47
Price of bean grains (USD kg^{-1})	0.66
Price of cowpea grains (USD kg^{-1})	0.59
Price of groundnut grains (USD kg^{-1})	2.20
Price of maize grains (USD kg^{-1})	0.24
Price of maize stover (USD t^{-1})	22.1

Exchange rate Ksh 68 = 1 USD (official rate in September, 2007 at ending of the trial period); price of legume grains and seed were considered equal as farmers generally recycle seed from the harvest obtained.

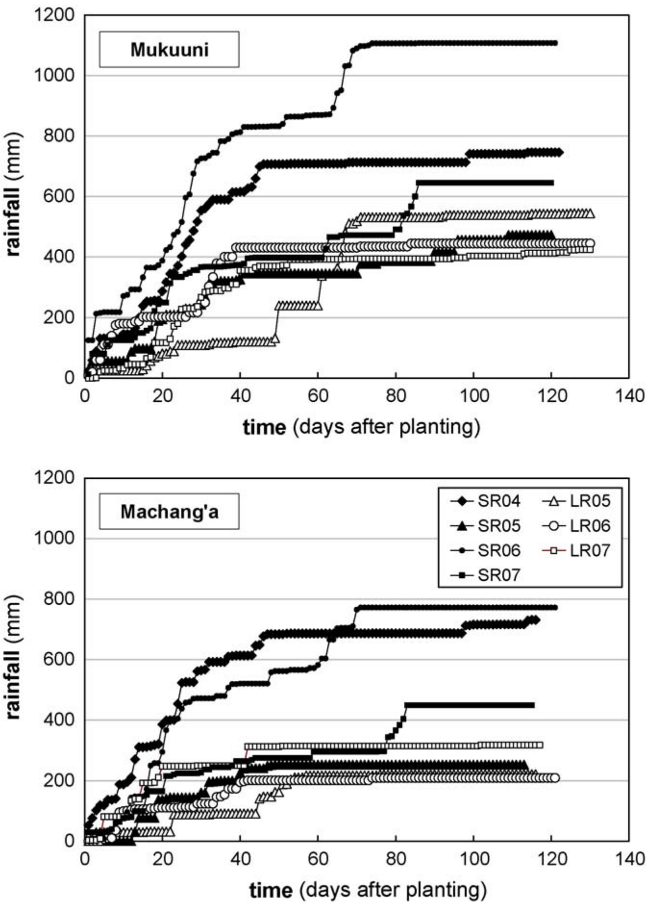

Fig. 1. Cumulative rainfall distribution as observed at the two trial sites (Mukuuni and Machang'a) during 7 consecutive seasons. The rainfall pattern is bimodal with the 'long rains' (LR) lasting from March to June, while 'short rains' (SR) last from October to December.

3. Results

3.1. Rainfall

Amounts of rainfall were higher in the short rainy seasons than in the long rainy seasons, and were generally higher in Mukuuni (on average 630 mm ± 38%) than in Machang'a (on average 420 mm ± 57%) (Fig. 1). Rainfall amounts and distribution varied largely between seasons. Distributions were rather similar for both sites when comparing individual seasons. Drought spells occurred frequently. In season LR06, for example, a 3-week drought occurred starting from the 3rd week after planting in both sites.

3.2. Grain yields

Maize yields were greatly affected by the amounts and distribution of rainfall in both sites. Maize yields in Mukuuni varied between 1.0 and 4.4 t ha^{-1}, and were higher than in Machang'a (0.1–1.7 t ha^{-1}) (Fig. 2). In both sites, maize yields were lowest in LR06 because of the early drought spell. In Mukuuni, no response to P was observed, while in Machang'a, P application more than double maize yields.

Legume yields similarly varied widely, but were differentially affected by rainfall than maize. Seasons with good legume yields generally gave average or poor maize yields, and *vice versa*. During LR06, for example, medium cowpea and bean yields were obtained. In Mukuuni, beans generally gave highest yields, followed by cowpea (maximally 0.7 and 0.5 t ha^{-1}, respectively). Groundnut yields were poor in all seasons (less than 0.2 t ha^{-1}). In Machang'a, highest grain yields were generally obtained for cowpea, initially about 1.3 t ha^{-1} but decreasing readily in following seasons. Bean and groundnut yields varied between 0.2 and 0.8 t ha^{-1}. Yields of all 3 legume species tended to decrease with the seasons. Response to P application was only observed in Machang'a, and was most pronounced for cowpea. P application resulted in highest yield increases during seasons SR04, SR06 and LR07, when rainfall amounts were highest in the first month after planting.

