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Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops

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ABSTRACT

Productivity of maize–pigeonpea cropping systems is dependent on facilitative and competitive interactive effects on resource availability. Controlling these interactions may benefit farmers through increased productivity associated with optimized crop yields. Previous research on maize–pigeonpea culture in Sub-Saharan Africa has focused on yield and soil fertility, but provided inadequate information on the mechanisms of possible interspecific competition. We employed a factorial field experiment to examine yield and nutritional responses of maize and pigeonpea to cropping systems (sole maize, intercropping, and improved fallow), N and P fertilizer additions, and cattle manure additions in Dodoma, Tanzania. The study objectives were to assess competition between crops and to determine how manure or fertilizer inputs may mitigate such interactions to improve yields. Intercropping enhanced maize yield over sole maize only when fertilized, reflecting probable nutrient competition. Improved fallows alone or with fertilizers (1.2–1.6 Mg ha^{-1}) increased maize yields over sole maize (0.6 Mg ha^{-1}). These increases were attributed to pigeonpea facilitation through soil nutrient replenishment, reduced competition associated with sequential cropping arrangements, and added nutrients from fertilization. Combined fertilizer and manure applications also improved maize and pigeonpea yields. Plant nutrient diagnosis indicated primary and secondary P and Ca deficiencies, respectively associated with P-fixation and leaching of cations due to high soil acidity and exchangeable Al. Maize competed strongly in mixture suppressing biomass and grain yields of the unfertilized pigeonpea by 60% and 33%, respectively due to limited soil nutrients and/or moisture. These yield reductions suggest that the intercropped pigeonpea did not recover from competition after maize harvesting that reduced competition. Optimizing yields of both maize and pigeonpea would require the addition of prescribed fertilizer when intercropped, but applications can be reduced by half under the improved fallow system due to alleviating interspecific competition.

1. Introduction

Traditionally, farmers in the semi-arid tropics intercrop cereals with grain legumes, especially pigeonpea (*Cajanus cajan* L. Millsp.), as a strategy for diversifying food production and household income since the legumes are both cash and food crops (Rao and Mathuva, 2000; Mafongoya et al., 2006). Also, pigeonpea plants tolerate drought due to deep rooting, thus providing insurance against total crop failure in low rainfall seasons (Rao and Mathuva, 2000). The legume may improve soil fertility and yields of associated crops as well through biological nitrogen (N) fixation, nutrient pumping and incorporation of green manure (Chikowo et al., 2004; Ghosh et al., 2006). However, the yield advantage of mixed relative to monoculture cropping systems is dependent on net effects of facilitative and competitive interactions on growth resources (García-Barrios and Ong, 2004).

Deeper rooting and slower initial growth of pigeonpea relative to most cereal crops (Mafongoya et al., 2006) may reduce interspecific competition through differentiation of root niche and peak resource demand; hence facilitating coexistence of pigeonpea and maize (*Zea mays* L.) in mixture. For instance, the legume may access soil water below the maize rooting zone and enhance moisture supply to intercropped maize plants through hydraulic lift (Sekiya and Yano, 2004). Relay cropping systems, in which pigeonpea is planted 2–3 weeks after maize sowing (Akanvou et al., 2002; Gathumbi et al., 2004), may also minimize competition as pigeonpea is planted soon after the maize crop is established. The delayed planting as well as the slow initial growth

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of the legume, provides maize with an early competitive advantage. In semi-arid areas, however, growing seasons are increasingly becoming shorter because of low and sporadic rainfall patterns (Rao and Mathuva, 2000; Chikowo et al., 2004). Consequently, yield of intercropped pigeonpea can be adversely affected by the combined effects of delayed planting and drought. Thus, it is important to the understand component interactions and their impacts on resource capture and use under intercropping (simultaneous) and improved-fallow (sequential) agroforestry systems in order to sustain yields of maize and pigeonpea in semi-arid climates.

Pigeonpea plants have both physiological and morphological attributes that may reduce interspecific competition in mixed culture. However, yield of maize intercropped with pigeonpea in semi-arid conditions is often similar or less than that of sole-cropped maize (Rao and Mathuva, 2000; Snapp et al., 2002; Chikowo et al., 2004; Myaka et al., 2006), indicating probable yield suppression due to competition for soil nutrients and/or moisture. This interaction also may affect pigeonpea yield, thereby reducing overall system productivity. As noted earlier, previous studies assessed crop yield and soil nutrient replenishment by legumes, giving insufficient information on interspecific competition for growth resources. Such information may be useful for optimizing yields of both crops to diversify food and income sources of smallholder farmers (Snapp et al., 2002; Rao and Mathuva, 2000). Yet research evaluating the mechanisms for interspecific competition between maize (cereals) and pigeonpea (grain legumes) in sub-Saharan Africa is limited.

Vector competition analysis (VCA) (Imo and Timmer, 1998) and vector diagnostic analysis (VDA) (Salifu and Timmer, 2003; Isaac et al., 2007) have been used to assess interspecific competition and nutritional status of plants in response to fertilization. Unlike the critical level approach and other diagnostic techniques, based on a single measure of nutrient concentration, vector analysis concurrently compare plant biomass, nutrient concentration, and nutrient content in one diagram. Interpretation of this diagram is based on site-specific comparisons of plant responses to nutrient supply relative to control, making the diagnosis independent of published critical ratios or levels (Gregoire and Fisher, 2004). We employed vector analysis to evaluate crop responses to nutrient replenishment (facilitation) and competition associated with pigeonpea fallowing or intercropping with maize and to indicate how manure or fertilizer inputs may modify these interactions to increase yield. Cattle manure and inorganic fertilizer were tested because these are alternative practices for improving soil fertility and crop yield in livestock keeping areas. It was hypothesized that pigeonpea fallowing is more productive than intercropping due to reduced competition for growth resources. Specific objectives were to assess effects of maize–pigeonpea cropping systems, cattle manure, and N and P fertilizers on yields, nutrient uptake, soil nutrient replenishment, and competition for nutrients. The results will broaden understanding of plant nutritional interactions and may improve productivity and management of the traditional intercropping system of maize and pigeonpea under semi-arid conditions.

2. Materials and methods

2.1. Study site and treatments

The research was carried out at Ihumwa village (6°10′S, 35°53′E), Dodoma, Tanzania located in a semi-arid zone (elevation of 640 m above sea level) with mean annual rainfall of 560 mm (Fig. 1) and a dry period of 7–8 months. Rainfall in the 2004 cropping season was above the average, but in the 2005 season it was below the average with 48% falling towards the end of the growing season (March). Apparently this seasonal precipitation changes suppressed crop yields as discussed in section 4.1. Soils are acidic (pH 4.6 ± 0.1), classified as ferric acrisols according to the FAO Classification System and have a sandy loamy texture. Nutrient levels at the 0–20 cm soil depth were low for crop production: organic carbon (0.35 ± 0.05%), total N (0.03 ± 0.003%), extractable P (7.0 mg kg^{-1} ± 0.9), and exchangeable cations in cmol kg^{-1} (Ca = 0.56 ± 0.01; K = 0.30 ± 0.01; Mg = 0.24 ± 0.02; H = 0.4 ± 0.07; Al = 0.98 ± 0.05). The native vegetation was degraded Miombo woodland dominated by thickets or widely spaced bushes of *Brachystegia* spp. Major land use systems at this site are subsistence farming and livestock keeping.

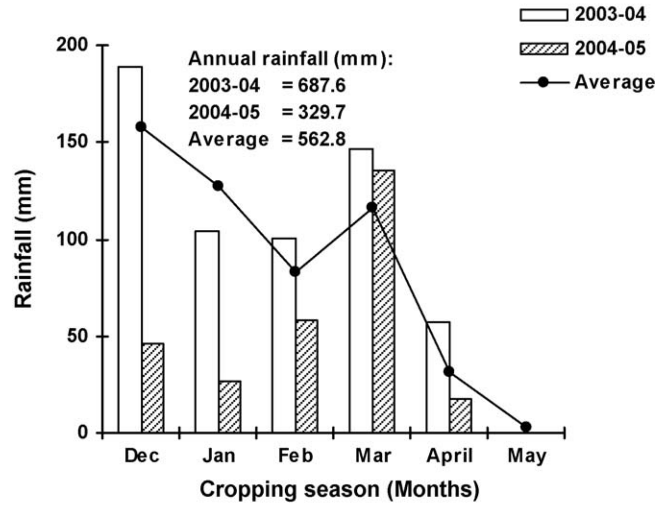

Fig. 1. Annual and monthly rainfall received during the 2004 and the 2005 cropping seasons and the long-term average (2000–2006) at Ihumwa, Dodoma, Tanzania.

