THE CURSE OF LOW SOIL FERTILITY AND DIMINISHING MAIZE YIELDS IN SEMI-ARID KENYA: CAN PIGEONPEA PLAY SAVIOUR?[1]

[LA MALDICIÓN DE LA BAJA FERTILIDAD DE SUELO Y RENDIMIENTOS REDUCIDOS DE MAÍZ EN LA KENIA SEMI-ÁRIDA: ¿SERÁ EL FRIJÓL GANDÚL EL SALVADOR?]

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SUMMARY

Little research has been conducted in Kenya to ascertain and exploit the ability of pigeonpea to improve soil fertility and increase cereal yields. An experiment was conducted at Katumani Research Centre between 2009 and 2013 to evaluate the effects of pigeonpea on soil fertility and productivity of maize cropping systems in semi-arid Kenya. The experiment was established as a split-split plot design with sole and intercrops of maize and pigeonpea varieties drawn from three maturity groups and three crop residue application rates as the treatments. Results showed that intercropping maize with pigeonpea reduced ($p \leq 0.05$) soil organic carbon and total soil N from 1.4 and 0.2 % in 2009 to less than 1 and 0.1 %, respectively, in 2013. Intercropping maize with long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues had no significant effect on available P. However, it increased ($p \leq 0.05$) available P from 26 ppm at the start of the study to 50 ppm and 47 ppm in eight seasons under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively. Exchangeable K, Mg and Ca also declined significantly ($p \leq 0.05$). Intercropping maize with long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues offers the best option since it gave higher maize (1.9 t ha^{-1}) and pigeonpea (1.4 t ha^{-1}) grain yields per season and sufficient crop residues to feed the livestock and plough back to improve soil fertility.

Key words: cereal yields; crop residues; soil fertility; pigeonpea.

RESUMEN

Poca investigación se ha realizado en Kenia para conocer y explotar la capacidad del Gandul para mejorar la fertilidad del suelo y aumentar los rendimientos de los cereales. Se realizó un experimento en Katumani Research Center entre 2009 y 2013 para evaluar los efectos del Gandul en la fertilidad del suelo y la productividad de los sistemas de cultivo de maíz en Kenia semi árida. El experimento se estableció como un diseño de parcelas subdivididas con maíz solo y como cultivo intercalado, con variedades de Gandul provenientes de tres grupos de madurez y tres proporciones de aplicación de residuos de cultivos como los tratamientos. Los resultados mostraron que el cultivo intercalado maíz-gandul redujo ($p \leq 0.05$) el carbono orgánico del suelo y el nitrógeno total del suelo de 1.4 y 0.2 % en 2009, a menos de 1 y 0.1 % en 2013, respectivamente. Intercalar maíz con gandul de ciclo largo y reincorporar 4 t ha^{-1} de residuos de cosecha no tuvieron efectos significativos en el P disponible. Sin embargo, aumentó ($p \leq 0.05$) el P disponible de 26 ppm al inicio del estudio a 50 y 47 ppm en ocho temporadas bajo los intercalados maíz-Mbaazi I y maíz-Kat 60/8, respectivamente. El potasio intercambiable, el magnesio y el calcio también disminuyeron significativamente ($p \leq 0.05$). El cultivo intercalado de maíz con gandul de ciclo largo con la reincorporación de 4 t ha^{-1} de residuos ofrece la mejor opción, puesto que dio mayores rendimientos de grano de maíz (1.9t ha^{-1}) y de Gandul (1.4 t ha^{-1}) por temporada y suficiente rastrojo como para alimentar el ganado y reincorporar una parte con el fin de mejorar la fertilidad del suelo.

Palabras clave: rendimientos de cereales; residuos de cosechas; fertilidad del suelo; frijól gandul.

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INTRODUCTION

Arid and semi-arid lands (ASALs) account for over 80 % of Kenya's landmass and support about a third of Kenya's population. This figure is expected to rise, given the current population growth rate of 3 % (GoK, 2013). However, the majority of the people (> 65 %) in ASALs lives in abject poverty and rely on Government relief supplies. Soils in these areas are low in essential plant nutrients, particularly nitrogen (N) and phosphorus (P), while rainfall is low and erratic, hence undermine crop production. Cereal and legume yields from farmers' fields rarely exceed 1.0 and 0.5 t ha^{-1} , respectively, per season compared to over 2.0 t ha^{-1} obtained from research stations and in commercial farms in these regions. The situation is bound to worsen with the expected increase in variability and change in climate (Jaetzold *et al*., 2006; Thornton *et al*., 2009).

Although this situation can be reversed through the use of mineral fertilizers and livestock manure, their widespread application is limited by their prohibitive prices and low quantities and quality, respectively (Bationo and Waswa, 2011). The few farmers who apply mineral fertilizers, hardly use the recommended rates, and often it is utilized with poor efficiency due to environmental or soil-related factors (e.g. P-fixation by sesquioxides, leaching and volatilization of N) as well as management factors, such as poor timing or placement of fertilizer (Vanlauwe *et al*., 2010; Chichongue *et al*., 2013).

However, other studies indicate that including legumes such as pigeonpea in maize cropping systems can reverse the trend effectively and cheaply (Adu-Gyamfi *et al*., 2007; Audi *et al*., 2008; Gwata and Shimelis, 2013; Høgh-Jensen *et al*., 2007; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008). Pigeonpea can improve soil fertility and increase maize yield by availing N to the companion or subsequent maize crop and by mobilizing large amounts of sparingly soluble P into organic forms, especially in N and P deficient soils predominant in semi-arid Eastern Kenya and the rest of Africa (Adu-Gyamfi *et al*., 2007). In Kenya, however, little research has been done to ascertain and exploit this opportunity.

The Kenya Agricultural Research Institute (now Kenya Agricultural and Livestock Research Organization (KALRO), jointly with the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) and the University of Nairobi have over the years developed and released numerous pigeonpea varieties suitable for Kenya's semi-arid lands. However, these efforts focused mainly on developing high yielding varieties that are resistant to *Fusarium* wilt and adaptable to a broad range of ecological conditions (Shiferaw *et al*., 2008). There have been few studies on how their inclusion in the cereal-based cropping systems influences soil N and P and long-term sustainability of these production systems. Therefore the objectives of this study were: (1) To determine the effect of maize-pigeonpea cropping systems on soil carbon, total nitrogen, available phosphorus and exchangeable potassium, calcium and magnesium, and (2) To evaluate the effect of pigeonpea on maize yields.