In Mukuuni, the MBILI system resulted in significant maize yield increases when intercropped with beans (by 43%) but not with cowpea or groundnut, relative to the conventional intercropping system (Fig. 3). This increase was consistently observed in 5 out of the 7 seasons. In seasons SR04 and LR07, both intercropping systems gave similar maize yields. Legume yields were not affected by the intercropping system in Mukuuni. In Machang'a, higher maize yields were observed in the MBILI system for maize intercropped with cowpea when no P was applied, and with beans when P was applied. MBILI intercropping increased maize yields by about 0.6 t ha^{-1}. In Machang'a, the MBILI system also resulted in significantly ($P < 0.05$) higher cowpea yields (by 88%), relative to the conventional intercropping system, but this effect only occurred when no P was applied. The yield benefits of the MBILI system occurred independent of the season, both when rainfall was ample or inadequate. The MBILI system did not result in lower crop yields in any of the sites or seasons.

3.3. ^{13}C isotopic discrimination

The seasons during which ^{13}C isotopic discrimination was assessed cover the range in rainfall amounts and distributions observed in Mukuuni. The $\delta^{13}C$ value was significantly correlated with maize grain yield ($r = 0.29$, $P < 0.001$), stover yield ($r = 0.45$, $P < 0.001$) and total aboveground biomass yield ($r = 0.41$, $P < 0.001$) (Fig. 4). Lower yields were observed with more negative $\delta^{13}C$ values. Lowest $\delta^{13}C$ values were observed during seasons with smallest rainfall amounts or unfavourable rainfall distribution, confirming that the $\delta^{13}C$ value can be used a proxy for water stress. The relation between maize yields and the $\delta^{13}C$ value was unaffected by the intercropping system, or by the legume intercropped or P application. In seasons with significant yield differences between the conventional intercropping system and the MBILI system, no significant differences in $\delta^{13}C$ values were observed. During the LR07 season, maize biomass samples were also collected at 4, 8 and 12 weeks after planting and at harvest. The $\delta^{13}C$ value decreased slightly with time, but was unaffected by intercropping system, legume intercropped or P application at all times (data not presented).

3.4. N fixation

The %Ndfa, determined during season LR06 in Mukuuni, was highest in cowpea and lowest in common beans (Table 3). Aboveground biomass yields, amounts of N fixed and amounts of N removed through the grains differed between the legumes, but were not influenced by the intercropping system or P application. Cowpea produced highest amounts of biomass and thus fixed highest amounts of N, of which half was removed through the grain. Biomass yields for groundnut were poor, but grain yields were likely low and little N was removed through the grain. For beans, the amount of N removed through the grain exceeded the amount of N fixed. As a result, N balances for the overall system, taking into account the amounts of N removed through the maize and legume grains and through the maize stover, differed depending on the legume intercropped (Table 4). Highly negative N balances were found when common beans were grown as

