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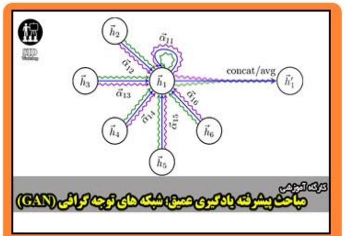
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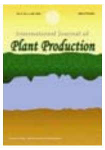

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Maize productivity and nutrient use efficiency in Western Kenya as affected by soil type and crop management

A.F. Ngome[a,*], M. Becker[a], M.K. Mtei[a], F. Mussgnug[b]

[a]*Institute of Crop Science and Resource Conservation (INRES), Department of Plant Nutrition, University of Bonn, Karlrobert Kreiten Straße 13, 53115 Bonn, Germany.*
[b]*Africa Rice Center (AfricaRice), 01 BP 2031, Cotonou, Benin.*
*Corresponding author. E-mail: ngomajebe@yahoo.com

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Abstract

Low soil fertility and high weed infestation are the main culprits for the declining maize production in Western Kenya. Technology packages to address these constraints exist, but their effectiveness is likely to be influenced by variability in soil types and farm management practices in the region. Trials were conducted during the 2008/2009 cropping seasons to investigate the nutrient use efficiency and yield response of maize to some recommended management options for smallholder farmers on three dominant soil types of Western Kenya namely Acrisol, Nitisol and Ferralsol. Irrespective of seasons, average maize yields were highest on Nitisol (3.6 t ha^{-1}) and lowest on Ferralsol (2.1 t ha^{-1}). Maize yield gaps (difference between potentially achievable and actual yields) differed by season and soils with 4-5 t ha^{-1} on Nitisol and about 6 t grain ha^{-1} on Acrisol and Ferralsol. On Nitisol, the largest share of this yield gap (80%) was closed by the addition of mineral fertilizer, while on Ferralsol, reduced tillage could close 25-60% of the yield gap. The highest agronomic (13-39 kg grain kg^{-1} N) and physiological (50-160%) N use efficiencies were obtained with mineral fertilizers, while the addition of organic amendments resulted in the highest P use efficiency (15-154 kg grain kg^{-1} P), irrespective of soil type and season. As soil types and management options differentially affect yields and nutrient use efficiency of maize, there is a need for field-specific targeting of technologies to address maize production constraints in Western Kenya.

Keywords: Acrisol; Ferralsol; Nitisol; Nutrient uptake; Yield gap.

Introduction

Maize (*Zea mays* L.) is the staple food crop in much of Kenya. It is grown across a wide range of agro-ecological zones (Ngome et al., 2012; Romney et al., 2003) and on the major share of the available cropland. However, the widely observed soil fertility decline and weeds infestation are causing a reduction in maize production (Karaya et al., 2012) with an average grain yield estimated at less than 1 t ha^{-1} (Mugwe et al., 2008; Ngome et al., 2011b). Consequently, the gap between the maize yield attainable on research stations and the actual farm yields is increasing. Some studies have reported yield gaps of more than 3 t ha^{-1} $year^{-1}$ from different localities in Kenya (Rutunga et al., 2003). Such yield gap studies are a useful tool to assess the magnitude of different yield-affecting factors and to set policy and research priorities. Furthermore, the share of the yield gap closed by a specific agricultural technology can improve the site-specific targeting of technology options in heterogeneous farming environments (Sileshi et al., 2010), thus increasing technology adoption by farmers.

The effectiveness of field-specific management options to enhance maize productivity is seen to depend largely on the use efficiency of applied nutrients (Cassman et al., 1998) and variability in soil types (Ngome et al., 2011b). If nutrient supply does not match crop nutrient demand, such management practices can negatively affect nutrient use efficiency and crop productivity in the long term (Wang et al., 2010). Furthermore, low use efficiency is likely to increase nutrient losses, potentially leading to environmental problems such as groundwater contamination.

In Western Kenya, there exist a wide range of soils with the Acrisols (Ultisols: US Soil Taxonomy), Nitisols and Ferralsols (Oxisols: US Soil Taxonomy) being the most dominant soils (Jaetzold et al., 2006). These soils differ in their physical and chemical properties. Therefore, it is essential to consider the prevailing heterogeneity in soil conditions that could possibly influence the effectiveness of applied technologies in the region.