MATERIALS AND METHODS

Study area

The study was conducted from 2009 to 2013 at KALRO - Katumani Research Centre in Machakos County, 80 km south-east of Nairobi (37˚ 14′ E and 1˚ 35′ S). Katumani, with a bimodal rainfall pattern, receives an average of 711 mm annually, and is about 1600 m above sea level. Average seasonal rainfall is between 250 and 400 mm, with long rains (LR) falling from mid-March to May and short rains (SR) from October to December (Jaetzold *et al.*, 2006). Inter-seasonal rainfall variation is large with coefficient of variation ranging between 45 and 58 % (Keating *et al*., 1992). Therefore, the timing and relative lengths of each growing period vary substantially. Any delay in planting maize at the start of the wet season, brings risks of significant losses in yield, almost proportional to the time delay (Keating *et al*., 1992). However, SR tend to be more reliable for crop production than LR (Jaetzold *et al*., 2006). Temperatures range between 17 and 24^{o}C with February and September being the hottest months of the year. Mean annual temperature is 20^{o}C. Evaporation rates (ETo) are high and exceed the amount of rainfall (r) except in the month of November. Mean potential evaporation is in the range of 1820 to 1840 mm per year, whilst evapotranspiration is estimated to be 1239 mm (Gicheru, 1996), giving an r/ETo ratio of 0.57. The terrain ranges from flat to hilly with slopes varying from 2 to 20 % (Gicheru and Ita, 1987). Katumani falls under agro-climatic zone IV, with a low potential for rainfed agriculture (Jaetzold *et al.*, 2006).

Soils in Katumani are predominantly Luvisols (FAO/UNESCO, 1997; WRB, 2006) derived from granitic parental material (Gicheru and Ita, 1987). They have weak surface structures due to low organic matter and high sand content, and are friable, deep to very deep, well drained and dark red to reddish brown (Gicheru and Ita, 1987). Soil at the experimental site have moderate levels of organic C (1.4 %) and sufficient quantities of P (> 300 ppm), K (229 ppm), Mg (177 ppm) and Ca (1256 ppm) to sustain a healthy maize and pigeonpea crop, without any fertilizer application. However, soils have low total N (0.15 %) and are slightly acidic with a pH of 5.52 (Okalebo *et al*., 2002). Given that both maize and pigeonpea thrive best at soil pH of 5.5 to 8.0 (Jaetzold *et al.*, 2006), soil at the study site was appropriate. The experimental site was a grazing field for many years. It was cleared of weeds and sparse bushes, and cropped uniformly with maize in the 2009 LR season to even it out and to also block the field layout before setting up the experiement. All the crop residues were removed from the field after harvesting to eliminate any confounding effect.

Mixed farming systems involving food crops and livestock are characteristic of the region. Crops grown are predominantly drought-escaping or early maturing varieties of pigeonpea, maize, beans, sorghum and millet (Jaetzold *et al.*, 2006). Due to the erratic nature of rainfall, most farmers around Katumani and the larger semi-arid Eastern Kenya, prefer to intercrop maize with at least a legume (pigeonpea, beans or cowpeas) on the same land. This is often done either in alternate or multiple rows, and is seen by many farmers as a form of security against total crop failure. However, rather than devote their entire arable land to either pure-stand cropping or intercropping, most farmers often dedicate one piece to pure-stand cropping and the remaining area to intercropping in a bid to spread the risk. Long duration pigeonpea is normally planted during SR in October-November and harvested in August-September the following year. Medium and short duration varieties can be planted and harvested in one season (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008). Crop combinations, planting patterns and plant populations of pigeonpea and other crops vary considerably, depending on the soil type, climate and farmer's preferences. However, dominant pigeonpea cropping systems practiced in the region include: pigeonpea intercropped with maize, sorghum, millets, cowpea and green gram; pigeon pea and cow pea intercrops; and maize/bean/pigeon pea intercrops (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008). There is significant conflict between livestock and soil fertility enhancing activities in the area. Crop residues, maize stover and pigeonpea stalks, could be returned to the field to curb run-off and supply nutrients for future crops; however, they are commonly used as livestock feed and fuelwood, particularly during the dry season when there is scarcity (Audi *et al*., 2008).

Experimental design

The experiment was established during the 2009 SR season as a split-split plot design, with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot, and sub-sub-plot, respectively. Treatments included sole and intercrops of maize and pigeonpea varieties drawn from three maturity groups (short, medium and long duration pigeonpeas), and three crop residue (pigeonpea stalks and maize stovers) application rates. Treatments were laid out in 4.8 m long x 4.5 m wide plots with an inter-plot spacing of 1.5 m and replicated four times. Pigeonpea stalks and maize stovers were weighed, chopped into 5 to 10 cm pieces and placed into the soil to a depth of 15 cm at the rate of 0, 2 and 4 t ha^{-1} , respectively. This was done every season after land preparation to allow sufficient time for the crop residues to decompose. Crop residue application rates and cropping systems used, represent as closely as possible those practiced by farmers and take into account the competing uses for crop residues in the ASALs. A total of 20 treatments were investigated and are summarized in Table 1.

Maize variety KDV1 was selected for the study owing to its good adaptability, early maturity (120 to 150 days to mature) and ability to yield highly under semi-arid conditions. Mbaazi 1 and KAT 60/8 were used for the short (100 days) and medium (150 days) duration pigeonpea varieties, respectively, due to their early maturity and high yields. Mbaazi II was used as the long duration variety owing to its resistance to common pests and diseases and high yield. It takes 180-220 days to mature. Generally, the three pigeonpea varieties are also popular among farmers and their seed is readily available. To obtain an integrated view of the legume effect, sole maize was used as the control.

Land was prepared using a hand hoe at the beginning of each cropping season, and crops sown at the on-set of the rains. Pigeonpea was planted at spacings of 90 x 60 cm, 75 x 30 cm and 50 x 25 cm for the long, medium and short duration varieties, respectively, at a rate of 2 seeds per hill. The two plants were thinned to one two weeks after emergence. Maize was planted with triple super phosphate (TSP) fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90c x 30 cm. However, in the intercrops, one row of pigeonpea was planted after every row of maize to replicate the farmers' practice. This way, it was assumed nitrogen was the only macronutrient limiting maize yields.

Pigeonpea was protected from major pests on a 'minimum-protection' basis, as many farmers spray insecticides during flowering/podding, and to avoid confounding the potential soil fertility benefits of legumes with variable pest infestations. They were sprayed two times per season during flowering and podding with Dimethoate^{TM} (dimethoate) at 0.5 L ha^{-1} per spray to control pod borer (*Helicoverpa armigera*) and pod fly (*Melanagromyza chalcosoma*). Bulldock^{TM} insecticide (beta-cyfluthrin) was applied on maize once every season before tasseling to control stalk borers. Plots were kept weed-free by weeding regularly using a hand hoe, depending on weed emergence/intensity and characteristics. The study was conducted for four LR and four SR seasons (8 seasons) from October 2009 to July 2013.