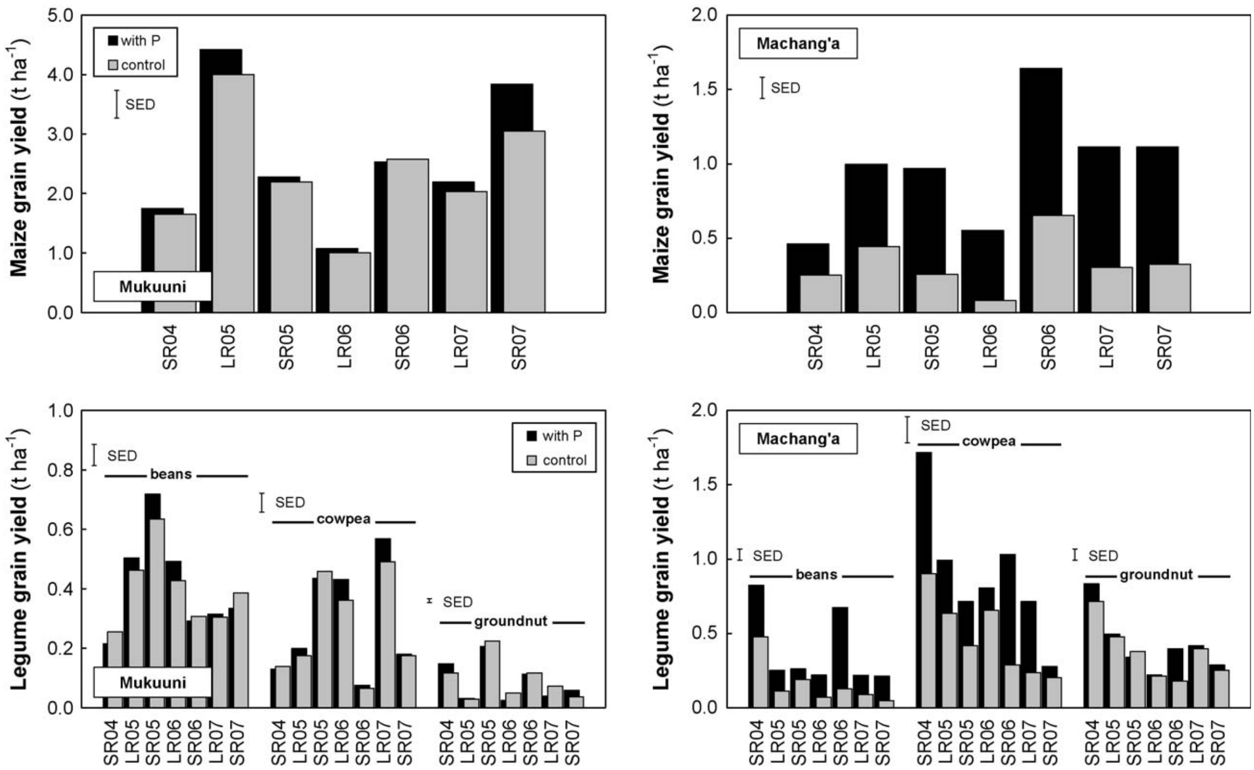

Fig. 2. Maize and legume grain yields in Mukuuni and Machang'a for 7 consecutive seasons as affected by TSP application. Maize yields are averaged across intercropping systems and legume intercrops, and legume yields across intercropping systems since no significant interaction was observed. Bars represent standard errors of difference for the season × P application interaction in Machang'a and for the season effects in Mukuuni, since no significant effect of P application was observed in the latter site.

intercrop. The MBILI system accelerated N depletion because of the higher maize yields and subsequent N removal. With groundnut, N balances were likewise negative. With cowpea grown as the intercrop, however, amounts of N fixed equalled amounts of N removed in both intercropping systems.

3.5. Economic analysis

The MBILI system allowed higher benefits without increases in cost, relative to the conventional system (Fig. 5). Labour costs did not differ between intercropping systems and comprised on average 33% of the total cost when P was applied, and 62% of the total cost without P application. Non-labour costs were higher when groundnut was grown as intercrop, because of the higher seed price and the higher plant population, relative to the other legumes (particularly in Mukuuni). In Machang'a, total costs were slightly higher in the MBILI system, relative to the conventional intercropping system, because of the higher plant populations (and higher seed rate) in the former system. In Machang'a, the MBILI system resulted in overall increased net benefits by 30%, relative to the conventional intercropping system. These increases were most pronounced with cowpea if no P was applied, and with groundnuts if P fertilizer was applied. Highest net benefits were obtained with groundnut as the legume intercrop. Benefit–cost ratios with groundnut (2.2–3.9) were superior to ratios with cowpea (1.3–2.4) or beans (0.7–1.1). P application increased net benefits by 45%, but benefit–cost ratios were significantly ($P < 0.05$) lower, relative to the control. P fertilizer application required an investment of almost 160 USD ha^{-1} per season, and resulted in net benefit increases of 0.8 USD/USD invested in the conventional system. In the MBILI system, however, higher returns were obtained, especially if groundnuts were grown (1.5 USD/USD invested). In Mukuuni, net benefits were likewise higher in the MBILI system, independent of the legume intercrop or P application. No response to P application was observed, and fertilizer addition increased costs and reduced net benefits. Only the control without P application was therefore considered in the economic analysis. Contrary to Machang'a, highest benefits were obtained with beans as the intercrop. The MBILI system with beans as the intercrop resulted in 40% higher net benefits relative to the conventional system with beans, and 50–70% higher benefits, relative to the MBILI system with cowpea or groundnut. The MBILI system with beans also had superior benefit–cost ratios and returns-to-labour. In Mukuuni, the superior profitability of the MBILI system was not affected by changes in fertilizer or labour prices. Effects of TSP application were independent of intercropping system and legume intercrop effects, and labour costs did not differ between intercropping systems. Differences in profitability between both intercropping systems were solely related to the yield improvements in the MBILI system, relative to the conventional intercropping system.

4. Discussion

The MBILI system resulted in increased crop yields and economic benefits, relative to the conventional intercropping system. Tungani et al. (2002) demonstrated that the MBILI arrangement mostly benefits the legumes. Woomer et al. (2004), however, reported that the MBILI system increased both legume yields (by on average 40%) and maize yields (by on average 20%). We similarly observed maize yield increases in the MBILI system. In Machang'a, these yield benefits could be attributed to the higher plant density in the MBILI system. An increase in maize density from 3.7 to 5.3 plants m^{-2} may result in yield increases by 10–30% under conditions without nutrient or water stress (Saha et al., 1994; Tetio-Kagho and Gardner, 1988). The observed benefits of

