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No rain but bumper harvest: the magic of pigeonpea in semi-arid Kenya

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Abstract: Land degradation and low rainfall seriously constrain agricultural production in arid and semi-arid areas. A study was conducted at Katumani Research Centre between 2009 and 2013 to investigate the effect of pigeonpea and crop residues on soil physical properties and maize yields. Sole- and inter-crops of maize and pigeonpea varieties drawn from three maturity groups and three crop residue application rates were evaluated 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. Results showed that maize-pigeonpea intercrops accumulated very low soil organic matter and hence, did not improve soil physical properties. Instead, they increased soil bulk density and reduced soil aggregation. Intercropping maize with pigeonpea requires more water compared to maize and pigeonpea sole crops. Mbaazi II-maize intercrop offers the best option since it gave the highest maize and pigeonpea grain yields and produced sufficient stover and stalks.

Keywords: aggregate stability; maize yields; crop residues; pigeonpea; Kenya.

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1 Introduction

Dominant features of agricultural production systems in arid and semi-arid lands (ASAL) in Kenya are land degradation and low crop yields (GoK, 2013; Gicheru et al., 2004). Cereal and legume yields from farmers' fields rarely exceed 1 t and 0.5 t ha^{-1}, respectively, per season compared to over 2 t ha^{-1} obtained from research stations and in commercial farms in these areas (Recha et al.,2012; Jaetzold et al., 2006). Majority of the people (> 65%) in ASALs live in abject poverty and rely on government relief supplies. Several authors (Recha et al., 2012; Itabari et al., 2011, 2004; Jaetzold et al., 2006) have described the situation evident on most farms in these areas as a 'poverty trap', in which the high subsistence population living on degraded soils receives low income, affords low or no farm inputs and consequently get low crop yields. The widespread land degradation in these areas is attributable to agricultural mismanagement, overgrazing and deforestation due to population pressure which has forced farmers to use land more intensively and to cultivate on marginal land (Gichangi et al., 2016; Itabari et al., 2011, 2004). Progressive land degradation is not only a threat to national food security, but also promotes climate change by denuding vegetative ground cover and depleting soil organic matter (SOM), thereby reducing their capacity to regulate atmospheric gas pools (Lawal et al., 2009; Steiner, 1996).

Low yields on the other hand are partly due to diminishing soil fertility, but mostly due to low and unreliable rainfall. The soils have low organic matter content due to poor natural vegetation cover and removal of crop residues for livestock feed. They also have low water-holding capacity, poor nutrient status and, are susceptible to erosion and surface sealing and capping due to poor structural development. Besides its unreliability, rainfall in the ASALs occurs in high intensity storms that result in excessive soil and water losses through erosion and run-off, especially at the start of the rainy season when most croplands are bare due to removal of crop residues. Frequent water deficits occur within the growing season and on average, there is a crop failure in two out of every five seasons. Run-off water also carries away dissolved nutrients, further reducing the capacity of the soil to support plant growth (Itabari et al., 2011).

Studies indicate that including legumes such as pigeonpea in maize cropping systems can effectively reverse the above scenario (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; USAID, 2010). Pigeonpea provides several important benefits. The crop is drought-tolerant and can produce yields in seasons when other crops fail. It is therefore an important food security crop for the ASALs. The protein-rich grain is an important component in the diet of subsistence farmers, who eat mainly low-protein cereals and root crops. Pigeonpea stems supplement an often deficient fuelwood situation. Further, pigeon pea is one of the few crops with the potential to ameliorate soils with minimal labour inputs, low seed costs and little or no fertiliser inputs, compared to other green manure and agroforestry species (Snapp et al., 1998; Sakala et al., 2003). It increases SOM substantially through leaf biomass and senescent material produced at a rate of 1–4.5 t ha^{-1} (Snapp and Silim, 2002; Omanga et al., 1990). This SOM improves soil structure and soil water-holding capacity; and supplies essential nutrients, N and P, through mineralisation. However, like other legumes, its contribution to SOM is site specific and therefore depends on the growing conditions, residue management and the duration of the crop in the field (Mafongoya et al., 2000; Snapp et al., 1998).

Pigeonpea also enriches the soil through nitrogen fixation and being a deep-rooted crop, mobilises nutrients, particularly phosphorus, from the deep soil horizons (Ae et al., 1990; Omanga et al., 1990; Snapp and Silim, 2002). In addition, intercropping pigeonpea with cereals enhances soil coverage, reduces soil erosion and boosts cereal yields tremendously (Myaka et al., 2006; Mapfumo and Mtambanengwe, 2004). It is an important component of traditional farming systems common in marginal areas where fertiliser use is minimal (Silim et al., 1990). However, whilst substantial work has been done on the nitrogen-fixing properties of pigeonpea and the effect of exporting or incorporating pigeonpea crop residues on soil nutrients (Adu-Gyamfi et al., 2007; Myaka et al., 2006; Sakala et al., 2000; Rao and Mathuva, 2000), there is scarcity of information on the effect of pigeonpea cropping systems and residue management practices on soil physical properties. This has been attributed to the time-consuming, cumbersome and expensive nature of most soil physical analyses (Chirwa et al., 2004).

Over the years, 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 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; USAID, 2010). There have been few studies on how their inclusion in the maize-based cropping systems influences soil physical properties and long-term sustainability of these production systems. The objective of this study therefore, was to determine the effect of pigeonpea-maize cropping systems on soil physical properties and maize yields.