Table 1. Summary of treatments investigated in the study, in a split-split plot design with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot, and sub-sub-plot, respectively.

Treatment	Description
T1	Virgin land/ bare plot (control)
T2	Sole maize, no maize stover incorporated
T3	Short duration pigeonpea sole crop, no pigeonpea residues incorporated
T4	Short duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T5	Short duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T6	Maize/short duration pigeonpea intercrop, no maize stover or pigeonpea residues incorporated
T7	Maize/short duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T8	Maize/short duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated
T9	Medium duration pigeonpea sole crop, no pigeonpea residues incorporated
T10	Medium duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T11	Medium duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T12	Maize/medium duration pigeonpea intercrop, no maize stover or pigeonpea residues incorporated
T13	Maize/medium duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T14	Maize/medium duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated
T15	Long duration pigeonpea sole crop, no pigeonpea residues incorporated
T16	Long duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T17	Long duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T18	Maize/long duration pigeonpea intercrop, no maize stover or pigeonpea residues incorporated
T19	Maize/long duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T20	Maize/long duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated

Soil and plant sampling

Soil samples were taken prior to setting up the trials and after harvesting the 2013 LR season crop (after eight cropping seasons). Soil samples were collected in a transect across the experimental site using a 600 cm^3 soil auger at depths of 0-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm. Soils from each depth were composted and mixed thoroughly in a bucket, and quartered to obtain a representative sample. The samples were air-dried, ground using a mortar and pestle, and passed through a 2 mm sieve for analysis of N, P Ca, Mg and K.

Maize and pigeonpea were harvested at full maturity, when the entire maize stalks are completely dry and pigeonpea pods brownish in colour. Plants lying within one metre of each side of the plot were omitted from the sample harvest to eliminate any plot border effects; the harvest area was 7 m^2. Plants within the harvest area were counted, harvested and weighed. Sub-samples of maize and pigeonpea plants were taken from the total number of plants harvested and divided into cobs and stover, and pods and stalks for maize and pigeonpea data collection, respectively. All samples were oven-dried to constant weight at 60^{0}C and ground to a fine powder using a Wiley Mill. Maize and pigeonpea grains were dried at 12.5 % moisture content; the ratio of dry weight to fresh weight and plot fresh weight used to estimate maize and pigeonpea grain and biomass yields in tonnes per hectare.

Soil and plant analysis

Plant samples at harvest were analyzed for N, P, Ca, Mg and K content, whilst soil samples at the onset and at the end of eight seasons were analysed for pH, organic C, total N, available P, total P and exchangeable bases (K, Mg and Ca). Soil pH was measured in water (1:2.5 soil: water w/v) using a pH meter and organic carbon by the Walkley and Black method as described by Nelson and Sommers (1982). Total N was determined by the Kjeldhal method as described by Bremner and Mulvaney (1982). Available P was measured using Bray 2 method as described by Olsen and Sommers (1982). Exchangeable Ca and Mg were determined using Atomic Absorption Spectroscopy (AAS). Na and K were determined by flame photometry using a flame photometer.

Data analysis

All data on maize and pigeonpea yields, and soil properties were subjected to a two-way analysis of variance (ANOVA) using GENSTAT software version 14.2 (GENSTAT, 2016). Mean comparisons for the individual treatments was done using both Least Significant Difference of means (LSD, $p \leq 0.05$) and the Duncan Multiple Range Test (DMRT) owing to the large number of some of the treatments.

RESULTS AND DISCUSSION

Effect of maize-pigeonpea cropping systems on soil carbon, total nitrogen, available phosphorus and exchangeable bases

Changes in soil chemical properties in the study area after eight seasons of continuous cropping are presented in Table 2.

Soil organic carbon (SOC)

Intercropping maize with the short duration pigeonpea (Mbaazi I) without ploughing back crop residues reduced ($p \leq 0.05$) SOC from 1.4 % at the onset of the study to 0.8 % after eight cropping seasons. A similar trend was observed with the medium duration variety (Kat 60/8) where SOC declined significantly ($p \leq 0.05$) from 1.4 % in 2010 to 0.9 % in 2013 (after eight cropping seasons). Similarly, intercropping maize with the long duration pigeonpea (Mbaazi II) significantly ($p \leq 0.05$) reduced SOC from 1.4 % at the start of the experiment to 0.8 % after eight seasons. Ploughing back 2-0 t ha^{-1} (1.0 t ha^{-1} each) of pigeonpea and maize crop residues did not decelerate the reduction in SOC as it declined ($p \leq 0.05$) from 1.4 % in 2010 to 0.8 % under both maize-Mbaazi I and maize-Kat 60/8 intercrops in 2013 (after eight seasons). The same trend was observed with the long duration variety (Mbaazi II) where SOC dropped significantly ($p \leq 0.05$) from 1.4 % at project inception to 0.7 % after eight continuous cropping seasons. Retaining and incorporating 4 t ha^{-1} of pigeonpea and maize crop residues into the soil also did not decelerate the decline in SOC as it dropped significantly ($p \leq 0.05$) from 1.4 % to 0.8, 0.9 and 0.8 % after eight continuous cropping seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively.

There were no significant differences in SOC between any of the three pigeonpea-maize cropping systems. The drop in SOC could be attributed to rapid mineralization and dissipation of soil organic matter due to continuous cropping without addition of organic materials (Mugwe *et al*., 2009; Itabari *et al*., 2011) and high temperatures. These results agree with the findings by Rao and Mathuva (2000), who reported a significant decline in soil organic C after 5 years of maize-pigeonpea cropping in Machakos, where soil organic C declined by about 6 %. The study, however, did not measure the contribution of residue management to soil carbon stocks of the cropping system and was based on the traditional long duration pigeonpea variety only. Similarly, working in Ghana, Yeboah *et al*. (2004) reported a 2.5 % decline in mean organic carbon content of soils after just one year of pigeonpea cultivation. Conversely, also in Ghana, Abunyewa and Karbo (2005) reported a 30.5 % increase in soil organic carbon on pigeonpea fallow plots after a two-year fallow period. The disparity in pigeonpea contribution to SOC in these two scenarios was due to differences in the amount of pigeonpea biomass returned to the soil. However, working in Malawi, Chirwa *et al*. (2006) found no change in SOC when pigeonpea was included in agroforestry systems. Similarly, Adu-Gyamfi *et al*. (2007) reported no significant change in total soil C after two seasons of maize-pigeonpea intercropping in Malawi and Tanzania. They noted, however, that in Tanzania the maize-pigeonpea intercrop tended to accumulate more C in the upper soil layer, whilst at Nyambi in Malawi it was the reverse, total C content decreased in intercropped plots compared to sole maize plots.