A 3^3 factorial experiment with three replications was established in a randomized complete block design (RCBD). Treatments included cropping systems (continuous sole maize, intercropping and improved fallows) and three rates (control, half, and full) of cattle manure (Table 1), and combined N and P fertilizers. Intercropping and fallow treatments represented simultaneous and sequential cropping systems, respectively. The full rate of manure applied (10 Mg ha^{-1}) was based on local rates and falls within a range (10–15 Mg ha^{-1}) used by farmers in Sub-Saharan Africa (Mafongoya et al., 2006). The source of N was urea and P was triple super phosphate. These fertilizers were applied at 80 kg N ha^{-1} and 40 kg P ha^{-1} for full rate, which are levels used in other semi-arid areas of Tanzania (Kimaro et al., 2008).

Plots of 6 m × 6 m were laid out at the beginning of the 2004 cropping season after plowing using a farm tractor. Plots and blocks were separated by 3 and 5 m-wide unplanted buffer strips,

Table 1
Concentration and content of nutrients in cattle manure applied to maize and pigeonpea at Ihumwa, Dodoma, Tanzania.

Nutrient	Concentrations (%)	Amount applied (kg ha^{-1})	
		Half rate[a]	Full rate
Nitrogen	1.30	65	130
Phosphorus	0.28	14	28
Potassium	5.00	250	500
Calcium	1.74	87	174
Magnesium	0.77	38	77

[a] Application rates used were 5 and 10 Mg ha^{-1} for half and full rates, respectively. Prescribed rates are 80 kg N ha^{-1} for nitrogen and 40 kg P ha^{-1} for phosphorus.

respectively. Maize (var. *Kito*) and pigeonpea (Var. *Babati white*) were sown at a spacing of 0.9 m between rows and 0.5 m within rows, resulting in additive mixtures for evaluating interspecific competition (Kelthy and Cameron, 1995). *Kito* is a short-duration maize variety that is used in areas with low precipitations (Kimaro et al., 2008) and *Babati white* is a traditional pigeonpea variety grown in semi-arid Tanzania (Myaka et al., 2006). Maize and pigeonpea were sown simultaneously in alternate rows in each plot under intercropping but were rotated annually in the fallow treatment. The fallow treatment was duplicated such that pigeonpea was sown in one plot in the 2004 cropping season followed by maize in the 2005 season and vice versa for the second plot. This arrangement permits comparison of fallow effects with other cropping systems without being confounded by seasons (Rao and Mathuva, 2000).

2.2. Soil and plant sampling

Prior to sowing crops, soil samples were collected from five random points within each block at 0–20 cm depth using soil auger to assess initial soil fertility status. These samples were mixed thoroughly and sub-sampled to get a composite sample. Similarly, 2 weeks after the onset of rain in the 2005 cropping season, soil samples were also collected from the 4 m × 4 m inner plot area (leaving 1-m border strip on both sides of each plot) to minimize boundary effects on treatment responses. Then samples were transported to the laboratory in a cooler and frozen prior to analysis of inorganic N and extractable P within a week. Maize was harvested from the inner plot area partitioned into grain, stover, and cobs; weighed separately and sub-sampled for the determination of grain and aboveground biomass yields based on the ratio of dry (70 °C)-to-fresh weights. Grain and biomass yields were then extrapolated to 1 ha based on yield per sampled area. These sampling procedures were also used to assess pigeonpea grain yield 3 months after maize harvesting and to determine wood and foliage biomass of pigeonpea calculated using developed regression models. Leafy biomass was incorporated into soil as green manure during site preparation for the 2005 season while wood biomass was harvested for fuel wood supply.

2.2.1. Pigeonpea biomass assessment

All pigeonpea plants in the 4 m × 4 m inner plot area were measured for height (m) and stem diameter (cm) using a graduated pole and a veneer caliper, respectively. Diameter (D) measurements were taken at 10 cm above the ground to minimize variation. Small ($D < 0.60$ cm), medium ($D = 0.60$–1.10 cm), and large ($D > 1.10$ cm) sized plants per plot were destructively sampled for determination of foliage and wood biomass based on dry weight (70 °C). Tree measurements and sampling were carried out when at least 50% of pigeonpea plants flowered to coincide with the active growth period. This was considered an appropriate time for evaluating interspecific competition because nutrient demand for pigeonpea was at peak and maize plants were not yet harvested. Allometric models for estimating pigeonpea biomass were developed based on measured dimensions of 30 sampled trees: height (1.12–2.7 m) and stem diameter (0.45–1.70 cm) and the remaining trees (21) were used for model validation. These variables were fitted into allometric equations: $Y = aD^b$ and $Y = aD^b H^c$, where Y is the dry weight (g tree^{-1}), D is stem diameter (cm), and H is height (m) after logarithmic transformation to fit linear regressions (Haase and Haase, 1995). The estimated biomass was multiplied by a correction factor (CF) to account for bias associated with this transformation (Sprugel, 1983). The following models were chosen to calculate tree biomass (g tree^{-1}) based on the highest coefficient of determination (R^2) and the lowest standard error of estimate (SEE):

$$\ln(\text{Leaves}) = 1.531 \ln D + 3.987; \quad R^2 = 0.79; \quad \text{SEE} = 0.31; \quad \text{CF} = 1.05; \quad p < 0.0001 \tag{1}$$

$$\ln(\text{Wood}) = 1.917 \ln D + 4.447; \quad R^2 = 0.91; \quad \text{SEE} = 0.24; \quad \text{CF} = 1.03; \quad p < 0.0001 \tag{2}$$

$$\ln(\text{Leaves} + \text{Wood}) = 1.758 \ln D + 4.952; \quad R^2 = 0.92; \quad \text{SEE} = 0.20; \quad \text{CF} = 1.02; \quad p < 0.0001 \tag{3}$$

where Ln is the natural logarithm and p is probability of the model.

2.3. Chemical analysis of soil and plant samples

Soil pH in 1:2.5 soil–water aqueous suspensions was determined by a pH meter, organic carbon by Walkley and Black method, extractable P by Bray-1 method, and exchangeable K, Ca, and Mg by atomic absorption spectrophotometer after extraction with 1N ammonium acetate. Exchangeable acidity (hydrogen and aluminum) was determined by leaching air-dried soil samples with 1 M KCl and measured quantitatively by titration. Cation exchange capacity was obtained by summation of exchangeable cations and exchangeable acidity. Samples for soil total N were wet-digested using hydrogen peroxide and sulphuric acid solution and the digests analyzed using the Kjeldahl method. Soil inorganic N was extracted using 2 M KCl solution, and the extracts analyzed for ammonium-N and nitrate-N, then added to obtain total inorganic N. Oven-dried samples of maize and pigeonpea were ground and wet-digested for analyses of N by Kjeldahl method, P by stannous chloride method; and K, Mg, and Ca using atomic absorption spectrophotometer. Nutrient content in these samples was calculated as a product of biomass (Mg ha^{-1}) and the corresponding concentration of each element and the values were expressed in kg ha^{-1}. Laboratory analyses followed standard procedures as described by Anderson and Ingram (1993).

2.4. Vector analysis

Vector competition analysis (Imo and Timmer, 1998) was employed to examine nutrient competition between maize and pigeonpea in the 2005 cropping season because the fallow treatment generated maize data after the first season. Treatment effects on the aboveground biomass and nutrient content of intercropped and fallowed maize and pigeonpea with or without fertilizer were expressed relative to those of the unfertilized improved fallow treatment that was set as a reference (normalized to 100). Vector shifts or direction reflect the type of competitive interactions (antagonism, synergism, and compensatory) and the ratio of uptake-to-biomass vector identifies specific nutritional interactions including antagonistic dilution, growth dilution, and deficiency of plants in mixture (maize and pigeonpea intercropping) relative to monoculture (improved fallow) cropping systems (Imo and Timmer, 1998).