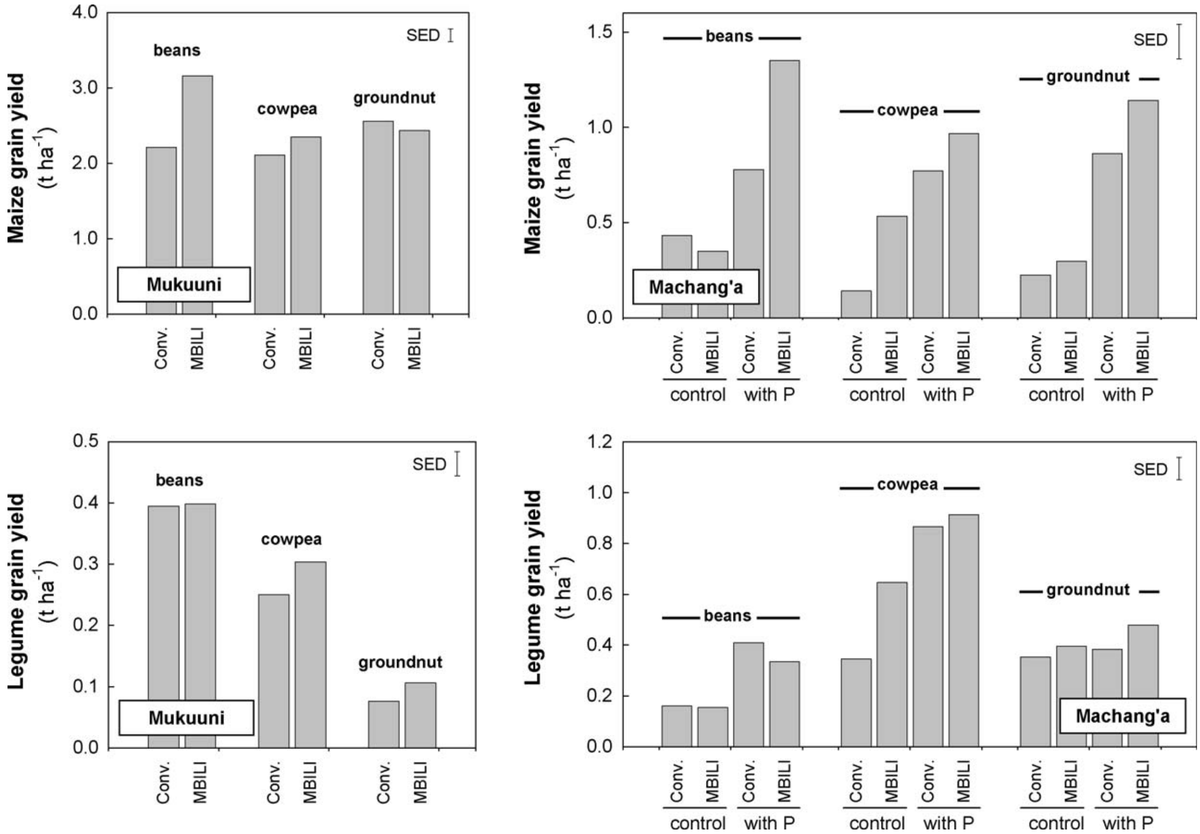

Fig. 3. Maize and legume grain yields as affected by intercropping system and legume intercrop in Mukuuni, and by intercropping system, legume intercrop and TSP application in Machang'a, averaged across 7 consecutive seasons (intercropping system effects were season-independent). P application did not affect grain yields in Mukuuni. Bars represent standard errors of difference for the intercrop × system interaction in Mukuuni, and the P application × intercrop × system in Machang'a.

the MBILI system however exceeded the expected yield increases due to higher plant density. Furthermore, highest maize yields are generally obtained for lower maize plant densities in drought-prone areas, such as Machang'a. Sani et al. (2008) demonstrated that decreasing the maize density from 5.3 to 3.8 plants m^{-2} increased maize yields by 10% under water-stressed conditions. Moreover, maize yield increases were also observed in Mukuuni, where plant densities were identical for both intercropping systems. Therefore, the MBILI system clearly increases maize yields due to the spatial arrangement of the crops, and not due to differences in plant densities. The MBILI system allows larger light

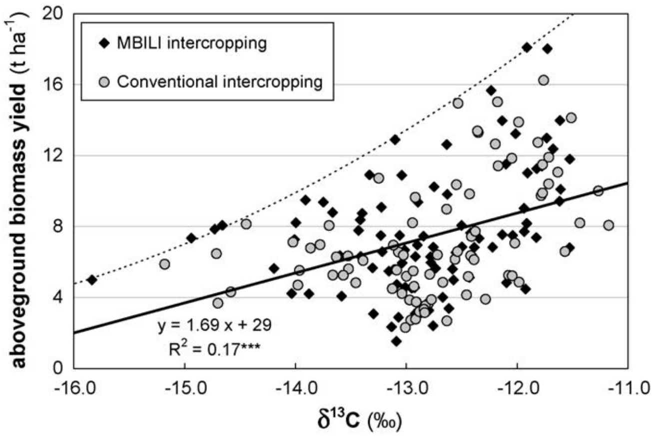

Fig. 4. Total aboveground maize biomass (grains + stover) as a function of the $\delta^{13}C$ value in maize stover observed grouped for five seasons in Mukuuni. The relationship is not affected by the intercropping system. The dotted line represents the boundary.

penetration, which likely benefits the maize as well as the legume (Woomer et al., 2004).