These results differ significantly with those reported by Singh *et al*. (2005) from a study in India, where inclusion of pigeonpea in cereal (wheat) cropping systems reportedly enhanced carbon accumulation in the soil profile by 13.9 %, after three years of continuous cropping, especially when N and P fertilizers were applied. Similarly, Singh and Dwivedi (2006) reported increases in soil organic carbon of 13 % at 0-15 cm, 11 % at 15-30 cm and 9 % at 30-45 cm soil depth after three years of pigeonpea-cereal cropping in the same region. Similar results have been reported by Diekow *et al*. (2005) for a long-term trial in Brazil, in which maize-pigeonpea cropping systems increased soil C stocks by 26 % after 17 years of cropping. Tolanur and Badanur (2003) also reported a significant increase in soil C after just one year of pigeonpea-cereal (pearl millet) cropping in India. These authors attributed the increase in soil C to massive litter fall from pigeonpea. This implies that the 2 or 4 t ha^{-1} of pigeonpea and maize crop residues returned to the soil in our study were insufficient to contribute to SOC. It also means that pigeonpea's contribution to SOC build-up is site-specific and might not depend on residue management and the duration of the crop in the field alone.

Table 2. Changes in soil chemical properties in Katumani after eight seasons of continuous cropping, with different pigeon pea varieties, cropping systems and crop residue application rates.

	Chemical properties[1]					
Cropping system	% Organic C	% Total N	Ext. P (ppm)	Exch. K (ppm)	Exch. Mg (ppm)	Exch. Ca ppm)
Control (virgin land)	1.4^{a}	0.15^{a}	26^{d}	229^{a}	177^{a}	1259^{a}
Mbaazi I/maize intercrop + 0 t ha^{-1*}	0.8^{bcd}	0.09^{bc}	57^{abc}	80^{c}	113^{bc}	650^{b}
Mbaazi I/maize intercrop + 2 t ha$^{-1\dagger}$	0.8^{bcd}	0.08^{c}	43^{abc}	93^{c}	143^{b}	1080^{b}
Mbaazi I/maize intercrop + 4 t ha$^{-1\ddagger}$	0.8^{bcd}	0.08^{c}	50^{abc}	100^{c}	117^{bc}	873^{b}
Kat 60/8/maize intercrop+0 t ha^{-1}	0.9^{b}	0.10^{b}	37^{bcd}	77^{c}	117^{bc}	987^{b}
Kat 60/8/maize intercrop + 2 t ha^{-1}	0.8^{bcd}	0.09^{bc}	65^{a}	93^{c}	113^{bc}	633^{b}
Kat 60/8/maize intercrop + 4 t ha^{-1}	0.9^{b}	0.09^{b}	47^{abc}	130^{b}	123^{bc}	640^{b}
Mbaazi II/maize intercrop + 0 t ha^{-1}	0.8^{bcd}	0.08^{bc}	22^{d}	87^{c}	117^{bc}	650^{b}
Mbaazi II/maize intercrop + 2 t ha^{-1}	0.7^{d}	0.08^{c}	30^{bcd}	100^{c}	117^{bc}	757^{b}
Mbaazi II/maize intercrop + 4 t ha^{-1}	0.8^{bcd}	0.08^{bc}	28^{cd}	93^{c}	100^{c}	600^{b}

[1] Data are treatment means averaged over four replicates, except for the control.

Any two means having a common letter are not significantly ($p \leq 0.05$) different.

*No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

Soil nitrogen

Soil N also declined significantly ($p \leq 0.05$) from 0.15 % at the start of the experiment to 0.09 % in eight seasons, when maize was intercropped with the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea, without ploughing back any crop residues. The trend was the same with the long duration pigeonpea (Mbaazi II), where soil N declined significantly ($p \leq 0.05$) from 0.15 % at inception to 0.08 % after eight seasons. Ploughing back 2 t ha^{-1} of pigeonpea and maize crop residues did not hamper the decline in soil N, as it dropped significantly ($p \leq 0.05$) from 0.15 to 0.08, 0.09 and 0.08 % after eight continuous cropping seasons, when maize was intercropped with the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea varieties, respectively. Similarly, retaining and incorporating 4 t ha^{-1} of pigeonpea and maize crop residues in the soil did not decelerate the drop in soil N, as it reduced significantly ($p \leq 0.05$) from 0.15 to 0.08, 0.09 and 0.08 % after eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II, respectively. The drop in soil N could be attributed to high biomass production by both, maize and pigeonpea, hence high N demand, immobilization of N by soil micro-organisms due to the high C:N ratio of the maize stovers and leaching of nitrates (NO_3) to lower depths beyond the rooting depth of maize and pigeonpea due to high rainfall received during the study (Table 3a) (Chirwa *et al.*, 2004; Sakala *et al.*, 2000; Mafongoya *et al.*, 2000). There were no significant differences in soil N between any of the three pigeonpea-maize cropping systems. These results agree with those of Singh and Dwivedi (2006) who also reported massive depletion of N when pigeonpea was intercropped with cereals (wheat) in India, where 121.2-135.2 kg N ha^{-1} was removed and a meagre 38.4 to 41.6 kg N ha^{-1} recycled from stubble, nodules and leaf litter by pigeonpea. Similarly, it corroborates findings by Adu-Gyamfi *et al.* (2007), where exporting all above-ground material gave a mean N budget of -26.1 kg ha^{-1} for sole maize crop and -40.3 kg ha^{-1} for maize-pigeonpea intercrop at two locations in Malawi, and -50.1 kg ha^{-1} for sole maize crop and -51.1 kg ha^{-1} for maize-pigeonpea intercrop at two sites in Tanzania. Conversely, retaining and incorporating all the aboveground material of maize and pigeonpea, except the edible parts, into the soil gave a positive value of 30.5 kg N for the maize-pigeonpea intercrop and a less negative one (-8.9 kg N) for the sole maize crop in Malawi, and a more negative value (-35.4 kg N) for sole maize, compared to the intercrops (-5.9 kg N) in Tanzania. The huge disparity in N budgets between the two countries was attributed to low and high maize grain yields realized in Malawi and Tanzania, respectively (Adu-Gyamfi *et al.*, 2007). Kumar Rao and Dart (1987) also reported negative budgets for pigeonpea cropping systems in India. However, Yeboah *et al.* (2004) and Chirwa *et al.* (2006) reported no change in total soil N after pigeonpea cultivation in Ghana and Malawi, respectively. Nonetheless, Rego *et al.* (2003) reported positive N for a two-year sorghum-pigeonpea-castor rotation system in farmers' fields in India, Abunyewa and Karbo (2005) reported a 48.5 % increase in total soil N on pigeonpea fallow plots after a two-year fallow period in Ghana. Diekow *et al.* (2005) reported a 28 % increase in soil N stock after 17 years of maize-pigeonpea cropping in Brazil Also, Tolanur and Badanur (2003) reported a significant increase in soil N after one year of pigeonpea- pearl millet cropping in India. This implies that pigeonpea's contribution to soil N depends more on the initial soil N content and to some extent, the companion crop.