Vector diagnostic analysis was used to assess nutritional responses as follows. Nutrient concentration, nutrient content and aboveground biomass of maize and pigeonpea in response to treatments were expressed relative to normalized reference points (Salifu and Timmer, 2003; Isaac et al., 2007). These points were sole maize, intercropping, and cattle manure without fertilizer. Treatments comparisons are depicted by vectors (arrows) that may differ in length and direction. Vector length represents response magnitude, and vector direction identifies specific nutritional responses such as deficiency, sufficiency, and growth

Table 2
Summary of ANOVA ($p > F$) testing the effects of cropping systems, cattle manure, and combined N and P fertilizers on yields (Mg ha^{-1}) and nutrient content (kg ha^{-1}) of maize and soil inorganic nitrogen and phosphorus (mg kg^{-1}) for the 2005 growing season at Ihumwa Dodoma, Tanzania.

Source of variation	df[a]	Maize							Soil	
		Grain	Biom.[b]	N	P	K	Mg	Ca	N	P
Block (Blk)[c]	2									
Cropping systems (CS)	2	<0.0001	0.0320	0.0744	0.0656	0.2207	0.2720	0.2114	0.0001	0.2800
Blk × CS	2									
Fertilizer (Fert.)	2	0.0074	<0.0001	0.0034	<0.0001	0.1830	0.2324	0.7580	<0.0001	<0.0001
Blk × Fert.	4									
CS × Fert.	4	0.0083	0.0061	0.0041	0.0046	0.0260	0.0418	0.0430	0.0051	0.0367
Blk × CS × Fert.	8									
Cattle manure (CM)	2	0.2371	0.0119	0.2673	0.2038	<0.0001	<0.0001	0.0266	0.0379	0.2614
Blk × CM	4									
CS × CM	4	0.1076	0.8126	0.2297	0.0676	0.9753	0.9560	0.3455	<0.0001	0.0610
Blk × CS × CM	8									
Fert. × CM	4	0.0459	0.0090	0.0129	0.0304	0.0350	0.0460	0.0480	0.0202	0.0291
Blk × Fert. × CM	8									
Residual error	24									
Corrected total	80									

[a] df = numerator degree of freedom.
[b] Biom. = aboveground biomass.
[c] No test statistics (i.e., F-ratios and probabilities) for block and block-by-treatment interaction because these were random effects variables in the mixed model that constituted error terms for testing main and interaction effects of cropping systems, fertilizer and cattle manure.

dilution (Isaac et al., 2007) associated with nutrient supply from pigeonpea and additions of manure and fertilizers.

2.5. Statistical analysis

Graphical analysis of residuals was employed to test for normality and constant variance. Soil mineral N and P measures were log-transformed to correct for deviations from these assumptions prior to conducting analysis of variance (ANOVA). The mixed model procedure in statistical analysis system (SAS Institute, 2000) was used to run the analyses at $\alpha = 5\%$. Cropping systems, manure, fertilizer, and interactions of these factors were fixed effects variables while block and block-by-treatment interaction were random effects variables in the model. The ANOVA for maize and soil data tested the effects of 3 cropping systems and 3 rates of both manure and fertilizer (a 3^3 factorial experiment) replicated three times in a RCBD (Table 2). For pigeonpea, the analysis was carried out as a 2×3^2 factorial experiment since one level of cropping systems (i.e., sole maize) does not have pigeonpea data (Table 3). There was no 3-way interaction between treatments. Hence, ANOVA was repeated to compare main effects and 2-way treatment combinations. Following ANOVA, least squares means for significant treatment interactions were ranked according to Tukey's studentized range test after slicing (sorting) the interactions by fertilizer.

3. Results

3.1. Maize and pigeonpea yields

There was a significant positive interaction between cropping systems and fertilizer inputs on maize and pigeonpea yields ($p = 0.0083$, Table 2 and $p = 0.0270$, Table 3) in both the 2004 and the 2005 cropping seasons (Fig. 2). Without fertilization, yields of maize in the intercropping system in these seasons (1.3 and 0.8 Mg ha^{-1}) were similar to those of unfertilized sole maize (1.1 and 0.6 Mg ha^{-1}), but doubled (1.2 Mg ha^{-1}) under the improved fallow system (Fig. 2a and b). Improved fallows alone also

Table 3
Summary of ANOVA ($p > F$) testing the effects of cropping systems, cattle manure, and combined N and P fertilizers on yield (Mg ha^{-1}) and nutrient content (kg ha^{-1}) of pigeonpea for the 2005 growing season at Ihumwa Dodoma, Tanzania.

Source of variation	df[a]	Grain	Biom.[b]	N	P	K	Mg	Ca
Block (Blk)[c]	2							
Cropping systems (CS)	1	0.0088	0.0033	0.0041	0.0004	0.0247	0.0559	0.0180
Blk × CS	2							
Fertilizer (Fert.)	2	0.0010	0.0018	0.0002	0.0008	0.0026	0.0013	0.1942
Blk × Fert.	4							
CS × Fert.	2	0.0270	0.0314	0.0322	0.0470	0.0344	0.0106	0.0473
Blk × CS × Fert.	4							
Cattle Manure (CM)	2	0.0528	0.0021	0.0007	0.0316	0.0062	0.0012	0.0120
Blk × CM	4							
CS × CM	2	0.2038	0.0167	0.0129	0.0894	0.6965	0.0456	0.0153
Blk × CS × CM	4							
Fert. × CM	4	0.0339	0.0264	0.0474	0.0269	0.0230	0.0475	0.0352
Blk × Fert. × CM	8							
Residual error	12							
Corrected total	53							

[a] df = numerator degree of freedom.
[b] Biom. = aboveground biomass.
[c] No test statistics (i.e., F-ratios and probabilities) for block and block-by-treatment interaction because these were random effects variables in the mixed model that constituted error terms for testing main and interaction effects of cropping systems, fertilizer and cattle manure.