2 Materials and methods

2.1 Description of the study site

The study was conducted at the KALRO Katumani Research Centre in Machakos County, 80 km south-east of Nairobi (37°14′E and 1°35′S) from 2009 to 2013. Katumani has bimodal rainfall pattern and receives an average of 711 mm annually. The long rains (LRs) occur from March to May and the short rains (SRs) from October to December with peaks in April and November, respectively (Recha et al., 2012; 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 such that any delays in planting, particularly of maize, at the start of the wet season brings risks of significant yield losses, almost proportional to the time delay (Keating et al., 1992). However, the second season (SRs) rains are more reliable for crop production (Recha et al., 2012). Temperatures range between 17°C and 24°C with February and September being the hottest months. The mean annual temperature is 20°C. Evaporation rates are high and exceed the amount of rainfall, most of the year, except in the month of November. The mean potential evaporation is in the range of 1,820 mm to 1,840 mm per year whilst evapotranspiration is estimated at 1,239 mm (Gicheru, 1996) giving an r/ETo ratio of 0.57. Katumani is 1,600 m asl and the terrain ranges from flat to hilly with slopes varying from 2%–20% (Gicheru and Ita, 1987). It falls under agro-climatic zone IV which has a low potential for rainfed agriculture (Jaetzold et al., 2006).

The dominant soils are chromic luvisols (FAO/UNESCO, 1997; WRB, 2006), which are low in organic C, highly deficient in N and P and to some extent znc and generally have poor structure (NAAIAP, 2014). The site was a grazing field for many years prior to the study. 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 experiment. All the crop residues were removed from the field after harvesting to eliminate any confounding effect.

2.2 Treatments and experimental design

The experiment was established during the 2009 SR season as a split-split plot arrangement with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot and sub-sub-plot, respectively. The treatments included sole and intercrops of maize and pigeonpea varieties drawn from three maturity groups (short, medium and long duration pigeonpeas), three crop residue application rates (0, 2 and 4 t ha^{-1}) and virgin land (bare plot) and maize sole crop as controls. The treatments were laid out in 4.8 m × 4.5 m plots with an inter-plot spacing of 1.5 m and replicated four times in a randomised complete block design. Pigeonpea stalks and maize stovers were weighed, chopped into 5–10 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, every season after land preparation to allow crop residues to decompose. These crop residue application rates and cropping systems 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 described in Table 1.

Table 1 Description of treatments investigated in the study

Treatment	*Description*	*Treatment*	*Description*
T1	Virgin land/bare plot (control 1)	T11	Medium duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T2	Sole maize+0t ha-1 maize stover incorporated (control 2)	T12	Maize/medium duration pigeonpea intercrop + 0 t ha^{-1} maize stover + 0 t ha^{-1} pigeonpea residues incorporated
T3	Short duration pigeonpea sole crop + 0 t ha^{-1} pigeonpea residues incorporated	T13	Maize/medium duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T4	Short duration pigeonpea sole crop + 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
T5	Short duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated	T15	Long duration pigeonpea sole crop + 0 t ha^{-1} pigeonpea residues incorporated
T6	Maize/short duration pigeonpea intercrop + 0 t ha^{-1} maize stover + 0tha^{-1} pigeonpea residues incorporated	T16	Long duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T7	Maize/short duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2tha^{-1} pigeonpea residues incorporated	T17	Long duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T8	Maize/short duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4tha^{-1} pigeonpea residues incorporated	T18	Maize/long duration pigeonpea intercrop + 0 t ha^{-1} maize stover + 0 t ha^{-1} pigeonpea residues incorporated
T9	Medium duration pigeonpea sole crop + 0 t ha^{-1} pigeonpea residues incorporated	T19	Maize/long duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T10	Medium duration pigeonpea sole crop + 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

Maize variety KDV1 was selected for the study owing to its good adaptability, early maturity (120–150 days to mature) and yields highly under semi-arid conditions. Mbaazi I and KAT 60/8 were used for the short and medium duration pigeonpea varieties, respectively, due to their early maturity and high yields. They take on average 100 and 150 days, respectively. 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 popular among farmers and their seeds are readily available. Virgin land (bare plot) and maize sole crops were used as the controls.

The 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 without fertiliser additions at spacing of 90 cm × 60 cm, 75 cm × 30 cm and 50 cm × 25 cm for the long, medium and short duration varieties, respectively, at two seeds per hill and thinned to one, two weeks after emergence. Maize was planted with triple super phosphate (TSP) fertiliser at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90 cm × 30 cm. However, in the intercrops, one row of pigeonpea was planted after every row of maize to replicate the farmers' practice.

Pigeonpea was protected from pests on a 'minimum-protection' basis, twice per season with DimethoateTM (dimethoate) at 0.5 L ha^{-1} to control pod borer (*Helicoverpa armigera*) and pod fly (*Melanagromyza chalcosoma*). Bulldock^{TM} pesticide (beta-cyfluthrin) was applied on maize once every season to control stalk borers. The plots were kept weed-free by weeding regularly depending on weed emergence/intensity and characteristics. The study was conducted for four LR and four SR seasons (eight seasons) from October 2009 to July 2013.

2.3 Data collection

2.3.1 Soil moisture measurements

Soil moisture measurements were taken fortnightly from sowing to maturity using the gravimetric method outlined in Anderson and Ingram (1993) to monitor changes in soil moisture content with pigeonpea and maize growth and crop residue retention. Soil samples were taken at 20, 40, 60, 80 and 100 cm depths from four spots across each plot using a 600 cm^3 soil auger and transferred into small metal moisture cans of known weights which were capped to prevent moisture loss. The samples were weighed using a portable battery-operated electronic balance to determine their fresh weights and dried in an oven at 105°C for 24 hours to determine their dry weight. Soil water content was calculated by subtracting the sample oven-dry weight from its fresh weight and dividing the difference by the oven- dry weight.