Effects on legume yield were less pronounced. In Mukuuni, groundnut performed poorly: pod-filling was poor, and often part of the yield was lost to rot if rains occurred just before harvest. The rapid maize growth caused significant shading in both systems, which may explain the modest bean and cowpea yields. Beans are relatively more shade-tolerant than the other two legumes (Giller, 2001). Groundnut and cowpea were better adapted to the agro-ecological conditions of Machang'a. Without P application, the MBILI system resulted in increased cowpea yields, relative to the conventional intercropping system. When TSP was applied, however, similar high cowpea yields were observed in both systems. Woomer et al. (2004) demonstrated that the MBILI system increases fertilizer use efficiency when moderate rates of fertilizer are applied. This concurs with our findings. Yield benefits of the MBILI system are largest when nutrient resources are in short supply.

Table 3
Legume biomass yield, N fixed, N removed through the grains and N input (N fixed – N removed), observed during the LR06 season in Mukuuni (averaged across intercropping systems and P treatments).

Legume	Biomass yield ($kg\,ha^{-1}$)	Ndfa (%)	N fixed ($kg\,N\,ha^{-1}$)	N removed ($kg\,N\,ha^{-1}$)	N input ($kg\,N\,ha^{-1}$)
Beans	485	60	10.8	17.4	−6.6
Cowpea	1398	73	43.4	17.6	25.8
Groundnut	492	56	11.9	2.0	9.9
SED	123***	5.0***.	4.3***	3.3***	3.4***

SED = standard error of difference.
*** Significant at $P < 0.001$.

Table 4
N removed through the maize (grains + stover), total N removed (maize grains + maize stover + legumes grains) and N balance (N fixed – total N removed), observed during the LR06 season in Mukuuni for two intercropping systems (conventional and MBILI) and 3 legume species. Effects of intercropping system did not interact with P treatment.

Intercropping system	Legume intercropped	N removed by maize (kg N ha^{-1})	Total N removed (kg N ha^{-1})	Overall N balance (kg N ha^{-1})
Conventional	Beans	37.7	54.9	−44.2
Conventional	Cowpea	23.7	39.9	3.0
Conventional	Groundnut	47.6	47.6	−35.1
MBILI	Beans	71.7	89.3	−78.4
MBILI	Cowpea	25.2	44.2	−0.3
MBILI	Groundnut	37.0	40.0	−28.7
SED (system × legume)		6.4***	7.3**	7.5*

SED = standard error of difference.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.

Competition for nutrients can result in substantial crop yield reductions in mixed cropping systems (Hardter and Horst, 1990). Maize has a competitive advantage because its roots occupy both shallow and deeper soil layers and have a superior ability to recover soil mineral N, whereas root systems of legumes are smaller and confined to the upper soil layer (Hauggaard-Nielsen et al., 2001). Woomer et al. (2004) suggested that the MBILI system may have advantages in terms of root development. Positive effects of the MBILI system were most pronounced under P-deficient conditions. Water stress may aggravate P deficiency (Al-Karaki et al., 1995). However, no differences in water stress based on $\delta^{13}C$ signatures were found in any of the seasons while rainfall amounts and distribution varied widely. The yield benefits of the MBILI system occurred in seasons with ample and well-distributed rainfall, as well as in seasons with inadequate or poorly distributed rainfall. Therefore, it is unlikely that the benefits of the MBILI system on maize production are related to improved water use efficiency. More likely, the MBILI system increases maize and legume yields through higher light penetration or improved nutrient uptake efficiency.

The findings demonstrate the need for adequate fertilizer application to sustain crop production. In Machang'a, secondary nutrient deficiencies may persist, since the decreasing trend in legume yields over the 7-season cropping period was not eliminated by sole P application. In Mukuuni, the soil is rich in P and no response to P application was observed. Maize-beans intercropping systems may not require P application in the area, only N application at 75 kg N ha^{-1} is recommended (KARI, 1994). In sites where P deficiency occurs, such as Machang'a, rates of P fertilizer rates should be adjusted and optimize economic returns. N fixation by the legumes cannot compensate for the N removed through the produce. Beans even do not contribute N to the system as they translocate more N to the grain than they derive from the atmosphere. Cowpea, however, has larger benefits. N balances were only determined in LR06, during which legume yields were moderate but maize yields were rather poor. As such, N balances were likely more negative in other seasons. In addition, other losses occur, mainly through leaching. A moderate N application, targeted to the cereal crop, is therefore necessary to sustain yields in cereal–legume intercropping systems. This has also been reported by other authors (Giller et al., 1994; Sanginga et al., 2000; Sanginga, 2003).