Several organic- and inorganic-based agricultural technology packages have been proposed to improve maize production in East Africa. Thus, Rao and Mathuva (2000) reported a 27% increase in maize grain yield due to green manure application in the drier areas of Kenya. Baijukya et al. (2005) showed significant yield increase following the application of 2 t ha^{-1} of farmyard manure in the sub-humid north of Tanzania. Significant maize grain yield increases (over 100%) due to the application of mineral fertilizer, particularly nitrogen and phosphorus, have been reported in smallholder farms across East Africa (Ngome et al., 2011a; Vanlauwe et al., 2006). To date, however, adoption rates of these technologies by farmers in the region are low (Odendo et al., 2006; Okalebo et al., 2006), probably because these technology options frequently do not consider differences in resource base quality (e.g. inherent soil attributes) and resource availability (e.g. available land, labor, capital) between growing environments and farm types. Thus, Tittonell et al. (2005) reported large differences in soil fertility between ‘poor’ and ‘rich’ farmers’ fields, while Vanlauwe et al. (2006) observed niches of high and low fertility within the same farm as a result of differential allocation of organic and inorganic fertilizer in Western Kenya. These site- and system-specific conditions are very likely to differentially influence the effectiveness of agricultural technologies to improve maize production and nutrient use efficiency in the region. The objectives of the current study were (i) to evaluate the effects of management options on yields and nutrient uptake of maize and (ii) to determine maize yield gaps and the share of the yield gap closed by management options on three soils of Western Kenya over two cropping seasons.

Materials and Methods

Description of experimental sites

The study was conducted in the short rainy season (September-November) of 2008 and the long rainy season (March-July) of 2009 at three sites in Kakamega, Western Kenya, namely (i) the Kenya Agricultural Research Institute (KARI) Kakamega, (ii) Lubao sub-location and (iii) Virhembe sub-location. The three sites were situated at approximately 2-30 km from Kakamega town and had contrasting soil types namely eutric Nitisol (KARI), ferralo-orthic Acrisol (Lubao) and nito-rhodic Ferralsol (Virhembe), according to the FAO classification system (FAO, 1990). The field experiment at KARI was conducted on plots with a multi-year history of maize varietal trials with the application of mineral fertilizer. The field experiments at Lubao and Virhembe were conducted on farmers’ fields where maize and bean were grown with minimal external input for over ten years prior to this study. Some selected climatic and soil attributes of the study sites are presented in Table 1. The three study sites will subsequently be referred to by their soil type as Nitisol, Acrisol and Ferralsol.

Table 1. Climatic conditions and soil characteristics of three sites (soils) in Kakamega, Western Kenya.

Parameter	Site (Soil)					
	Nitisol		Acrisol		Ferralsol	
Altitude (m a.s.l.)	1534		1558		1569	
Latitude	00° 16.962' N		00° 19.180' N		00° 14.548' N	
Longitude	034° 46.073' E		034° 47.793' E		034° 51.129' E	
Annual rainfall (mm)	1978	1186[a]	1612	967	2232	1450
Mean temperature (°C)	21		21		21	
Soil texture	Clay-loam		Sandy-loam		Clay	
Sand (%)	12.9		61.2		10.8	
Silt (%)	33.6		20.0		27.0	
Clay (%)	53.5		18.8		62.2	
Drainage	Good		Moderate		Moderate	
Basement rock	Basalt		Granite		Granite	
pH ($H_2$0)	5.4		5.4		4.9	
Total C (%)	4.1		1.4		3.0	
Total N (%)	0.3		0.1		0.2	
Available Bray-P (mg kg^{-1})	3.4		7.7		2.3	
Exchangeable K (cmol kg^{-1})	0.7		0.2		0.8	
Bulk density (g cm^{-3})	1.1		1.2		1.1	

Soil analysis method: Okalebo et al. (2002).

[a] Total rainfall during the long rainy season.

Experimental design, treatments and crop management

The experimental fields were under a weedy fallow for two months prior to the onset of the experiments. Weeds were cleared manually using cutlasses and raked using hand tools before setting up the experiments. Eight management options were comparatively assessed in a randomized complete block design. Experimental plots of 6×5 m were separated by 0.5 m borders. The management options included a low-input farmer practice without external input use, conventional manual tillage and one manual weeding at 14 days after maize seeding (control treatment) and seven regionally recommended yield-improving technologies (Table 2a). The eight treatments were applied at all three sites during the short rainy season of 2008 and repeated on the same plots during the long rainy season of 2009.

Maize variety HB 520 was seeded in all treatment plots on 4 September 2008 for the short and on 22 March 2009 for the long rainy season crop at a 60×25 cm spacing. Two maize seeds were used per planting hole and thinned to one plant per hill two weeks after emergence. Weeds were manually removed and weighed at 14, 28 and 42 days after maize seeding. The weed species diversity and biomass accumulation in the study sites are reported in a companion study (Ngome et al., 2012). As weeding represents a moderate disturbance of the soil, the zero-tillage treatment may better be referred to as minimum tillage. Details of the amount of organic and inorganic nutrients (N and P) added in the treatments are given in Table 2b.

Data collection and calculations

Maize biomass was evaluated sequentially at 4, 6, 8, 10, 12 and 14 weeks after seeding. Five maize plants were randomly selected from each treatment plot, cut at ground level, weighed to obtain the fresh weight and a sub-sample of 200 g was oven-dried at 70 °C to constant weight. Maize grain yield was determined at harvest (16 weeks after seeding) from two 1.2×2 m harvest areas selected in the middle rows of each treatment plot. All maize plants (32) within the harvest areas were cut at ground level and weighed. The maize cobs were pooled, weighed, dried and threshed. The grain moisture was determined using an electric moisture meter and yield was expressed at 14% moisture content.