2.3.2 Determination of soil texture, aggregate stability, organic carbon and bulk density

Soil samples were taken from each experimental plot prior to the start of the experiment in the 2009 SR season and also at the end of the 2013 LR season (i.e., after eight cropping seasons). Soil samples were collected in a transect across each plot using a 600 cm^3 soil auger to a depth of 0–20 cm. Soils from each plot were composted and mixed thoroughly in a bucket, quartered to obtain a representative sample and air-dried. The air-dry composite sample was then split into two sub-samples: one sub-sample was gently broken down along natural planes of weakness, passed through a 5 mm sieve and analysed for texture and aggregate stability using the hydrometer (Anderson and Ingram, 1993) and wet sieving (Cambardella and Elliott, 1993) methods, respectively; whilst the other sub-sample was ground using a mortar and pestle, passed through a 2mm sieve and analysed for organic carbon using the Walkley and Black method as described by Nelson and Sommers (1996). Bulk density was determined using the core sampling method as described by Blake and Hartge (1986).

2.3.3 Plant sampling

Maize and pigeonpea were harvested at full maturity when the entire maize stalks are completely dry and pigeonpea pods are brownish. Plants lying within one metre of each side of the plot were omitted from the sample harvest to eliminate any plot border effects; giving a harvest area of 7 m^2. Plants within the harvest area were counted, harvested and weighed using a precision weighing balance ±0.001 g. Sub-samples of maize and pigeonpea materials from the total number of plants harvested were divided into cobs and stover and pods and stalks for maize and pigeonpea data collection, respectively. Maize and pigeonpea grains were dried at 12.5% moisture content and the ratio of dry weight to wet weight and plot wet weight used to estimate maize and pigeonpea grain and biomass yields in tonnes per hectare.

2.3.4 Data analysis

Data on bulk density, soil aggregate stability, soil organic C and maize and pigeonpea yields were subjected to analysis of variance (ANOVA) using GENSTAT software version 14.2 (GENSTAT, 2016). Because of the large number of treatments involved, 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).

3 Results and discussions

3.1 Soil texture

Particle size analysis results indicate that soils at the study site were sandy clay loam in texture (69% sand, 26% clay and 5% silt) in the 0–20 cm depth. The textural results agree with Gichangi et al (2016) who reported a sandy clay loam texture in the 0–30 cm depth and clay in the lower depths in a study conducted in Katumani about 400 m from our site. Other researchers such as Gicheru and Ita (1987), Kilewe (1987) and Okwach (1994) also reported sandy clay loam texture in the topsoil of many sites in Katumani and this could be due to widespread occurrence of granitic and gneissic parent material, downward eluviation of clay, erosion of finer soil particles by massive run-off and chemical destruction of kaolinite in the topsoil (Jaetzold et al., 2006; Brady and Weil, 2009). The clay content in the topsoil was low (26%), but it is likely to have increased with depth going by the previous reports. The soils had a high sand content (69%), an indication that they were weakly structured, friable, highly erodible and susceptible to surface capping under raindrop impact resulting in poor infiltration of rain water leading to high run-off, serious erosion and loss of nutrients (Jaetzold et al., 2006; Okwach, 1994; Gicheru and Ita, 1987).

3.2 Soil aggregate stability, bulk density and organic carbon content

Soil aggregate stability refers to the ability of soil aggregates to remain intact when subjected to some stress. Aggregate stability is a crucial soil attribute that influences soil water movement and storage, aeration, erosion, biological activity and the growth of crops (Spohn and Giani, 2011; Pohl et al., 2012). Maintaining high soil aggregate stability is essential for preserving soil productivity, minimising soil erosion and degradation and minimising environmental pollution derived from soil degradation as well. Thus, maintaining high soil aggregate stability is a requisite for sustainable use of soil and for sustainable agriculture. Soil aggregate stability is very sensitive to changes in land management and is strongly correlated with soil erodibility. It is therefore widely used as an indicator of soil degradation (Mills and Fey, 2003; Wick et al., 2009; Fonte et al., 2014). The importance of SOM in stabilising soil aggregates has been well documented (Six et al., 2000, 2004; Bronick and Lal, 2005). SOM is an important binding agent for aggregation therefore the higher the SOM content the greater the stability of soil aggregates, especially in mineral soils (Onweremadu et al., 2007; Barreto et al., 2009; Lawal et al., 2009; Samahadthai et al., 2010). Conversely, loss of SOM reduces soil fertility, degrades soil structure and water holding capacity and eventually leads to land degradation. Soil bulk density is commonly used to measure soil compaction and is also a function of SOM and aggregate stability (Baldock and Nelson, 2000). A decrease in organic matter causes an increase in bulk density and a decrease in porosity which impedes free entry and movement of water and air, easy cultivation as well as germination and emergence of seedlings and growth of plant roots (Franzluebbers, 2000; Wall and Heiskanen, 2003; Celik, 2005). Changes in soil aggregate stability, bulk density and soil organic carbon (SOC) content after eight seasons of continuous pigeonpea-maize cropping are reported in Table 2.