The yield data also illustrate how intercropping effectively spreads risk. Seasons characterized by low maize yields are often compensated by relatively higher legumes yields, and *vice versa*. In Machang'a, for example, rains stopped early in season SR04, which resulted in poor maize performance, but legumes produced relatively higher yields during this season. The same holds for season SR05 in Mukuuni. When rainfall continues up to 10–12 weeks after planting, maize yields are relatively higher and legume yields lower (as can be observed in seasons SR06 and SR07 in Machang'a, and in seasons LR05, SR06 and SR07 in Mukuuni). Under unpredictable rainfall regimes, the legumes and the maize are differentially affected because they are most sensitive to drought at differing times. Maize is most sensitive during the grain filling stage, which occurs later than the sensitive stages for the legume (flowering and early pod-filling). Intercropping is thus an effective risk-spreading strategy (Willey, 1979).

In conclusion, the MBILI system resulted in robust increases in crop yields and net benefits, in comparison with the conventional intercropping system. The benefits occurred both in the fertile and unfertile site, and under conditions of ample and inadequate rainfall, which substantiates the broad applicability of the system. The MBILI system did not entail larger labour costs. Field operations were however carried out by labourers who were familiar with the system, and were assisted by field technicians, which may have obscured differences in labour requirements between both systems. Woomer (2007) showed that the MBILI system was profitable across a wide range of smallholders' croplands in western Kenya, and that, when combined with a fertilizer application at a modest rate, the benefit–cost ratio was

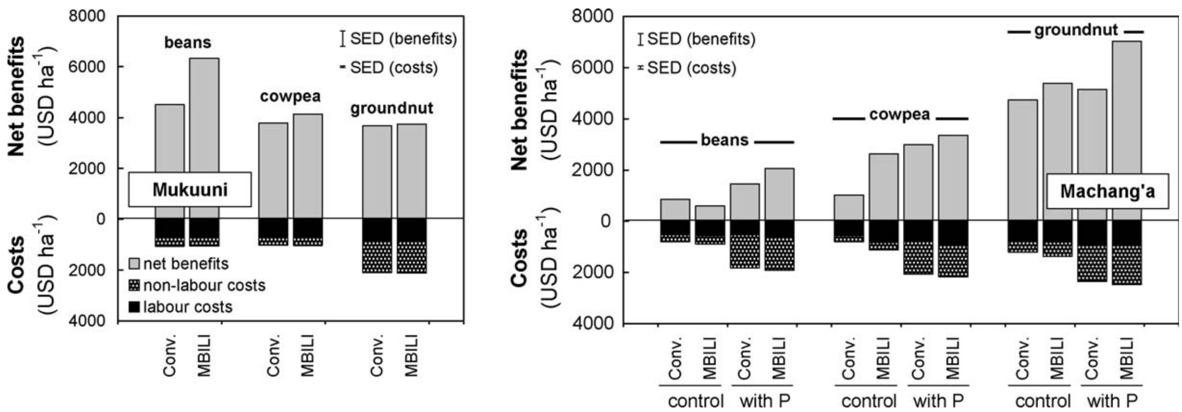

Fig. 5. Costs, and net benefits as affected by intercropping system and legume intercrop, cumulated for 7 consecutive seasons in the two trial sites. Non-labour costs include purchase of seed and fertilizer. In Mukuuni, no response to P application was observed and results presented are for the control only. In Machang'a, the effect of TSP application is shown. Bars represent standard errors of differences in total costs and net benefits for the intercrop intercrop × system interaction in Mukuuni, and the P application × intercrop × system in Machang'a.

higher relative to other recommended technologies in the area. They however also showed that the MBILI system requires more careful planting and weeding operations, which necessitates more complex and larger labour in actual farmers' context. In addition, retooling draft and weeding equipment is necessary. The choice of the legume intercrop should be adjusted to the agro-ecological conditions and growing season. While highest returns were obtained with the MBILI system and beans as legume intercrop in the Meru South district, diversifying with other legumes such as groundnut and cowpea is more profitable in Mbeere District. Also, the technology is knowledge-intensive and requires clear instructions to enable farmers to apply the MBILI system (Tungani et al., 2002). The yield benefits depend on the correct implementation of the intercropping system, and adoption by farmers will therefore require substantial investment in training.

Acknowledgements

The authors wish to thank the Belgian Directorate General for Development Cooperation (DGDC), through the Flemish Interuniversity Council – University Development Cooperation (VLIR-UDC) for providing financial support (Project nr. ZEIN2003PR287). They also appreciate the contribution and collaborative efforts by the Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT), Kenya Agricultural Research Institute (KARI), Kenya Forestry Research Institute (KEFRI) and Kenyatta University (Department of Environmental Sciences) in administering field activities.