Soil phosphorus

Intercropping maize with the short duration pigeonpea (Mbaazi I) without ploughing back any crop residues, increased ($p \leq 0.05$) available P by 119 % (from 26 to 57ppm) in eight seasons. The increase in available P could be attributed to pigeonpea's ability to mobilize P from deep soil horizons and bring it near the surface (Snapp and Silim, 2002; Sakala *et al*., 2003). However, intercropping maize with the medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea had no significant effect on available P. Ploughing back 2 t ha^{-1} of crop residues increased ($p \leq 0.05$) available P by 65 and 150 % in eight seasons, when maize was intercropped with the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea varieties, respectively. Intercropping maize with the long duration variety (Mbaazi II) had no significant effect on available P. Retaining and incorporating 4 t ha^{-1} of crop residues also increased ($p \leq 0.05$) available P by 92 and 81 % in eight seasons under maize-Mbaazi I and maize-Kat 60/8 intercrop, respectively. The increase in available P under the two varieties could be attributed to rapid decomposition and mineralization of the crop residues ploughed back (Abunyewa and Karbo, 2005; Yeboah *et al*., 2004). However, intercropping maize with the long duration variety (Mbaazi II) had no significant effect on available P, and this could be attributed to its tendency to utilize most of the nutrients it mobilizes, due to its high biomass production and long duration in the field (Peoples and Herridge, 1990; Rego and Rao, 2000). These results agree with Rego *et al.* (2003) and Tolanur and Badanur (2003), who reported positive P budgets for sorghum-pigeonpea-castor rotation and pigeonpea-pearl millet cropping systems in farmers' fields in India, after two and one year, respectively. However, they contrast sharply with the findings by Rao and Mathuva (2000), who reported a significant decline in extractable P after 6.5 years of maize-pigeonpea cropping in Machakos, where extractable P declined from the initial 16 to 11 ppm by the end of 6.5 years. The researchers also noted that pigeonpea-maize intercrop recycled a meagre 1.6 kg P ha^{-1} per year through litterfall. Unlike this study, their results were based on the traditional long duration pigeonpea variety and did not factor in the contribution of residue management to extractable soil P. Yeboah *et al.* (2004) also reported a 26 % decline in available P after one year of pigeonpea cultivation in Ghana. Similarly, Singh *et al*. (2005) reported massive depletion of P when pigeonpea was intercropped with cereals (wheat) in India. Available P diminished by 16 % in the first year, 22 % in the second, and 29 % in the third year. It is apparent that, depending on the companion crop and duration in the field, pigeonpea may deplete or increase soil available P.

Exchangeable bases (potassium, magnesium and calcium) in soil

The exchangeable potassium (K) declined significantly ($p \leq 0.05$) by 65 % (from 229 to 80 ppm), 66 % (from 229 to 77ppm) and 62 % (from 229 to 87 ppm) in eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when no crop residues were ploughed back. Ploughing back 2 or 4 t ha^{-1} of crop residues markedly arrested the decline in soil exchangeable K to 59-56, 59-43 and 56-59 % in eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. A similar trend was exhibited by exchangeable magnesium (Mg), where it significantly dropped ($p \leq 0.05$) by 36 % (from 177 to 113 ppm), 34 % (from 177 to 117 ppm) and 34 % (from 177 to 117 ppm) in eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when no crop residues, were retained and incorporated in the soil. Ploughing back 2 or 4 t ha^{-1} of crop residues did not deter soil exchangeable Mg from diminishing, as it declined ($p \leq 0.05$) by 19-34, 36-31 and 34-44 % after eight seasons of continuous cropping under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. Similarly, exchangeable calcium (Ca) declined ($p \leq 0.05$) by 48 % (from 1259 to 650 ppm), 22 % (from 1259 to 987 ppm) and 48 % (from 1259 to 650 ppm) after eight seasons of continuous cropping under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when no crop residues were ploughed back. The situation was the same when 2 or 4 t ha^{-1} of crop residues were ploughed back; exchangeable Ca dropped ($p \leq 0.05$) by 14-31, 50-49 and 40-52 % under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. The drop in these exchangeable bases (K, Mg and Ca) could be attributed to high biomass production by maize (Tables 3a and 3b) and pigeonpea (Tables 4a and 4b), hence high K, Mg and Ca demand. However, the reduction in the decline of soil exchangeable K could be attributed to improvement in K fertility, due to decomposition and mineralization of the crop residues ploughed back (Abunyewa and Karbo, 2005; Yeboah *et al*., 2004). There were no significant differences in exchangeable bases between any of the three pigeonpea-maize cropping systems, implying that all the three pigeonpea varieties lacked the capacity to mobilize exchangeable bases in the soil. These results contrast sharply with findings by Mapfumo and Mtambanengwe (2004), who in a two-year study in northeast of Zimbabwe to determine the rotational effects of pigeonpea of different maturity genotypes on maize yields observed that application of pigeonpea residues improveed K, Mg and Ca in the soil. However, unlike our study site which had sufficient amounts of exchangeable bases, the site in Zimbabwe was nutrient-depleted hence the positive response.

It is apparent from this study that, incorporating pigeonpea in low input maize-based cropping systems predominant in semi-arid eastern Kenya did not improve soil fertility as envisaged. Soil organic matter and nitrogen declined significantly regardless of the pigeonpea variety and amount of crop residues returned to the soil. Available P increased significantly but this was because of the inherently high P levels at the study site. Exchangeable bases, such as potassium, calcium and magnesium also declined significantly. Whilst this decline may be attributed to high nutrient demands due to high maize and pigonepea yields reported during the study, it is apparent that factors other than cropping system, residue management and the duration of the crop in the field influenced the contribution of pigeonpea to soil fertility improvement in this study. Most probably it was influenced by the intial soil fertility status of the study site. This confirms that pigeonpea's contribution to soil fertility improvement is site-specific and perhaps helps to explain why, despite being the fourth largest producer of pigeonpea in the world, most pigeonpea growing areas in the country are among the most degraded in the region.

Effect of intercropping and crop residue incorporation on maize and pigeonpea yields

Maize yield

Maize yields obtained from different maize-pigeonpea cropping systems and crop residue management options are presented in Tables 3a and 3b**.** Growing maize alone without returning any stovers to the soil yielded 0.948 t ha^{-1} of grain and 1.217 t ha^{-1} of stover per season. Yields were higher in the LR compared to SR season (Tables 3a and 3b), probably due to to high rainfall received in the long season compared to the short season.