Both SOC and aggregate stability were higher under the control (virgin land) compared to cropped land, probably due to dense vegetation cover and minimal soil disturbance (Lawal et al., 2009). These results corroborate findings by Lawal et al. (2009), Spaccini et al. (2001), Bear et al. (1994) and Barzegar et al. (1994) who reported that cultivation destroys soil structural stability and virgin soils have much higher aggregate stability than cultivated ones, especially where crop residues are removed as it was the case with some of the treatments in this study. The results also agree with reports by Chenu et al. (2000), Hamblin (1980), Dormaar (1983) and Angers and Mehuis (1989) who observed that upon cultivation the organic matter content of soils typically decreased with a corresponding decrease in aggregate stability. Growing maize alone continuously for eight seasons without ploughing back crop residues significantly ($P \leq 0.05$) reduced SOC from 1.4% to 0.7%. The proportion of macro- and micro-aggregates also declined and increased by 8% (from 44.9% to 36.8%) and 9% (from 54.8% to 63.8%), respectively, in the same period. The increase in the proportion of micro-aggregates could be due to dispersion of clay from the soil due to the growth of maize roots resulting in disintegration of macro-aggregates into micro-aggregates. Maize roots exude chelates and organic acids which remove polyvalent cations from the bonds between clay and organic matter thereby dispersing the clay which acts as a cementing agent (Reid et al., 1982). A similar trend was observed under pigeonpea sole crop where SOC declined from 1.4% to < 0.9% and both macro- and micro-aggregates declined (from 44.9% to < 40%) and increased (from 54.8% to > 59%) by over 5%, respectively, across the three pigeonpea varieties. The decline in SOC under both maize and pigeonpea sole crops could be attributed to rapid mineralisation and dissipation of SOM due to high rainfall and high temperatures (Table 4; Itabari et al., 2004, 2011; Mugwe et al., 2009) whilst the increase in micro-aggregation under pigeonpea sole crop may have been caused by the reduction in SOC and the breakdown of macro-aggregates into micro-aggregates by tillage during land preparation and weeding (Lawal et al., 2009). Contrary to observations by Lynch and Bragg (1985) and Oades (1993) that monocotyledonous plants such as maize are superior to dicotyledonous plants like pigeonpea in stabilising soil aggregates, there were no significant differences in both macro- and micro-aggregate stability between maize and pigeonpea sole crops in this study. Similarly, there were no significant differences in aggregate stability between sole crops of the three pigeonpea varieties, especially when no crop residues were ploughed back. Ploughing back crop residues did not hamper the decline in SOC, neither did it decelerate the decline in soil aggregation, attesting to the fact that it takes time for organic matter levels to build up in the soil and influence soil physical properties. These results agree with those of Dowuona et al. (2011) from a study in Ghana who reported a marked decline in aggregate stability of soils under pigeonpea and other legumes compared to the natural fallow, despite addition of pigeonpea biomass.

Table 2 Effect of maize-pigeonpea cropping systems and crop residue incorporation on soil aggregation, bulk density and organic carbon content

Treatment	*Soil aggregate size distribution (%)*[1]		*Bulk density ($g\ cm^{-3}$)*	*Soil organic C (%)*
	Macro-aggregates (> 250 μm)	*Micro-aggregates (<250 μm)*		
Control (virgin land)	44.9^{a}	54.8^{f}	1.49^{c}	1.4^{a}
Maize sole crop + 0 t ha^{-1}	36.8^{ef}	63.0^{ab}	1.68^{a}	0.7^{d}
Mbaazi I sole crop + 0 t ha^{-1}	38.7^{bcde}	60.9^{bcd}	1.57^{abc}	0.9^{b}
Mbaazi I sole crop + 2 t ha^{-1}	38.0^{cde}	61.9^{abc}	1.56^{abc}	0.8^{bcd}
Mbaazi I sole crop+ 4 t ha^{-1}	34.8^{f}	64.8^{a}	1.57^{abc}	0.8^{bcd}
Kat 60/8 sole crop+ 0 t ha^{-1}	39.0^{bcde}	60.9^{bcd}	1.61^{abc}	0.9^{b}
Kat 60/8 sole crop+ 2 t ha^{-1}	36.3^{ef}	63.5^{ab}	1.58^{abc}	0.8^{bcd}
Kat 60/8 sole crop+ 4 t ha^{-1}	38.7^{bcde}	61.2^{bcd}	1.56^{abc}	0.8^{bcd}
Mbaazi II sole crop + 0 t ha^{-1}	39.1^{bcde}	60.8^{bcde}	1.56^{abc}	0.8^{bcd}
Mbaazi II sole crop + 2 t ha^{-1}	40.8^{bc}	59.0^{de}	1.55^{abc}	0.8^{bcd}
Mbaazi II sole crop + 4 t ha^{-1}	35.1^{f}	64.2^{a}	1.57^{abc}	0.8^{bcd}
Mbaazi I/maize intercrop + 0 t ha^{-1}	40.5^{bc}	59.3^{cde}	1.56^{abc}	0.8^{bcd}
Mbaazi I/maize intercrop + 2 t ha^{-1}	37.9^{cde}	62.0^{abc}	1.56^{abc}	0.8^{bcd}
Mbaazi I/maize intercrop + 4 t ha^{-1}	1.3^{b}	58.6^{de}	1.57^{abc}	0.8^{bcd}
Kat 60/8/maize intercrop + 0 t ha^{-1}	40.1^{bcd}	59.8^{cde}	1.56^{abc}	0.9^{b}
Kat 60/8/maize intercrop + 2 t ha^{-1}	38.1^{cde}	61.8^{abc}	1.58^{abc}	0.8^{bcd}
Kat 60/8/maize intercrop + 4 t ha^{-1}	41.4^{b}	57.6^{ef}	1.57^{abc}	0.9^{b}
Mbaazi II/maize intercrop + 0 t ha^{-1}	41.1^{b}	58.5^{de}	1.56^{abc}	0.8^{bcd}
Mbaazi II/maize intercrop + 2 t ha^{-1}	37.2^{de}	62.5^{abc}	1.55^{abc}	0.7^{d}
Mbaazi II/maize intercrop + 4 t ha^{-1}	39.0^{bcde}	60.8^{bcde}	1.57^{abc}	0.8^{bcd}

Notes: [1] Averaged over four replicates.
Any two means in the same column having a common letter are not significantly ($P < 0.05$) different.