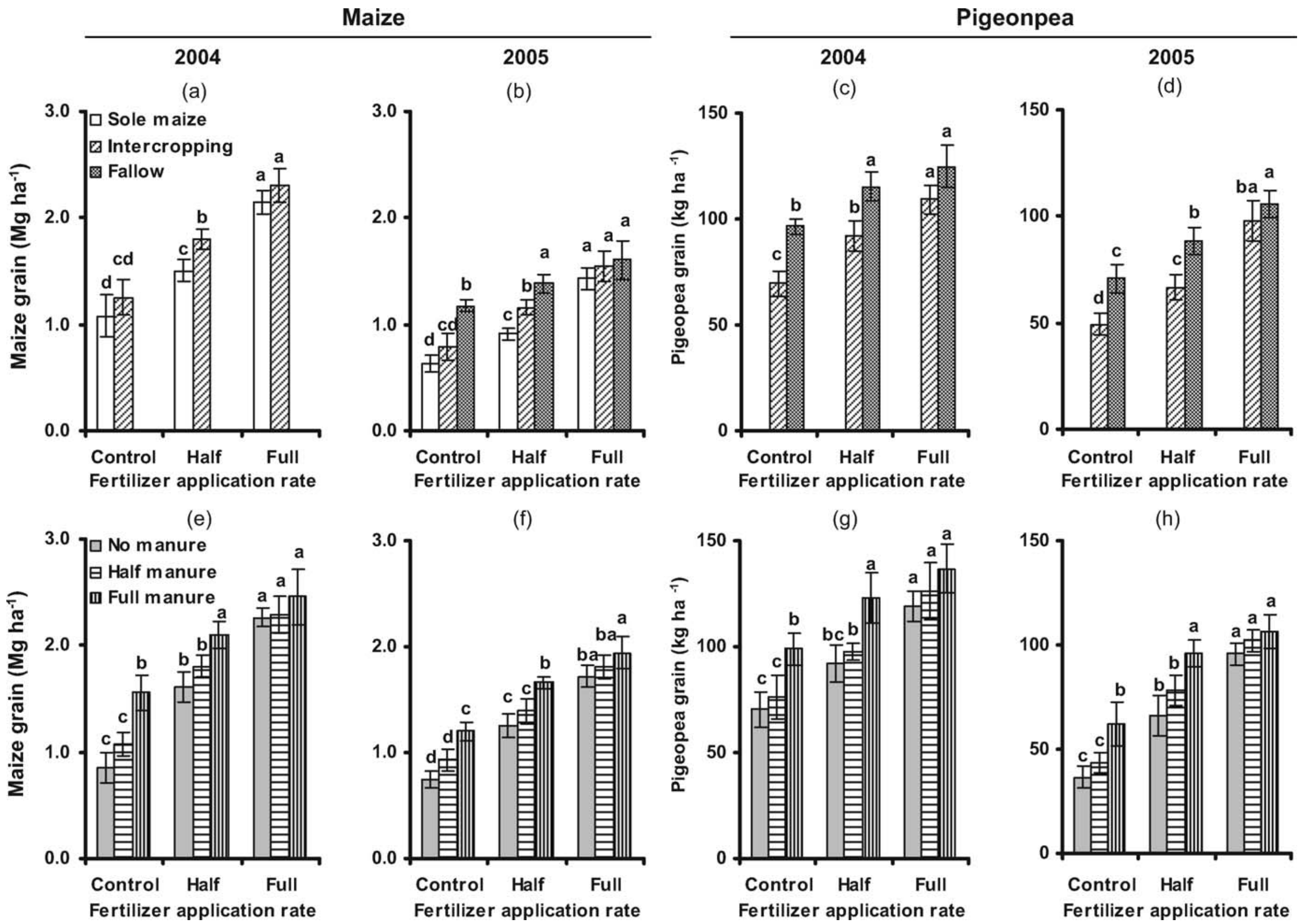

Fig. 2. Maize and pigeonpea grain yields for the interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow (a–d)] or cattle manure (e–h) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: control = no manure, half = 5 Mg ha^{-1}, full = 10 Mg ha^{-1}; and for inorganic fertilizers were: control = no fertilizer, half = 40 kg N ha^{-1} and 20 kg P ha^{-1}, full = 80 kg N ha^{-1} and 40 kg P ha^{-1}. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at $p < 0.05$ according to Tukey's studentized range test. Vertical bars indicate standard error of means ($n = 3$).

increased pigeonpea grain yield by 39–43% relative to the unfertilized intercropping (Fig. 2c and d). At half rates of N and P fertilization, yield responses of maize and pigeonpea to both intercropping and fallow treatments increased substantially relative to unfertilized sole maize. However, at full fertilizer rate grain yield between the three tested systems were not statistically different, indicating that crop growth responses were mainly driven by fertilizer inputs (Fig. 2a–d).

Both fertilizer and manure applications also resulted in significant increase in maize ($p = 0.0459$) and pigeonpea ($p = 0.0339$) grain yields (Tables 2 and 3), especially at higher N and P fertilizer rates (Fig. 2e–h). Relative to the unfertilized control, crop yields at the full manure rate were generally doubled without fertilization and tripled with full fertilization (Fig. 2e–h). As noted by non-significant differences, manure addition responses on maize and pigeonpea yields were masked at higher fertilizer rates. Treatments effects on foliage and wood biomass of pigeonpea were similar to those observed for pigeonpea grain yields (Fig. 3).

3.2. Maize and pigeonpea nutrient uptake

Significant treatment interactions, especially between fertilizer and cropping systems or manure, were noted for above ground biomass production and nutrient content of maize and pigeonpea (Tables 2 and 3). Improved fallowing with or without fertilizer addition increased maize N and P content relative to the unfertilized sole maize, whereas intercropping treatments stimulated nutrient content only after fertilizer application (Table 4). Without fertilization, maize tissue N and P in the fallow treatment were higher than values in the sole maize treatment, but similar to those of intercropped maize with half fertilizer rate. Except at full fertilizer rate, the improved fallow system generally doubled N and P content of pigeonpea compared to the intercropping system (Table 4). Cattle manure application, either alone or with N and P fertilizers significantly increased maize and pigeonpea nutrient uptake (Tables 2–4). While N and P content of crops in response to the interacting effects of fertilizer and cropping systems or manure were masked at full rates of N and P fertilizers, uptake of other elements increased even at higher fertilization rates (Table 4).

3.3. Soil nutrient availability

Without fertilization, the fallow treatment resulted in a significantly ($p = 0.0051$, Table 2) higher total soil inorganic N status compared to continuous sole maize (Fig. 4a), but soil P ($p = 0.0367$, Table 2) increased only after fertilization (Fig. 4c). No significant soil N or P increase was observed under intercropping in the absence of fertilizer inputs. Soil N and P levels at the full rate of fertilizer application were similar among the cropping systems, but statistically higher than that of the unfertilized sole maize treatment (Fig. 4a and c). As expected, combined fertilizer and cattle manure applications elevated soil N ($p = 0.0202$) and P

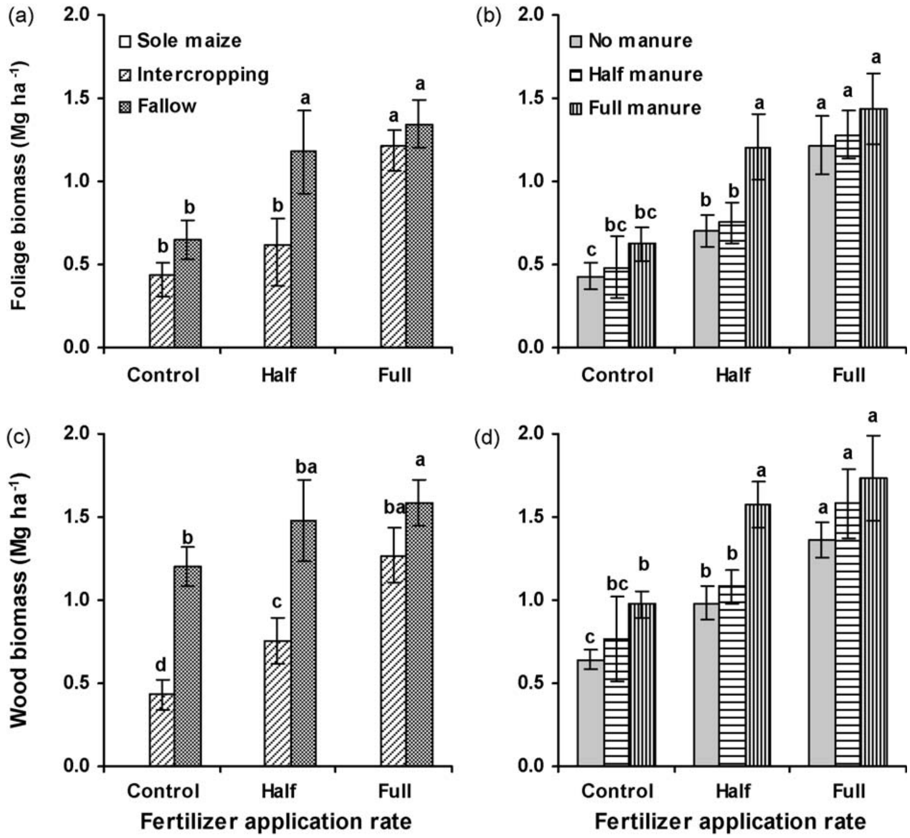

Fig. 3. Foliage and wood biomass of pigeonpea for the interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow (a and c)] or cattle manure (b and d) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: control = no manure, half = 5 Mg ha^{-1}, full = 10 Mg ha^{-1}; and for inorganic fertilizers were: control = no fertilizer, half = 40 kg N ha^{-1} and 20 kg P ha^{-1}, full = 80 kg N ha^{-1} and 40 kg P ha^{-1}. For each Figure, values represent least squares means of treatment combinations and those marked by the same letter are not statistically different at $p < 0.05$ according to Tukey's studentized range test. Vertical bars indicate standard error of means ($n = 3$).