References

Abuja Fertilizer Summit, 2006. Abuja Declaration on Fertilizer for African Green Revolution, African Union Special Summit of the Heads of State and Government, Abuja, Nigeria.

Al-Karaki, G.N., Clark, R.B., Sullivan, C.Y., 1995. Effects of phosphorus and water stress levels on growth and phosphorus uptake of bean and sorghum cultivars. Journal of Plant Nutrition 18, 563–578.

Anders, M.M., Potdar, M.V., Francis, C.A., 1996. Significance of intercropping in cropping systems. In: Ito, O., Johansen, C., Adu-Gyamfi, J.J., Katayama, K., Kumar-Rao, J.V.D.K., Rego, T.J. (Eds.), Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-arid Tropics. Japan International Research Centre for Agricultural Sciences, Tokyo, pp. 1–18.

Barrett, C.B., Place, F., Aboud, A., Brown, D.R., 2002. The challenge of stimulating adoption of improved natural resource management practices in African agriculture. In: Barrett, C.B., Place, F., Aboudn, A.A. (Eds.), Natural Resource Management in African Agriculture. CAB International, Wallingford, pp. 1–21.

Bationo, A., Mokwunye, A.U., 1991. Alleviating soil fertility constraints to increased crop productivity in West Africa. Fertilizer Research 20, 95–115.

Boddey, R.M., Peoples, M.B., Palmer, B., Dart, P.J., 2000. Use of the ^{15}N natural abundance technique to quantify biological nitrogen fixation by woody perennials. Nutrient Cycling in Agroecosystems 57, 235–270.

Choi, B., Ohe, M., Harada, J., Daimon, H., 2008. Role of belowground parts of green manure legumes, *Crotolaria spectabilis* and *Sesbania rostrata*, in N uptake by the succeeding tendergeen mustard grass. Plant Production Sciences 11, 116–123.

Dercon, G., Clymans, E., Diels, J., Merckx, R., Deckers, J., 2006. Differential ^{13}C isotopic discrimination in maize at varying water stress and at low and high nitrogen availability. Plant and Soil 282, 313–326.

Fan, F., Zhang, F., Song, Y., Sun, J., Bao, X., Guo, T., Li, L., 2006. Nitrogen fixation of faba bean (*Vicia faba* L.) interacting with a non-legume in two contrasting intercropping systems. Plant and Soil 283, 275–286.

FAO, 1991. World Soil Resources: An Explanatory Note on the FAO World Soil Resources Map at 1:25,000,000 Scale. Food and Agriculture Organization of the United Nations, Rome.

Fujita, K., Ofusu-Budu, K.G., Ogata, S., 1992. Biological nitrogen fixation in mixed legume–cereal cropping systems. Plant and Soil 141, 155–175.

Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems, 2nd edition. CAB International, Wallingford.

Giller, K.E., McDonagh, J.F., Cadisch, G., 1994. Can biological nitrogen fixation sustain agriculture in the tropics? In: Syers, J.K., Rimmer, D.L. (Eds.), Soil Science and Sustainable Land Management in the Tropics. CAB International, Wallingford.

Government of Kenya, 2001. The 1999 Kenya National Census Results. Ministry of Home Affairs, Nairobi, Kenya.

Government of Kenya, 1997. Mbeere District Development Plan 1997–2001. Ministry of Planning and National Development, Nairobi, Kenya.

Hardter, R., Horst, W.J., 1990. Nitrogen and phosphorus use in maize sole cropping and maize/cowpea mixed cropping systems on an Alfisol in northern Guinea Savannah of Ghana. Biology and Fertility of Soils 10, 267–275.

Hauggaard-Nielsen, H., Ambus, H., Jensen, E.S., 2001. Temporal and spatial distribution of roots and competition for nitrogen in pea-barley intercrops; a field study employing ^{32}P technique. Plant and Soil 236, 63–74.

Jaetzold, R., Schmidt, H., Hornetz, B., Shisanya, C.A., 2006.. Farm Management Handbook of Kenya. Natural Conditions and Farm Information, 2nd edition, vol. 11/C. Ministry of Agriculture/GTZ, Nairobi, Kenya (Eastern Province).

Jerenyama, P., Hestermann, O.B., Waddington, S.R., Hardwood, R.R., 2000. Relay intercropping of sunnhemp and cowpea into a smallholder maize system in Zimbambwe. Agronomy Journal 92, 239–244.

KARI, 1994. Fertilizer Use Recommendations, vols. 1–22. Fertilizer Use Recommendation Project. Kenya Agricultural Research Institute (KARI), Nairobi, Kenya.

Kimura, S.D., Schmidtke, K., Tajima, R., Yoshida, K., Nakashima, H., Rauber, R., 2004. Seasonal N uptake and N_2 fixation by common and adzuki bean at various spacings. Plant and Soil 258, 91–101.