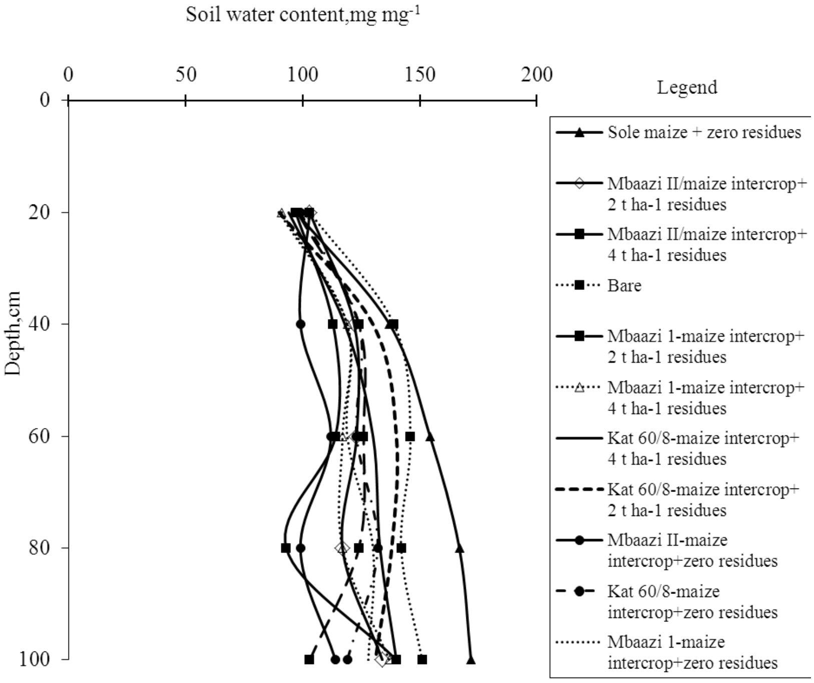
Intercropping maize with pigeonpea significantly reduced SOC (from 1.4% to < 0.9%), but decelerated the decline in aggregate stability by about 4%. Macro-aggregates declined from 45%–41% whilst the micro-aggregates increased from 55%–63%. The deceleration in the decline in aggregate stability could be attributed to extensive shallow root systems of maize and pigeonpea, especially the short and medium duration pigeonpea varieties. Roots serve as temporary binding agents (Tisdall and Oades, 1982). They enmesh fine soil particles into stable macro-aggregates; dry the localised soil environment around the roots, reorienting clay particles parallel to the axis of the root and drawing soil particles together; supply decomposable organic residues to soil; support a large microbial population in the rhizosphere; provide food for soil animals such as earthworms and mesofauna; and release polyvalent cations and increase the concentration of ions in the soil solution which promote soil aggregation (Franchini, et al., 2007; Leifeld and Kögel-Knabner, 2005; Amezketa, 1999). There were no significant differences in soil aggregate stability between intercrops of the three pigeonpea varieties. Similarly, ploughing back crop residues did not hamper the decline in soil aggregate stability, perhaps due to low SOM accumulation because of rapid mineralisation and dissipation of crop residues attributable to the high rainfall and temperatures (Tables 2 and 4; Lal et al., 2003; Marquez et al., 2004; Denef et al., 2007). These results are in contrast with findings by Dowuona and Adjetey (2010) from a study in Ghana where pigeonpea plots had more stable aggregates than natural fallow and bare plots. The greater stability of soil aggregates under pigeonpea and other tree legumes was attributed to the protective cover of their canopy and binding action of their roots. In a related study in Zambia, Chirwa et al. (2004) reported the highest percentage of water stable aggregates in pigeonpea land use systems at 76.9% followed by natural fallow at 65.8%. The least was recorded in maize without fertiliser at 44%. The disparity was attributed to high organic matter content under pigeonpea cropping systems compared to maize with or without fertiliser. Other researchers (Lawal et al., 2009; Gichangi et al., 2016) also observed that continuous deposition of biomass improved aggregate stability, although their findings were based on litterfall from forest trees and pasture grasses. Generally, all the maize-pigeonpea cropping systems tested in this study generated high proportions of micro-aggregates compared to macro-aggregates, an indication that they were all susceptible to water erosion since micro-aggregates are generally easily eroded by water (Adesodun et al., 2005). This could explain why most pigeonpea growing areas in the country are among the most degraded areas in the region. Otherwise improved soil aggregation improves infiltration, aeration and root penetration and increases crop yields (Spohn and Giani, 2011; Pohl et al., 2012).