Table 4
Biomass yield (Mg ha^{-1}) and nutrient content (kg ha^{-1}) of maize and pigeonpea for the 2005 cropping season for different cropping systems and cattle manure treatments without (−) or with half (+) and full (++) rates of N and P fertilizers at Ihumwa Dodoma, Tanzania.

Treatment	Maize						Pigeonpea					
	Biom.[a]	N	P	K	Mg	Ca	Biom.	N	P	K	Mg	Ca
Cropping system × fertilizer[b]												
−SM: unfertilized sole maize	1.73d[c]	12.9e	1.84e	22.3d	20.7d	2.19c						
−IC: unfertilized intercropping	1.99d	16.5de	2.52de	25.7d	24.4d	2.43bc	0.87d	14.3c	0.73c	6.68c	0.87c	6.53b
−IF: unfertilized fallow	2.52c	22.4dc	3.41dc	36.9bc	33.3bc	3.92ba	1.86b	30.6b	1.32b	13.2b	1.79b	11.2a
+SM: sole maize and half rate	2.48c	19.8d	3.25d	29.0cd	26.2cd	2.67c						
+IC: intercropping and half rate	2.91c	25.4c	4.06c	34.4c	30.6c	3.05ba	1.37c	23.9b	1.29b	10.3bc	1.36bc	9.19ba
+IF: fallow and half rate	3.52b	38.9b	6.01b	40.4bc	39.4ba	3.84ba	2.66a	46.9a	2.91a	19.0a	2.29a	13.8a
++SM: sole maize and full rate	3.68ba	40.0ba	6.61ba	41.2b	37.1b	3.67b						
++IC: intercropping and full rate	3.94a	43.9a	7.10a	49.0ba	44.0ba	4.48ba	2.48a	42.5a	2.66a	17.6a	2.14ba	12.8a
++IF: fallow and full rate	4.05a	46.5a	7.52a	52.6a	47.5a	4.89a	2.93a	52.7a	3.24a	20.9a	2.42a	14.0a
Cattle manure × fertilizer[d]												
−CM: no manure and no fert.[e]	1.76d	13.7d	1.81d	21.0d	19.3d	1.13d	1.17c	19.8c	0.86c	8.47c	0.96d	4.66c
−HM: half manure and no fert.	2.04d	16.3d	2.45d	27.5dc	24.3cd	1.53d	1.25c	22.5bc	1.05bc	10.7cb	1.13d	5.94bc
−FM: full manure and no fert.	2.79c	24.2c	3.81c	35.3bc	32.6bc	2.28c	1.60b	27.2bc	1.41b	12.9cb	1.35dc	7.45b
+CM: no manure and half fert.	2.89c	27.0c	4.10c	29.9c	28.8c	1.53d	1.68b	29.8b	1.55b	11.3c	1.32dc	5.94bc
+HM: half manure and half fert.	3.11c	31.7c	4.82c	40.4b	37.9b	2.83b	1.83b	31.6b	1.77b	14.5cb	1.58c	9.10b
+FM: full manure and half fert.	3.65b	39.0b	6.39b	55.3a	52.6a	3.58ba	2.78a	50.4a	2.90a	23.2a	2.54b	14.8a
++CM: no manure and full fert.	3.85ba	40.0ba	6.50ba	40.0b	38.7b	2.07c	2.58a	47.7a	2.67a	16.1b	1.92cb	8.51bc
++HM: half manure and full fert.	4.00ba	43.2ba	7.28ba	55.7a	53.0a	4.18a	2.86a	55.5a	3.22a	26.0a	2.85ba	16.7a
++FM: full manure and full fert.	4.30a	51.4a	8.27a	63.9a	60.5a	4.44a	3.17a	65.4a	3.82a	32.6a	3.47a	19.3a

[a] Biom. = aboveground biomass.
[b] Cropping system interaction fertilizer.
[c] Values represent least squares means and those within a column followed by the same letter are not statistically different at $p < 0.05$ according to Tukey's studentized range test.
[d] Cattle manure interaction fertilizer.
[e] Fert. = Fertilizer.

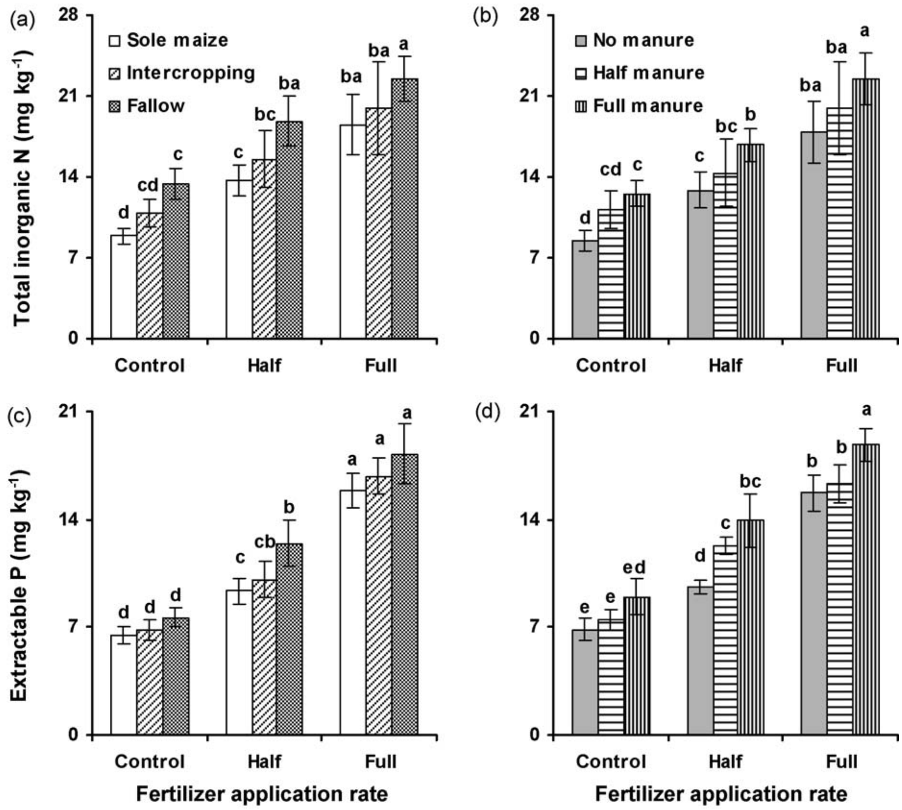

Fig. 4. Soil N and P status in response to interactions between combined N and P fertilizers and cropping systems [sole maize, intercropping, and one-year improved fallow (a and c)] or cattle manure (b and d) at Ihumwa, Dodoma, Tanzania. Application rates for cattle manure were: control = No manure, half = 5 Mg ha^{-1}, full = 10 Mg ha^{-1}; and for inorganic fertilizers were: control = no fertilizer, half = 40 kg N ha^{-1} and 20 kg P ha^{-1}, full = 80 kg N ha^{-1} and 40 kg P ha^{-1}. For each Figure, values represent untransformed least squares means of treatment combinations and those marked by the same letter are not statistically different at $p < 0.05$ according to Tukey's studentized range test. Vertical bars indicate standard error of means ($n = 3$).

($p = 0.0291$) status as compared to the control (Table 2). Cattle manure was relatively low in P content (Table 1), hence did not increase soil P over the control when applied alone (Fig. 4d). In contrast, soil N levels were significantly higher from this treatment.