They were also higher than what most farmers in the region obtain from their farms (less than 0.5 t ha^{-1} per season) and could be attributed to good agronomic practices, such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protection against maize stalk borers applied in this study. The high yields in the LR seasons also indicate that, unlike typical farmers's fields, the study site was not nutrient-depleted.

Table 3a. Maize grain yields obtained from different maize-pigeonpea cropping systems and crop residue manangement options from 2010 to 2013.

Cropping system	Maize grain yield (t ha^{-1})[1]								
	2010		2011		2012		2013		Mean grain yield / season
	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	
Maize sole crop + 0 t ha^{-1} (control)	0.997	0.580	1.153	0.541	1.751	0.645	0.896	1.020	0.948
Mbaazi I-maize intercrop + 0 t ha^{-1}[*]	0.986	0.879	0.842	0.813	0.842	0.759	0.635	0.808	0.821
Mbaazi I-maize intercrop + 2 t ha^{-1}[†]	1.009	0.906	0.986	0.915	0.968	0.836	0.713	0.850	0.898
Mbaazi I-maize intercrop + 4 t ha^{-1}[‡]	1.216	1.008	1.103	1.214	1.567	1.321	1.460	1.420	1.289
Kat 60/8-maize intercrop + 0 t ha^{-1}	0.998	0.765	0.793	0.763	0.968	0.712	0.753	0.747	0.812
Kat 60/8-maize intercrop + 2 t ha^{-1}	1.060	0.878	0.967	0.816	1.013	0.815	0.890	0.813	0.907
Kat 60/8-maize intercrop + 4 t ha^{-1}	1.984	1.598	1.490	1.479	1.793	1.583	1.498	1.499	1.616
Mbaazi II[c]-maize intercrop + 0 t ha^{-1}	-	0.748	-	0.768	-	0.746	-	0.776	0.760
Mbaazi II-maize intercrop + 2 t ha^{-1}	-	0.976	-	0.991	-	0.987	-	0.964	0.980
Mbaazi II-maize intercrop + 4 t ha^{-1}	-	1.789	-	1.894	-	1.796	-	1.978	1.864
SED[d]	0.185	0.195	0.120	0.210	0.215	0.210	0.180	0.205	0.190
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Data are treatment means averaged over 4 replicates; [a] Long rain season (March-May); [b]Short rain season (October-December); [c]Normally planted in the short rain season only; [d]Standard error of treatment means; [*]No crop residues were incorporated; [†]2 t ha^{-1} of crop residues were incorporated; [‡]4 t ha^{-1} of crop residues were incorporated.

Table 3b. Maize stover yields obtained from different maize-pigeonpea cropping systems and crop residue management options from 2010 to 2013.

Cropping system	Maize stover yield (t ha^{-1})[1] 2010 LR[a]	SR[b]	2011 LR	SR	2012 LR	SR	2013 LR	SR	Mean stover yield / season
Maize sole crop + 0 t ha^{-1} (control)	1.018	1.015	2.191	0.995	1.129	1.066	1.192	1.133	1.217
Mbaazi I/maize intercrop + 0 t ha^{-1}[*]	1.118	1.058	1.649	1.163	1.575	1.128	1.562	0.955	1.276
Mbaazi I/maize intercrop + 2 t ha^{-1}[†]	1.469	1.222	1.887	1.35	1.619	1.129	1.707	1.16	1.443
Mbaazi I/maize intercrop + 4 t ha^{-1}[‡]	1.898	1.371	2.073	1.388	1.779	1.927	1.835	1.88	1.769
Kat 60/8/maize intercrop + 0 t ha^{-1}	1.046	1.565	1.581	1.37	1.527	1.147	1.496	1.042	1.347
Kat 60/8/maize intercrop + 2 t ha^{-1}	1.617	1.783	2.086	1.905	1.734	1.286	1.857	1.297	1.696
Kat 60/8/maize intercrop + 4 t ha^{-1}	2.059	2.101	2.436	1.946	1. 817	1.62	1.968	1.771	1.986
Mbaazi II[c]/maize intercrop + 0 t ha^{-1}	-	1.022	-	1.569	-	1.51	-	1.305	1.352
Mbaazi II/maize intercrop + 2 t ha^{-1}	-	1.124	-	1.761	-	1.65	-	1.412	1.487
Mbaazi II/maize intercrop + 4 t ha^{-1}	-	2.093	-	1.937	-	1.881	-	2.407	2.080
SED	0.263	0.220	0.153	0.171	0.273	0.175	0.132	0.231	0.315
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Data are treatment means averaged over 4 replicates; [a] Long rain season(March-May); [b] Short rain season (October-December); [c]Normally planted in the short rain season only; [*]No crop residues were incorporated; [†]2 t ha^{-1} of crop residues were incorporated; [‡]4 t ha^{-1} of crop residues were incorporated.

This implies that farmers in the region can double their maize grain yields in good seasons without applying fertilizer, especially in newly opened farms, provided they adhere to other sound agronomic practices, such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protecting against maize stalk borers. Low grain yields in the short seasons (less than 1.0 t ha^{-1}) reflect what most farmers in the region get (less than 0.5 t ha^{-1} per season) and could be due to the relatively low rainfall received in those seasons compared to the long seasons.