Bulk density ranged from 1.49 to 1.68 g cm^{-3} which was higher than the prescribed range of 1.10–1.30 g cm^{-3} for non-restricted plant growth (Landon, 1991). Generally, soil bulk density exceeding 1.6 g cm^{-3} for such soils would impair root growth and curtail soil aeration through reduced porosity (Brady and Weil, 2009). However, the results agree with findings by Kilewe (1987) and Okwach (1994) who reported bulk densities of 1.52 and 1.45 g cm^{-3}, respectively, in topsoils from studies in Katumani. Similarly, Gichangi et al. (2016) reported bulk densities of 1.32–1.45 g cm^{-3} in topsoils from a study in Katumani, albeit under pasture grasses.

3.3 Soil water content

Katumani receives an average of 711 mm of rain annually. However, during this study, about 665.7 mm was received in 2010, 506.8 mm in 2011, 617 mm in 2012 and 590.8 mm in 2013. Thus, the amounts of rainfall received in the eight seasons of experimentation were high and adequate to sustain maize and pigeonpea crop if well conserved. Soil water contents of the dominant maize-pigeonpea cropping systems and three residue application rates tested in this study for eight cropping seasons are provided in Figure 1. As expected, bare plots conserved more water than the cropped plots because apart from surface evaporation, there was no crop to utilise the water allowing most of it to be retained in the profile. They also had a much better soil structure than other treatments due to minimal soil disturbance (Table 2). Sole maize cropping system extracted the least amount of water from the profile compared to other cropping systems and most of it was extracted from the upper soil horizons. These results contrast with reports by Chirwa et al. (2004), Lal (1989) and Hulugalle and Ndi (1993) that pigeonpea cultivation leads to high cumulative water intake than maize sole crop and could be due to maize's extensive but shallow root system and low population due to wide spacing hence low demand for water and nutrients (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979). Maize-Mbaazi II (long duration pigeonpea) intercrop emptied the profile the most followed by maize-Mbaazi I (short duration pigeonpea) and maize-Kat 60/8 (medium duration pigeonpea) in the second and third position, respectively. However, Mbaazi II-maize intercrop extracted most of its water from deeper horizons in the profile whilst Mbaazi I-maize and Kat 60/8-maize intercrops obtained most of their water from the upper soil layers. These results corroborate findings by Kay (1979) that root penetration and water extraction are deeper in late-maturing pigeonpea varieties compared to early maturing ones. The high water uptake by maize-Mbaazi II intercrop may be due to Mbaazi II's extensive deep root system, long maturity period and high biomass production (Table 4) hence high water demand (Kay, 1979). Maize is generally harvested earlier leaving long duration pigeonpea varieties such as Mbaazi II to continue in the field. This enables the long duration pigeonpea to utilise residual moisture or any rain that comes after the maize is harvested. The moderately high water uptake by maize-Mbaazi I intercrop may be attributed to high plant population and rapid growth by both maize and Mbaazi I resulting in increased demand for water and nutrients (Mehrotra et al., 1977; Singh et al., 1986). The low water uptake by the maize-Kat 60/8 intercrop may be attributed to suppression of Kat 60/8 by maize. Ploughing back crop residues increased the amount of water conserved across the cropping systems, perhaps because of improvement in soil structure due to decomposition of crop residues (Table 2; Akanvou et al., 2002; Kwesiga et al., 2003; Degrande, 2001). These results corroborate reports by Cassel et al. (1995) that retaining crop residues on or near the soil surface enhanced rain water infiltration. Otherwise, extraction of soil water was detected to the full depth sampled, indicating pigeonpea's ability to extract water from deep into the profile. These results correspond with reports by other researchers who detected extraction at 120 cm (De Vries, 1986), 150 cm (Sheldrake and Narayanan, 1979), 180 cm (Sardars and Russell, 1981) and down to 220 cm (Nene et al., 1990). Although this study did not estimate the rate of water extraction by roots, Sardars and Russell (1981) reported from a two-year maize-pigeonpea intercropping study in India, that rates of water extraction by roots ranged from 0.003 to 0.055 mm/cm/day and varied with time, depth in the profile and available water content.

Figure 1 Effect of maize-pigeonpea cropping systems and incorporation of crop residues on soil water content in Katumani



Similarly, although this study did not determine the water use efficiency (WUE) of the pigeonpea-maize cropping systems, other researchers (Saxena and Yadar, 1975; Sardars and Russell, 1981) observed that on average, pigeonpea uses about 20–25 cm of water to produce about 1 t ha^{-1} of grain under traditional production systems. However, because of high densities due to closer spacing intensively managed pigeonpea systems that involve short duration varieties have a higher water requirement (Mehrotra et al., 1977; Singh et al., 1986). Mehrotra et al. (1977) estimated water use by one such variety to be in the range of 55–60 cm. Sardars and Russell (1981) found that maize had higher WUE than pigeonpea from a two-year maize–pigeonpea intercropping study in India. The low WUE by pigeonpea was attributed to low grain yields due to poor season. Thus, given the high maize and pigeonpea yields reported under maize-Mbaazi II intercrop in this study (Tables 3 and 4), it is probable that maize-Mbaazi II intercrop had a higher WUE compared to maize-Mbaazi I and maize-Kat 60/8 intercrops.

3.4 Maize and pigeonpea yields

3.4.1 Maize yield

Maize yields obtained from different maize-pigeonpea cropping systems and crop residue management options are reported in Table 3. Unlike what most farmers in the region harvest from their farms (less than 0.5 t/ha per season), growing maize sole crop without ploughing back stovers in this study yielded 0.9 t/ha of grain and 1.2 t/ha of stover per season. Since through its root exudates maize destroys soil structure (Reid et al., 1982; Table 3), the high yields could be attributed to other factors like 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. This means that by merely adhering to sound agronomic practices such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protecting against maize stalk borers, farmers in newly opened farms in the region can double their maize yields.