3.4. Vector analysis of competition between maize and pigeonpea

Vector competition diagrams in Fig. 5 illustrate interspecific nutrient competition (Fig. 5a) and give insight on the role of fertilizer addition in modifying this competition (Fig. 5b–e). Before fertilization, both yield and nutrient uptake of intercropped maize and pigeonpea decreased relative to the fallow treatment exemplifying antagonistic interactions. Vectors of nutrient uptake were comparatively shorter than the biomass vector (vector ratio <1), which indicate nutrient competition (Fig. 5a). The unfertilized intercropping treatment reduced pigeonpea biomass by 60% ($100 - 40$) compared to a 30% ($100 - 70$) decrease in maize, reflecting a stronger competitive effect of maize (Fig. 5a). Half rates of N and P fertilizers did not significantly increase relative biomass and nutrient uptake of intercropped maize and pigeonpea (Fig. 5b) compared to the reference point, i.e., improved fallowing without fertilizer (Table 4). As expected, the increase was significant at the full fertilizer application rate (Fig. 5c and Table 4). Similar results were found for improved fallows at both half and full fertilizer rates (Fig. 5d and e). After fertilization, the biomass vector was shorter than vectors of N and P (vector ratio >1), but longer than vectors of other elements (Fig. 5c–e). This change of vector ratio depicts probable plant deficiency responses to N and P fertilizers and growth dilution of K, Mg, and Ca.

3.5. Vector diagnosis of maize and pigeonpea nutrient uptake

Vector diagnosis of yield and nutritional responses of maize and pigeonpea to interacting effects of cropping systems and N and P fertilizers revealed that the largest responses were associated with P (Fig. 6a and b). For instance, relative increases in concentration, content and biomass of maize in the fallow treatment with full fertilizer rate were 71%, 309%, and 134%, respectively (Fig. 6a). This response reflected a primary P deficiency because both biomass and uptake were improved. Except for N, concentrations of other elements declined with increase in both content and biomass in treatment combinations containing N and P fertilizers (Fig. 6a and b). For pigeonpea, this decline was also noted for all elements in the unfertilized fallow treatment (Fig. 6b). These responses reflected dilution of nutrients due to accelerated growth associated with fertilization and the improved fallow system. Inorganic N and P fertilizers improved pigeonpea biomass and N content without changes in N concentrations relative to unfertilized intercropping (Fig. 6b), typifying a sufficiency response.

In addition to P deficiency, vector diagnosis of maize and pigeonpea response to additions of cattle manure and fertilizer showed that Ca was likely the second limiting nutrient for plant growth, as illustrated by comparative vector length (Fig. 6c and d). At full rate of manure and fertilizer applications, relative increases in concentration (63% and 53%), content (293% and 314%) and biomass yields (145% and 170%) of maize and pigeonpea associated with Ca ranked second after P responses. Manure also increased concentration and uptake of other nutrients, except for treatments with N and P fertilizers alone (without manure addition).

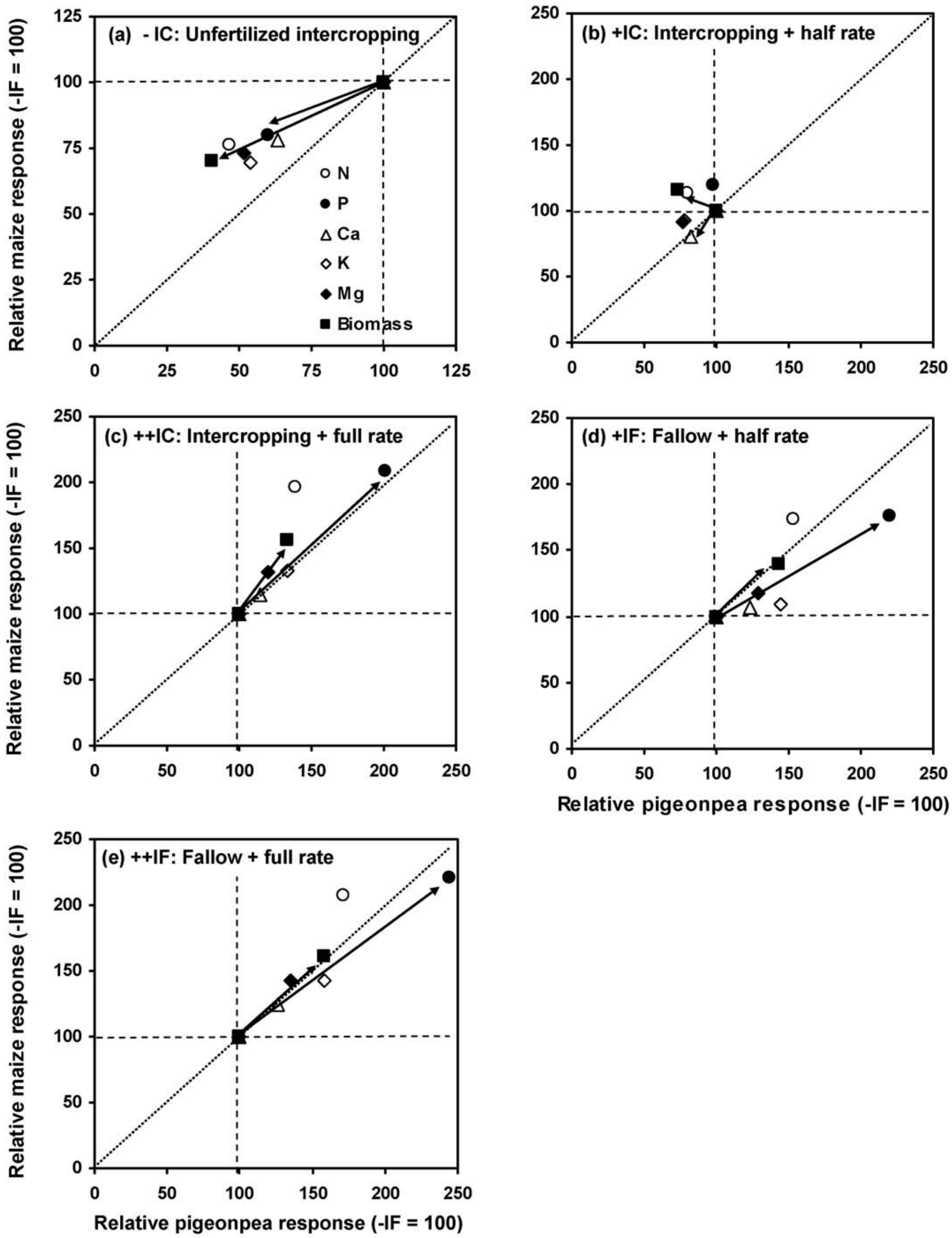

Fig. 5. Vector competition diagrams of aboveground biomass and nutrient content of maize and pigeonpea under intercropping (a–c) and one-year improved fallow (d and e) systems without (−), with half (+) or full (++) rates of N and P fertilizers at Ihumwa, Dodoma, Tanzania. Responses are expressed relative to the unfertilized fallow treatment (−IF) that was normalized to 100. Vector shifts or direction reflect types of competitive interactions (antagonism, synergism, and compensatory) and the uptake-to-biomass vector ratio identifies specific nutritional interactions (antagonistic dilution, growth dilution, and deficiency) between maize and pigeonpea. Thus, decreases of relative uptake and biomass of both crops associated with vector ratio <1 represented antagonistic dilution due to interspecific nutrient competition. A similar vector ratio accompanied with increases of these variables depicted growth dilution due to stimulated growth after additions of limiting nutrients. Nutrient deficiency responses were illustrated by relative increase in plant uptake and biomass and vector ratio >1. To minimize clutter, only the biomass and the most responsive nutrient vector (arrow) are drawn. See Table 4 for statistically different vectors (treatments). Note scale for Fig.5a is half that of others.

4. Discussion

4.1. Maize and pigeonpea yields

Significant positive interactions between cropping systems or manure and fertilizer treatments were consistently noted for yields and nutrient content of maize and pigeonpea as well as soil N and P status (Figs. 2–4, Table 4). These treatment interactions tended to reflect the low nutrient inputs from cattle manure (Table 1) and green manure (Fig. 3 and Table 4) as well as the comparatively slow release of nutrients from organic sources. Both manure and senesced pigeonpea leaves decompose slowly and show initial immobilization of N during the first 8-week decomposition period due to high contents of lignin, carbon, and polyphenols (Sakala et al., 2000; Mafongoya et al., 2000). However, fresh pigeonpea leaves mineralize more rapidly and have been found to release about 50% of N content within 60 days due to low C:N ratio (Sakala et al., 2000).