Marschner, H., 1995. Mineral Nutrition of Higher Plants, 2nd edition. Academic Press, Munchen.

McCann, J.C., 2005. Maize and Grace. Africa's Encounter with a New World Crop 1500–2000. Harvard University Press, Cambridge.

Myaka, F.M., Sakala, W.D., Adu-Gyamfi, J.J., Kamalongo, D., Ngwira, A., Odgaard, R., Nielsen, N.E., Hogh-Jensen, H., 2006. Yields and accumulations of N and P in farmer-managed intercrops of maize-pigeonpea in semi-arid Africa. Plant and Soil 285, 207–220.

Nambiar, P.T., Rao, M.R., Reddy, M.S., Floyd, C.N., Dart, P.J., Willey, R.W., 1983. Effect of intercropping on nodulation and N fixation by groundnut. Experimental Agriculture 19, 79–86.

Ncube, B., Twomlow, S.J., van Wijk, M.T., Dimes, J.P., Giller, K.E., 2007. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. Plant and Soil 299, 1–15.

Nguluu, S.N., Probert, M.F., McCown, R.L., Myers, R.J.K., Warring, S.A., 2002. Isotopic discrimination associated with symbiotic nitrogen fixation in stylo (*Stylosanthes hamata* L.) and cowpea (*Vigna unguiculate* L.). Nutrient Cycling in Agroecosystems 62, 11–14.

Peoples, M.B., Bergersen, F.J., Turner, G.L., Sampet, C., Rerkeasem, B., Bhromsiri, A., Nurhayati, D.P., Faizah, A.W., Sudin, M.N., Norhayati, M., Herridge, D.F., 1991. Use of natural enrichment of ^{15}N in plant available soil N for the measurement of symbiotic N_2 fixation. In: Stable Isotopes in Plant Nutrition. Soil Fertility and Environmental Studies, IAEA/FAO, Austria, pp. 117–130.

Rhodes, E., Bationo, A., Smaling., E.M.A., Visker, C., 1996. Nutrient stocks and flows in West African soils. In: Mokwunye, A.U., de Jager, A., Smaling, E.M.A. (Eds.), Restoring and Maintaining the Productivity of West African soils: Key to Sustainable Development. IFDC Miscellaneous Fertilizer studies No. 14, Lome, Togo, pp. 22–32.

Sanchez, P.A., Jama, B.A., 2002. Soil fertility replenishment takes off in east and southern Africa. In: Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. (Eds.), Integrated Plant Nutrient Management in Sub-Saharan Africa. CAB International, Wallingford, pp. 23–45.

Sanginga, N., Lyasse, O., Singh, B.B., 2000. Phosphorus use efficiency and nitrogen balance of cowpea breeding lines in a low P soil of the derived savanna zone in West Africa. Plant and Soil 220, 119–129.

Sanginga, N., 2003. Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems. Plant and Soil 252, 25–39.

Saha, H.M., Gacheru, E.N., Kamau, G.M., O'Neill, M.K., Ransom, J.K., 1994. Effect of nitrogen and plant density on the performance of Pwani hybrid maize. African Crop Science Journal 2, 63–67.

Sani, B.M., Oluwasemire, K.O., Mohammed, H.I., 2008. Effect of irrigation and plant density on the growth, yield and water use efficiency of early maize in the Nigerian Savanna. Journal of Agricultural and Biological Science 3, 33–39.

SAS Institute Inc., 2003. SAS User's Guide: Statistics. SAS Institute, Inc., Cary, NC.

Tetio-Kagho, F., Gardner, F.P., 1988. Responses of maize to plant population density. II Reproductive development, yield and yield adjustments. Agronomy Journal 80, 935–940.

Tungani, J.O., Mukhwana, E., Woomer, P.L., 2002. Mbili is Number 1: A Handbook for Innovative Maize–Legume Intercropping. SACRED Africa, Bungoma, Kenya.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R.E., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E., Woomer, P.L., Sanginga, N., in press. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook on Agriculture.

Willey, R.W., 1979. Intercropping – its importance and research needs. Part 1. Competition and yield advantages. Field Crops Abstracts 32, 1–10.

Woomer, P.L., 2007. Costs and returns of soil fertility management options in Western Kenya. In: Bationo, A., Waswa, B., Kihara, J., Kimetu, J. (Eds.), Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities. Springer, the Netherlands, pp. 881–890.

Woomer, P.L., Langat, M., Tungani, J.O., 2004. Innovative maize–legume intercropping results in above- and below-ground competitive advantages for understorey legumes. West African Journal of Applied Ecology 6, 85–94.

Yu, G.R., Wang, Q.F., Zhuang, J., 2004. Modelling the water use efficiency of soybean and maize plants under environmental stresses: application of a synthetic model of photosynthesis-transpiration based on stomatal behaviour. Journal of Plant Physiology 161, 303–318.