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

Cropping system	*Maize grain and stover yield (t/ha)*[1]									
	2010		*2011*		*2012*		*2013*		*Av. yield*	
	Gr	*St*	*Gr*	*St*	*Gr*	*St*	*Gr*	*St*	*Gr*	*St*
Maize sole crop + 0t ha^{-1} (control)	0.8	1.0	0.8	1.6	1.2	1.1	1.0	1.2	0.9	1.2
Mbaazi I-maize intercrop + 0t ha^{-1}	0.9	1.1	0.8	1.4	0.8	1.4	0.7	1.3	0.8	1.3
Mbaazi I-maize intercrop + 2t ha^{-1}	1.0	1.3	1.0	1.6	0.9	1.4	0.8	1.4	0.9	1.4
Mbaazi I-maize intercrop + 4t ha^{-1}	1.1	1.6	1.2	1.7	1.4	1.9	1.4	1.9	1.3	1.8
Kat 60/8-maize intercrop + 0t ha^{-1}	0.9	1.3	0.8	1.5	0.8	1.3	0.8	1.3	0.8	1.3
Kat 60/8-maize intercrop + 2t ha^{-1}	1.0	1.7	0.9	2.0	0.9	1.5	0.9	1.6	0.9	1.7
Kat 60/8-maize intercrop + 4t ha^{-1}	1.8	2.1	1.5	2.2	1.7	1.7	1.5	1.9	1.6	2.0
Mbaazi II-maize intercrop + 0t ha^{-1}	0.7	1.0	0.8	1.6	0.7	1.5	0.8	1.3	0.8	1.4
Mbaazi II-maize intercrop + 2t ha^{-1}	1.0	1.1	1.0	1.8	1.0	1.7	1.0	1.4	1.0	1.5
Mbaazi II-maize intercrop + 4t ha^{-1}	1.8	2.1	1.9	1.9	1.8	1.9	2.0	2.0	1.9	2.1
SED[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Total annual rainfall (mm)	665.7		506.8		617		590.8			

Notes: [1] Data are treatment means averaged over two seasons; Gr: maize grain; St: maize stover.
[a] Standard error of difference of treatment means.

Intercropping maize with the short, medium and long duration pigeonpea varieties without ploughing back crop residues reduced average maize grain yields per season by 11% (0.9 to 0.8 t/ha). However, average stover yields increased by 8%–17%. The drop in maize grain yield and increase in stover yields could be attributed to scarcity of water to carry the crop through the grain filling stage because of low soil water retention capacity due to poor soil structure (Table 3). Due to low SOM accumulation (Table 2), ploughing back 2 t/ha^{-1} of crop residues did not improve soil structure (Table 2) and soil water content substantially (Figure 1) and hence, had no significant effect on maize grain yield, however, it significantly increased stover yields by 17%–42%. The significant increase in stover yield could be attributed to improvement in soil fertility due to decomposition and mineralisation of the crop residues (Akanvou et al., 2002; Kwesiga et al., 2003; Degrande, 2001). These results differ with findings by Silim et al. (1998) who noted from a study in semi-arid Eastern Kenya that the yield of intercropped maize was substantially lower than its sole crop. The disparity could be attributed to differences in the amount of crop residues ploughed back. Average grain yields also increased by 44% (from 0.9 to 1.3 t ha^{-1}), 78% (from 0.9 to 1.6 t ha^{-1}) and 111% (from 0.9 to 1.9 t ha^{-1}) per season under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when 4 t/ha^{-1} of crop residues were ploughed back. Stover yields increased too by 50% (from 1.2 to 1.8 t ha^{-1}), 67% (from 1.2 to 2.0 t ha^{-1}) and 75% (from 1.2 to 2.1 t ha^{-1}) per season when maize was intercropped with the short, medium and long duration pigeonpea, respectively. Apart from improvement in soil nutrient supply, the huge increase in both grain and stover yields could be attributed to improvement in soil physical properties due to decomposition of the crop residues (Table 2; Figure 1; 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 mobilise and avail extra nutrients from deep soil horizons and improve soil structure due to its deep strong tap root system and massive litterfall (Table 3; Figure 1; 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. Chirwa et al. (2004), Mapfumo and Mtambanengwe (2004), Rao and Mathuva (2000), Adjei-Nsiah et al. (2007), Degrande (2001), Akanvou et al (2002), Abunyewa and Karbo (2005) and Chamango (2001) also reported significant improvement in maize yields attributable to pigeonpea, albeit from long duration pigeonpea fallows. They attributed the increase in maize (cereal) yield to improvement in soil chemical and physical properties due to decomposition and mineralisation of pigeonpea's massive litterfall.

In a nutshell, intercropping maize with pigeonpea, especially the long duration variety, and ploughing back crop residues improves both soil physical properties leading to significant increase in maize grain yields and production of sufficient stover to plough back and feed the livestock.

3.4.2 Pigeonpea yield

Pigeonpea yield data is presented in Table 4. Compared to what most farmers obtain from their fields (less than 500 kg/ha of grain per season), significantly higher grain yields were obtained in this study when the short (0.9 t ha^{-1}), medium (1.0 t ha^{-1}) and long (1.1 t ha^{-1}) duration pigeonpea varieties were grown as sole crops without ploughing back crop residues. About 1.0, 1.3 and 1.9 t ha^{-1} of pigeonpea stalks was harvested from the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea variety, respectively, too. These higher yields 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. The significantly higher yields by Mbaazi II (the long duration variety) compared to the rest

(Mbaazi II and Kat 60/8) could be due to its phenological complementarity with maize and its ability to mobilise nutrients and access water from deeper soil horizons due to its strong deep root system and massive litterfall (McCown et al., 1992; Myaka et al., 2006).