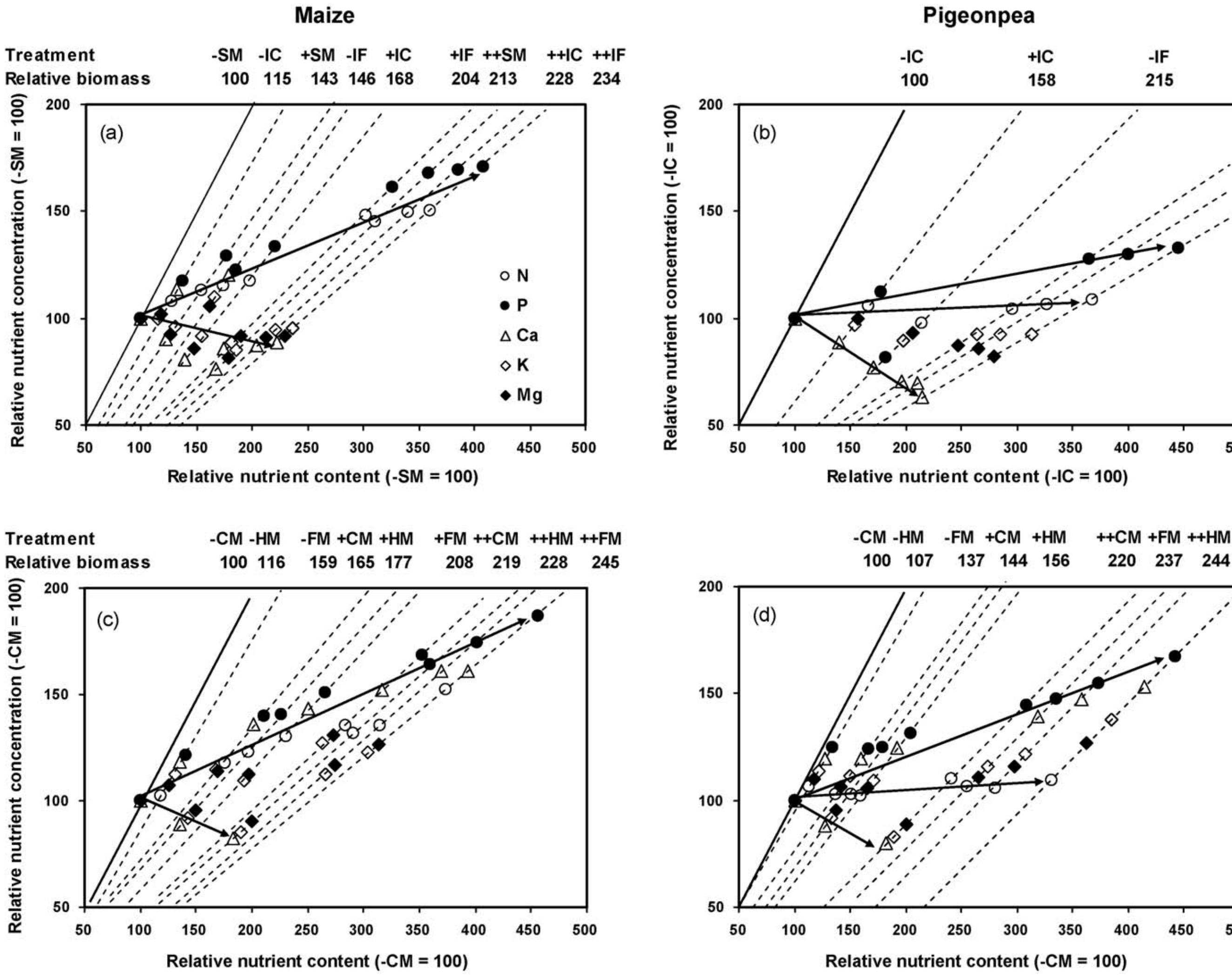

Fig. 6. Vector diagnosis of the relative change in aboveground biomass, nutrient concentrations and content of maize and pigeonpea in response to cropping systems (a and b) and cattle manure (c and d) without (−), with half (+) or full (++) rates of inorganic fertilizers at Ihumwa, Dodoma, Tanzania. Cropping systems included: SM = sole maize, IC = intercropping, and IF = one-year improved fallow. Application rates for cattle manure were: control (CM) = no manure, half (HF) = 5 Mg ha^{-1}, full (FM) = 10 Mg ha^{-1}; and for inorganic fertilizers were: control (−) = no fertilizer, half (+) = 40 kg N ha^{-1} and 20 kg P ha^{-1}, full (++) = 80 kg N ha^{-1} and 40 kg P ha^{-1}. Responses are relative to controls (−SM, −CM and −IC) that were normalized to 100. To minimize clutter, only the largest vector (arrow) for each nutritional response is drawn. See Table 4 for statistically different vectors (treatments).

The combined use of mineral and organic nutrient sources, however, can have the advantage of extended release of nutrients, especially N, throughout the growth period and in the subsequent seasons (Sakala et al., 2000; Mafongoya et al., 2000). This would be crucial at low rates where synergisms between fertilizer and cropping systems or cattle manure on crop yield and soil nutrients were evident (Figs. 2 and 4). For example, maize and pigeonpea yields in the improved fallow system at half fertilizer rate were similar to yields obtained with cropping systems at full rate. Such positive large responses possibly were due to nutrient inputs, especially N, from green manure (Fig. 3) and pigeonpea fallowing either alone or with fertilizers (Fig. 4a); and also due to the effects of reduced competition for nutrients (Fig. 5a) and/or moisture associated with sequential cropping arrangements. These could also be the reasons for higher maize yields obtained in the unfertilized fallow treatment compared to intercropping without fertilizer treatment (Fig. 2b). It should be noted that nutrients recycled by pigeonpea through litter turnover may not be immediately available to the intercropped plants because the shrub sheds leaves towards the end of the growing season when companion maize crops have matured. However these nutrients, especially for N, may well benefit subsequent crops as senesced leaves decay slowly (Sakala et al., 2000). Unlike soil N, pigeonpea fallowing alone failed to improve soil P levels probably due to low P inputs (Table 4, Fig. 4b). Under low soil P conditions as in this site (7.0 mg kg^{-1}), pigeonpea may have limited capacity to recycle P because of high retranslocation rates to meet internal P demand for fixation (Sinclair and Vadez, 2002; Ishikawa et al., 2002).

Enhanced maize and pigeonpea responses to the interacting effects of fertilizer and cattle manure (Fig. 2e–h) also indicated that manure treatments alone were not sufficient to alleviate nutrient deficiencies. These synergistic interactions were mainly attributed to the additional P supply from fertilization since manure treatments alone did not improve soil P, but increased N status (Fig. 4a and d). The comparatively low P input by manure was due to its low P concentration (Table 1). In contrast to this study, Lupwayi et al. (1999) did not observe positive interactions between cattle manure and urea possibly due to the use of N fertilizer alone, low manure rates (3 Mg ha^{-1}), and differences in site conditions. Mafongoya et al. (2006) reported that livestock manures at recommended rates (10–15 Mg ha^{-1}) containing 0.49–1.98% N should be adequate for maize production (Table 1).

Generally, the lack of both manure and pigeonpea treatment effects on crop and nutrient uptake at full fertilizer rate (Fig. 2 and Table 4) was likely due to low nutrient inputs, especially P (Tables 1 and 4, Fig. 4b).

Overall, the results indicated that the availability of N and P controlled the growth of maize and pigeonpea because the largest grain and biomass yields were associated with treatments comprised of full fertilizer rates and cropping systems or cattle manure (Fig. 2, Table 4). Evidently, a combination of half rate of N and P fertilizers and the improved fallow system or a full manure rate was sufficient to optimize maize and pigeonpea production, because the yield associated with this treatment was similar to those obtained with application of the full prescribed fertilizer rate (Fig. 2, Table 4).