Ploughing back crop residues had a significant effect on both maize grain and stover yields across seasons and cropping systems. For instance, intercropping maize with the short, medium and long duration pigeonpea varieties without ploughing back crop residues reduced mean maize grain yields per season by 13 % (0.948 to 0.821 t ha^{-1}), 14 % (0.948 to 0.812 t ha^{-1}) and 20 % (0.948 to 0.760 t ha^{-1}), respectively. The reduction in grain yield could be attributed to low availability of essential nutrients due to continuous cropping without any nutrient restitution. However, mean stover yields per season increased by 4.8 % (from 1.217 to 1.276 t ha^{-1}), 10.7 % (from 1.217 to 1.347 t ha^{-1}) and 11 % (from 1.217 to 1.352 t ha^{-1}) under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, presumably due to the high rainfall received during the study, especially in the long seasons. A similar trend was observed when 2 t ha^{-1} of crop residues were ploughed back, where mean grain yields per season dropped by 5 % (from 0.948 to 0.898 t ha^{-1}) and 4 % (from 0.948 to 0.907 t ha^{-1}) under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, but increased marginally by 3 % (from 0.948 to 0.980 t ha^{-1}) under maize-Mbaazi II intercrop. On the contrary, mean stover yields per season increased significantly by 18.5 % (from 1.217 to 1.443 t ha^{-1}), 39 % (from 1.217 to 1.696 t ha^{-1}) and 22.2 % (from 1.217 to 1.487 t ha^{-1}) under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. The reduction in the decline of grain yields and significant increase in stover yield could be attributed to improvement in soil fertility due to decomposition and mineralization of the crop residues (Akanvou *et al*., 2002; Degranade, 2001). These results agree with Silim *et al.* (1997) who noted from a study in semi-arid Eastern Kenya that the yield of intercropped maize was substantially lower than its sole crop, especially in seasons when moisture supply was limiting. Ploughing back 4 t ha^{-1} of crop residues increased mean grain yields significantly by 35 % (from 0.948 to 1.289 t ha^{-1}), 70 % (from 0.948 to 1.616 t ha^{-1}) and 97 % (from 0.948 to 1.864 t ha^{-1}) per season under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. Similarly, it increased stover yields by 45 % (from 1.217 to 1.769 t ha^{-1}), 63 % (from 1.217 to 1.986 t ha^{-1} and 71 % (from 1.217 to 2.080 t ha^{-1}) per season when maize was intercropped with the short, medium and long duration pigeonpea, respectively. The significant increase in both grain and stover yields could be attributed to improvement in soil nutrient supply and soil physical properties such as bulk density, infiltration and water-holding capacity due to decomposition of the crop residues (Chirwa *et al*, 2004), however, the high increase in yield by Mbaazi II (long duration pigeonpea) compared to the rest could be attributed to its ability to mobilize and avail extra nutrients from deep soil horizons due to its deep root system and massive litterfall (Snapp and Silim, 2002; Silim *et al*., 2005; Myaka *et al*., 2006; Adu-Gyamfi *et al*., 2007; Kumar *et al*., 2011). These results corroborate findings of Kumar and Goh (2000) that the magnitude of the yield increase of cereals in such systems depends on the amount of materials returned to the soil. Similar results were reported by Wanderi *et al.* (2011) from a study in Thika near Nairobi where maize grain and stover yields increased by about 15 and 30 %, respectively, under maize-long duration pigeonpea intercrop. Other authors such as Chirwa *et al.* (2004), Mapfumo and Mtambanengwe (2004), Rao and Mathuva (2000), Adjei-Nsiah *et al.* (2007), Degrande (2001), Akanrou *et al.* (2002), Abunyewa and Karbo (2005) and Chamango (2001) reported significant improvement in maize grain yields attributable to pigeonpea, but mostly based on long duration pigeonpea fallows. They attributed the increase in maize yield to improvement in soil chemical and physical properties due to decomposition and mineralization of pigeonpea’s massive litterfall.

Thus, it is possible to increase maize grain yields from < 0.5 t ha^{-1} per season currently obtained by most farmers in semi-arid Eastern Kenya to 1.289 t ha^{-1}, 1.616 t ha^{-1} and 1.864 t ha^{-1} cheaply by intercropping maize with the short, medium and long duration pigeonpea, respectively, and by ploughing back 4 t ha^{-1} (2 t ha^{-1} each) of pigeonpea and maize crop residues every season to improve soil fertility. However, intercropping maize with the long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues offers the best option as it increases maize grain yields significantly and generates sufficient stover to plough back and feed the livestock. Framers should therefore be encouraged to adopt this practice to avert land degradation and food insecurity.

Pigeonpea yield

Pigeonpea yields obtained from different maize-pigeonpea cropping systems and crop residue management options are presented in Tables 4a and 4b**.**

Pigeonpea yield varied significantly across varieties, seasons, cropping systems and residue management options. For instance, the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea varieties yielded 0.895, 1.023 and 1.136 t ha^{-1} of grain, respectively, per season when grown without ploughing back crop residues. The same trend was observed in biomass yields where 1.04, 1.345 and 1.927 t ha^{-1} of pigeonpea stalks was obtained from the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea variety, respectively, per season. These higher yields compared to what most farmers farmers obtain from their farms (less than 0.5 t ha^{-1} of grain per season) could be attributed to the good agronomic practices such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protection against maize stalk borers applied in this study. However, the significantly higher yields by Mbaazi II (the long duration variety) compared to other varieties (Mbaazi II and Kat 60/8) could be due to its phenological complementarity with maize and its ability to mobilize nutrients from deeper soil horizons due to its deep root system and massive litterfall (McCown *et al.*, 1992; Myaka *et al.*, 2006).

Intercropping the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea with maize without ploughing back crop residues reduced their average grain yields per season by 92 % (from 0.895 to 0.071 t ha^{-1}) and 94 % (from 1.023 to 0.065 t ha^{-1}), respectively. However, long duration pigeonpea (Mbaazi II) grain yield increased marginally by 5.5 % (from 1.136 to 1.199 t ha^{-1}). Similarly, relative to the control, mean pigeonpea stalk yield per season dropped by 83.5 and 84.5 % under maize-Mbaazi I and maize-Kat 60/8 intercrop, respectively, but increased ($p \leq 0.05$) by 21.8 % under maize-Mbaazi II intercrop. The reduction in the short and medium duration pigeonpea grain and stalk yields could be attributed to maize’s longer duration in the field, since the longer the duration of the cereal, the lower the pigeonpea yield (Tarhalkar and Rao, 1981; Ali, 1990). However, the increase in the long duration pigeonpea yield could be due to its longer duration in the field, which allowed it to recover from the initial slow growth after the maize was harvested and also its ability to mobilize extra nutrients from deeper soil horizons due to its deep root system (Snapp and Silim, 2002; Mapfumo and

Mtambanengwe, 2004; Silim *et al*., 2005; Kumar *et al*., 2011). Similar results were reported by Natarajan and Wiley (1981) from a study in India, in which the pigeonpea component of a cereal (sorghum)-pigeon pea intercrop suffered considerable competition from the cereal initially, but recovered after the cereal was harvested and produced seed yields equivalent to 70 % of the sole crop.

Ploughing back 2 t ha^{-1} of crop residues reduced the decline in average pigeonpea grain yields per season to 88.4 and 90.3 % under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, before increasing by 15.9 % under maize-Mbaazi II intercrop. The average pigeonpea stalk yields per season also declined by 75.5 and 79.2 % under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, before increasing by 33.4 % under maize-Mbaazi II intercrop. Retaining and incorporating 4 t ha^{-1} of crop residues in the soil hampered further drop in mean pigeonpea grain yield per season to 85.8 and 87.4 % under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, but increased it by 25.6 % under maize-Mbaazi II intercrop. Average stalk yields per season declined by 67.5 and 72.2 % under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, but increased by 51.6 % under maize-Mbaazi II intercrop. The deceleration in the decline in the short and medium duration pigeonpea yields and increase in long duration pigeonpea yield could be attributed to improvement in soil fertility, due to mineralization of the added crop residues. These results agree with those of Tarhalkar and Rao (1981), and Ali (1990) who indicated that intercropping cereals with early-maturing pigeonpea often led to reduction in pigeonpea yield. Similar results were reported by Egbo and Ngumalen (2010) from a two-year study in Nigeria, where intercropping decreased the number of pods per plant, dry pod weight and grain yield of the pigeonpea component, as well as the panicle length, panicle weight and dry grain yield of the cereal component. It is apparent from this study that, irrespective of how much crop residues is returned to the soil, both short and medium duration pigeonpea are not the best candidates for incorporation into maize-based cropping systems in the study area, since doing so depressed their grain and stalk yields significantly. However, due to its phenological complementarity with maize, long duration pigeonpea is the best option for intercropping with maize. Long duration pigeonpea is able to give higher yields with or without ploughing back crop residues, because its deep root system allows it to mobilize extra nutrients from deeper soil horizons, besides its ability to recycle massive litterfall.