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

Cropping system	*Pigeonpea grain and stalk yield (t/ha)1*									
	2010		*2011*		*2012*		*2013*		*Av. yield*	
	Gr	*Stk*	*Gr*	*Stk*	*Gr*	*Stk*	*Gr*	*Stk*	*Gr*	*Stk*
Mbaazi I sole crop + 0 t ha^{-1}	0.9	1.0	0.9	1.0	0.9	1.1	1.0	1.1	0.9	1.0
Kat 60/8 sole crop + 0 t ha^{-1}	1.0	1.6	1.0	1.1	1.1	1.4	1.0	1.2	1.0	1.3
Mbaazi II sole crop + 0 t ha^{-1}	1.0	1.5	1.0	1.2	1.2	2.2	1.4	2.8	1.1	1.9
Mbaazi I/maize intercrop + 0 t ha^{-1}	0.1	0.2	0.1	0.1	0.1	0.1	0.0	0.2	0.1	0.2
Mbaazi I/maize intercrop + 2 t ha^{-1}	0.1	0.3	0.1	0.2	0.1	0.2	0.1	0.3	0.1	0.3
Mbaazi I/maize intercrop + 4 t ha^{-1}	0.2	0.5	0.1	0.2	0.1	0.3	0.1	0.3	0.1	0.3
Kat 60/8/maize intercrop + 0 t ha^{-1}	0.1	0.2	0.0	0.1	0.1	0.3	0.1	0.2	0.1	0.2
Kat 60/8/maize intercrop + 2 t ha^{-1}	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.2	0.1	0.3
Kat 60/8/maize intercrop + 4 t ha^{-1}	0.1	0.3	0.2	0.4	0.1	0.5	0.1	0.2	0.1	0.4
Mbaazi II/maize intercrop + 0 t ha^{-1}	1.3	1.5	1.0	2.3	1.1	2.7	1.3	2.8	1.1	2.3
Mbaazi II/maize intercrop + 2 t ha^{-1}	1.4	2.0	1.1	2.6	1.1	2.7	1.4	3.0	1.3	2.6
Mbaazi II/maize intercrop + 4 t ha^{-1}	1.5	2.5	1.1	2.9	1.3	3.0	1.4	3.3	1.4	2.9
SED[a]	0.2	0.4	0.2	0.4	0.2	0.4	0.3	0.4	0.3	0.5
Total annual rainfall (mm)	665.7		506.8		617		590.8			

Notes: [1]Data are treatment means averaged over two seasons; Gr: pigeonpea grain; Stk: pigeonpea stalks.
[a]Standard error of difference of treatment means.

The short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea performed dismally when intercropped with maize as their average yields dropped by 80%–90%. The reduction in yield 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, long duration pigeonpea (Mbaazi II) grain and stalk yields increased by 18%–27% and 20%–53%, respectively, especially when crop residues were ploughed back. 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 mobilise extra nutrients and water from deeper soil horizons due to its strong deep tap root system (Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim et al., 2005; Kumar et al., 2011). Natarajan and Willey (1981) reported similar results from a study in India in which the pigeonpea component of a cereal (sorghum)-pigeonpea intercrop suffered considerable competition from the cereal (sorghum) initially, but recovered after the cereal (sorghum) was harvested and produced seed yields equivalent to 70% of the sole crop. Other researchers such as Tarhalkar and Rao (1981), Ali (1990) and Egbo and Ngumalen (2010) also reported that intercropping cereals with early-maturing pigeonpea often leads to drastic reduction in pigeonpea yield. From the foregoing, it is apparent that intercropping maize with the long duration pigeonpea variety gives both higher maize and pigeonpea yields as opposed to the short and medium duration varieties which only guarantee higher maize yields at the expense of pigeonpea yields. Long duration pigeonpea is able to mobilise nutrients and water from deeper soil horizons due to its strong and deep tap root system and massive litterfall and is therefore the best variety for incorporation into maize-based cropping systems in marginal areas such as semi-arid eastern Kenya.

4 Conclusions

Ordinarily, because of pigeonpea's strong deep root system and massive litterfall, one would expect that intercropping it with maize would improve soil physical properties and crop yields. However, it is apparent from this study that intercropping maize with the three pigeonpea varieties used in this study does not improve soil physical properties. Instead, it increases soil bulk density beyond the prescribed range for non-restricted plant growth which may impair root growth and curtail soil aeration through reduced porosity and lead to reduction in yields. It also reduces aggregate stability due to low organic matter accumulation thereby exposing land to severe degradation. Nonetheless, it had no effect on soil texture.

Intercropping maize with the three pigeonpea varieties, especially the long duration variety (Mbaazi II), requires more water compared to maize and pigeonpea sole crops. However, this can be addressed by conserving sufficient water in the profile by ploughing back crop residues instead of feeding all of them to livestock. Finally, intercropping long duration pigeonpea with maize offers the best option for farmers in marginal areas similar to Katumani since it significantly increases maize and pigeonpea grain yields and produces sufficient maize stover and pigeonpea stalks to plough back and minimise soil degradation and feed livestock.

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