Precipitation in the 2004 season was above the long-term average and was well distributed throughout the cropping season (Fig. 1). However, yields of the unfertilized intercropped maize in the first and second seasons (1.3 and 0.8 Mg ha^{-1}) were not statistically different from yield (1.1 and 0.6 Mg ha^{-1}) in the continuous sole maize treatment (Fig. 2a and b). Although such low yields are common in other semi-arid sites in southern Africa (Snapp et al., 2002; Chikowo et al., 2004; Myaka et al., 2006), these results suggest that the benefits of intercropping pigeonpea are mainly due to the additional grain and wood yields from pigeonpea (Figs. 2c, d and 3). Crop yield in 2005 was severely affected by low and sporadic rainfall patterns occurring on the study site (Fig. 1) such that yield declined by 20–30% of the 2004 level (Fig. 2). Below average precipitation in February presumably affected maize growth adversely because the planted maize was in the active growth stage (6 weeks after maize sowing) requiring high supplies of growth resources (Kimaro et al., 2008). Despite this drought effect, however, grain yields of maize under improved fallows without fertilizer or after modest additions of fertilizer and cattle manure were comparatively higher than the average maize yield (1 Mg ha^{-1}) in Sub-Saharan Africa (Mafongoya et al., 2006). Thus, these treatments can be employed to minimize possible maize yield losses in legume intercropping systems in years of low precipitations that have been reported in the region (Snapp et al., 2002; Myaka et al., 2006).

4.2. Nutrient competition

Pigeonpea is intercropped with cereals in semi-arid Africa on the basis that its slow initial growth may minimize interspecific competition (Snapp et al., 2002; Mafongoya et al., 2006). Also the legume may grow well during offseason by accessing subsoil moisture due to deeper rooting (Sekiya and Yano, 2004; Mafongoya et al., 2006) possibly compensating for impaired early growth after harvesting cereal crops (Zhang and Li, 2003). However, our results clearly indicated that interspecific competition reduced yields and nutrient uptake of both maize and pigeonpea when little or no fertilizer was applied (Fig. 5a and b). As expected, pigeonpea was a weak competitor due to its slow initial growth rate relative to maize crop. Biomass yield of this legume was reduced by 60% compared to a 30% decrease in that of maize (Fig. 5a). Three months after maize harvesting, pigeonpea grain yield in the unfertilized intercropping was 33% lower than that of the unfertilized fallow treatment (Fig. 2d). This signifies that pigeonpea growth during offseason was adversely affected by an earlier nutrient depletion induced by maize and/or the effects of drought (Figs. 1 and 5a). Recovery of growth and nutrient uptake after harvest of an early maturing component has been demonstrated for soybean plants in wheat–soybean intercropping systems in semi-arid China (Zhang and Li, 2003). Consistent with our study, such recovery was not observed for unfertilized pigeonpea plants in the pigeonpea–soybean intercropping system in semi-arid India due to the high competitive effect of soybean (Ghosh et al., 2006).

The addition of full fertilizer rates to the intercropping system, and half rates in the improved fallow system alleviated nutrient competition and enhanced yields and nutrient content of both maize and pigeonpea relative to the control (Fig. 5c–e). These responses illustrate the comparative advantages of improved fallow systems in controlling interspecific resource competition and reducing fertilizer inputs without compromising crop yield. Unlike N, which is fixed biologically, external input of P is necessary to sustain crop production on P-deficient soils (Smithson and Giller, 2002). Apparently, farmers can minimize P applications by half while optimizing yields of both maize and pigeonpea to diversify income and food sources.

Farmers are concerned with yield loss of maize intercropped with grain legume, especially in drier years, when additional yield from the legumes may not offset such losses (Snapp et al., 2002). However, our results suggest that adopting improved fallows with or without fertilizer addition may stimulate crop growth and minimize such loses even in semi-arid conditions.

4.3. Nutrient limitation

Substantial increases of maize and pigeonpea nutrient uptake in the fertilizer and cropping system treatments (Table 4) exemplified the occurrence of nutrient deficiency, with P being the most limiting nutrient (Fig. 6a and b). The interacting effects of cattle manure and fertilizer further revealed a secondary Ca deficiency (Fig. 6c and d). These responses were likely associated with the effects of high pH (4.6) and exchangeable aluminum (0.98 cmol kg^{-1}) on soil P and Ca availability. Mobilization of aluminum under this strong acidic condition probably reduced soil P availability by forming insoluble complexes with phosphate ions and accelerated loss of exchangeable calcium by displacing calcium ions from the exchange sites (Marschner, 1995; Brady and Weil, 2004). The deficiency response of pigeonpea to P can also be attributed to high P-demand for root nodulation (Sinclair and Vadez, 2002; Ishikawa et al., 2002). As reflected by multiple nutrient deficiencies in treatments containing cattle manure (Fig. 6c and d), native soil fertility was poor and insufficient to sustain crop production.

Pigeonpea intercropping or fallowing was expected to enhance maize yield and nutrient uptake through biological N fixation. However, comparatively low nutrient content and biomass yield of maize in the intercropping and fallow treatments without fertilizer inputs (Table 4) suggest that this process had little impact on maize growth due to P limitation (Fig. 6a). On the other hand, pigeonpea showed sufficiency response to N (Fig. 6b and d) despite low soil N (0.03%) status. This would suggest that the pigeonpea crops required little or no external N inputs; hence did not adversely compete for this resource with maize that responded positively to N fertilization (Table 4, Fig. 6a). However, a previous study in semi-arid India suggests that pigeonpea can suffer N deficiency when intercropped with soybean on N-deficient sites (Ghosh et al., 2006).

Growth dilution of K, Mg and Ca was attributed to increased maize and biomass yields following N and P fertilization because these elements were not added (Fig. 6). However, the dilution of all elements in pigeonpea under in the unfertilized fallow treatment (Fig. 6b) likely reflects stimulated growth due to non-nutrient limitations such as moisture because pigeonpea alone had limited capacity to recycle P (Fig. 4b) and possibly other nutrients as well.

5. Conclusions

Yield and nutritional interactions between maize and pigeonpea under intercropping (simultaneous) and improved fallow (sequential) systems with and without fertilizer or manure additions were evaluated for two cropping seasons. Intercropping did not increase maize grain yield over sole maize except after fertilization, implying that nutrient competition suppressed maize growth. On the other hand, improved fallows with or without fertilization enhanced yields of maize and pigeonpea compared to the unfertilized sole maize. This increase was mainly associated with combined effects of pigeonpea facilitation through nutrient replenishment and reduced competition for soil nutrients and/or moisture by sequential cropping arrangements. Significant treatment interaction effects on maize and pigeonpea yields were also observed between cattle manure and inorganic fertilizers. Apparently, low P inputs from the pigeonpea crop and the manure was the main reason for these positive interactions since the site was deficient of P. Combining the half fertilizer rate and the improved fallow system or full rate of cattle manure may be sufficient to optimize maize and pigeonpea production. However, considering additional yields of grain and fuelwood from pigeonpea, improved fallows may be more beneficial to smallholder farmers for enhancing farm productivity compared to using bulky low P-content manure.

Vector competition analysis revealed antagonistic nutrient competition between maize and pigeonpea when intercropped without fertilization that was associated with inherently low soil fertility. As a result, biomass and grain yields of unfertilized pigeonpea under intercropping were decreased by 60% and 33%, respectively. Overcoming nutrient competition would involve addition of full rates of N and P fertilizers when intercropping. However, improved fallows may reduce fertilizer applications by half without adversely affecting crops yields due to alleviating interspecific competitions through sequential cropping arrangements. Vector diagnosis depicted multiple nutrient deficiency responses, especially for low P and Ca, attributed to high soil acidity and exchangeable aluminum. Nitrogen application to pigeonpea may not be necessary even on this N-poor site because the legumes responded weakly to N additions reflecting self-sufficiency through biological fixation. This study has demonstrated that the intercropped pigeonpea may not recover from interspecific competition even after maize harvesting possibly due to earlier depletion of nutrients and/or moisture by maize plants. Consequently, suppressed grain yield of pigeonpea grown simultaneously in mixture suggests that improved fallows utilizing sequential cropping may be more effective than intercropping systems in sustaining both maize and pigeonpea yields.

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