Table 4a. Pigeonpea grain yields obtained from different pigeonpea-maize cropping systems and crop residue management options from 2010 to 2013

	Pigeonpea grain yield (t ha^{-1})[1]								
	2010		2011		2012		2013		Mean grain yield/ season
Cropping system	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	
Mbaazi I sole crop + 0 t ha^{-1}[*]	0.872	0.882	0.978	0.766	0.690	1.043	0.934	0.992	0.895
Kat 60/8 sole crop + 0 t ha^{-1}	1.023	1.009	0.981	1.083	1.021	1.079	1.031	0.956	1.023
Mbaazi II[c] sole crop + 0 t ha^{-1}	-	1.000	-	0.990	-	1.193	-	1.359	1.136
Mbaazi I/maize intercrop + 0 t ha^{-1}	0.185	0.014	0.042	0.119	0.089	0.020	0.048	0.048	0.071
Mbaazi I/maize intercrop + 2 t ha^{-1}[†]	0.191	0.034	0.147	0.119	0.160	0.021	0.096	0.064	0.104
Mbaazi I/maize intercrop + 4 t ha^{-1}[‡]	0.247	0.068	0.171	0.128	0.149	0.031	0.137	0.087	0.127
Kat 60/8/maize intercrop + 0 t ha^{-1}	0.204	0.020	0.035	0.034	0.076	0.036	0.062	0.051	0.065
Kat 60/8/maize intercrop + 2 t ha^{-1}	0.220	0.028	0.072	0.168	0.136	0.047	0.069	0.052	0.099
Kat 60/8/maize intercrop + 4 t ha^{-1}	0.234	0.043	0.112	0.238	0.185	0.088	0.073	0.057	0.129
Mbaazi II/maize intercrop + 0 t ha^{-1}	-	1.253	-	0.990	-	1.093	-	1.250	1.199
Mbaazi II/maize intercrop + 2 t ha^{-1}	-	1.445	-	1.129	-	1.145	-	1.361	1.317
Mbaazi II/maize intercrop + 4t ha^{-1}	-	1.527	-	1.143	-	1.347	-	1.403	1.426
SED[d]	0.176	0.320	0.201	0.241	0.174	0.297	0.206	0.321	0.289
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1] Treatment means of four replicates; [a] Long rain season(March-May); [b] Short rain season (October- December); [c] Normally planted in short rain season only; [d] Standard error of treatment means; [*] No crop residues were incorporated; [†] 2 t ha^{-1} of crop residues were incorporated; [‡] 4 t ha^{-1} of crop residues were incorporated.

Table 4b. Amount of pigeonpea stalks obtained from different pigeonpea-maize cropping systems and crop residue management options from 2010 to 2013.

	Pigeonpea stalks yield (t ha^{-1})[1]								
Cropping system	2010		2011		2012		2013		Mean stalk yield/ season
	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	
Mbaazi I sole crop + 0 t ha^{-1}[*]	1.001	0.989	0.996	0.999	0.933	1.238	1.089	1.071	1.040
Kat 60/8 sole crop + 0 t ha^{-1}	1.951	1.331	1.053	1.213	1.414	1.371	1.293	1.135	1.345
Mbaazi II[c] sole crop + 0 t ha^{-1}	-	1.475	-	1.241	-	2.241	-	2.750	1.927
Mbaazi I-maize intercrop + 0 t ha^{-1}	0.311	0.117	0.111	0.177	0.229	0.065	0.241	0.122	0.172
Mbaazi I-maize intercrop + 2 t ha^{-1}[†]	0.361	0.321	0.259	0.179	0.310	0.065	0.373	0.169	0.255
Mbaazi I/maize intercrop + 4 t ha^{-1}[‡]	0.523	0.484	0.277	0.194	0.518	0.085	0.440	0.180	0.338
Kat 60/8-maize intercrop + 0 t ha^{-1}	0.389	0.086	0.159	0.060	0.248	0.345	0.240	0.143	0.209
Kat 60/8-maize intercrop + 2 t ha^{-1}	0.404	0.154	0.352	0.260	0.306	0.353	0.255	0.158	0.280
Kat 60/8-maize intercrop + 4 t ha^{-1}	0.441	0.177	0.460	0.395	0.576	0.452	0.305	0.184	0.374
Mbaazi II-maize intercrop + 0 t ha^{-1}	-	1.531	-	2.347	-	2.674	-	2.837	2.347
Mbaazi II-maize intercrop + 2 t ha^{-1}	-	2.006	-	2.569	-	2.692	-	3.013	2.570
Mbaazi II-maize intercrop + 4 t ha^{-1}	-	2.535	-	2.921	-	2.968	-	3.260	2.921
SED[d]	0.365	0.429	0.193	0.543	0.201	0.577	0.209	0.649	0.530
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Treatment means of four replicates; [a]Long rain season (March-May); [b]Short rain season (October- December); [c]Normally planted in short rain season only; [d]Standard error of treatment means; [*]No crop residues were incorporated; [†]2 t ha^{-1} of crop residues were incorporated; [‡]4 t ha^{-1} of crop residues were incorporated.

CONCLUSIONS

Intercropping maize with short and medium duration pigeonpea varieties in water-deficit environment of Katumani is not feasible, as it depresses both grain and biomass yields. However, intercropping the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea varieties with maize and ploughing back 4 t ha^{-1} of crop residues can increase maize yields from what is currently obtained by most farmers in semi-arid Eastern Kenya, up to 1.6 t ha^{-1} per season. Nevertheless, farmers would be hesitant to adopt this option, since they prefer a system that would guarantee them both bumper maize and pigeonpea yields. Thus, intercropping maize with long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues would be the best option, since it is able to give higher maize and pigeon pea yields, and sufficient crop residues to feed the livestock and plough back to improve soil fertility. The contribution of pigeonpea-maize cropping systems to soil fertility improvement in semi-arid areas might depend more on the intial soil fertility status, besides the cropping system, residue incorporation and the duration of the crop in the field.

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