Table 2a. Treatments applied at the Nitisol, Acrisol and Ferralsol in Kakamega, Western Kenya, to determine maize productivity and nutrient use efficiency as affected by soil type and crop management.

Management option	Tillage	Manual weeding	External input
Farmer's practice (control)	Conventional	Once at 14 [a]DAS	None
Clean weeding	Conventional	Three times; 14, 28 & 42 DAS	None
Seed priming	Conventional	Three times; 14, 28 & 42 DAS	Seeds primed with 2% phosphorus solution before sowing
Farm yard manure (FYM)	Conventional	Three times; 14, 28 & 42 DAS	FYM applied at a rate of 5 Mg ha^{-1} before sowing maize
Green manure (*Mucuna pruriens*)	Conventional	Once at 14 DAS	6 weeks old mucuna biomass was incorporated between rows of 4 weeks old maize
Zero tillage combined with a cover crop (*Arachis pintoi*)	Minimum	Once at 14 DAS	Mineral nitrogen (100 kg ha^{-1}) and phosphorus (100 kg ha^{-1})
Zero tillage combined with mineral fertilizer	Minimum	Three times; 14, 28 & 42 DAS	Mineral nitrogen (100 kg ha^{-1}) and phosphorus (100 kg ha^{-1})
Mineral fertilizer	Conventional	Three times; 14, 28 & 42 DAS	Mineral nitrogen (100 kg ha^{-1}) and phosphorus (100 kg ha^{-1})

[a] DAS: Days after sowing maize.

Table 2b. Nitrogen (N) and phosphorus (P) inputs from management options on three contrasting soil types in Western Kenya during the short rainy season of 2008 and the long rainy season of 2009.

Soil type	[a]Management option	Dry matter (kg ha^{-1})		[b]Total nitrogen (kg ha^{-1})		[c]Total phosphorus (kg ha^{-1})	
		SR 08	LR 09	SR 08	LR 09	SR 08	LR 09
Nitisol	FYM	5000	5000	60	60	13	13
	GM	1010	1200	42	55	33	34
	ZANP			100	100	100	100
	ZNP			100	100	100	100
	NP			100	100	100	100
Acrisol	FYM	5000	5000	60	60	13	13
	GM	1170	1305	38	52	34	35
	ZANP			100	100	100	100
	ZNP			100	100	100	100
	NP			100	100	100	100
Ferralsol	FYM	5000	5000	60	60	13	13
	GM	900	1155	33	50	33	34
	ZANP			100	100	100	100
	ZNP			100	100	100	100
	NP			100	100	100	100

[a] FYM=farmyard manure, GM=green manure using *Mucuna*, ZANP=zero tillage combined with *Arachis* as cover crop, ZNP=zero tillage combined with mineral fertilizer, NP=mineral fertilizer.

[b] BNF contribution from ZANP was not included in total N input since *Arachis* was not incorporated.

[c] GM received mineral phosphorus (30 kg ha^{-1}P) at planting of *Mucuna pruriens*.

[b] SR=Short rainy season (September-December).

[c] LR=long rainy season (March-July).

The maize yield gap was defined as the difference between the attainable yield of variety HB 520 under researcher-managed high input trials (about 7 t ha^{-1}-Kenyaseed, 2008) and actual farm yields at the three study sites. The share of the yield gap closed by management options was calculated as:

$$\text{Yield gap closed (\%)} = \left(\frac{\text{grain yield in treatment - grain yield in control}}{\text{yield gap}} \right) \times 100.$$

Nutrient uptake by maize was determined at harvest. Dried sub-samples of maize (stover + grain) were finely ground (1 mm) using a micro impact-grinding mill (model IKA MF10 B) and stored until analyzes. Five milligram sample was weighed from each ground maize sample and analyzed for nitrogen (N) concentration with an automatic elemental analyzer (EA Euro

3000). Phosphorus (P) in the maize samples was measured colorimetrically with a spectrophotometer (Eppendorf ECOM 6122) after dry-ashing (which includes heating at 500 °C for 5 h followed by 4 h at 450 °C after ash dissolution in saturated NH_4NO_3 solution) and extraction with 6M HCl (Mussgnug et al., 2006). Net nutrient uptake was calculated as the difference between the nutrient uptake by a treatment and that of the control. Calculations of nutrient use efficiency were adopted from Cassman et al. (1996). The agronomic and physiological N or P use efficiencies were determined as:

$$\text{Agronomic N or P use efficiency} = \left(\frac{\text{kg of grain yield increase over control}}{\text{kg of N or P applied}} \right)$$

$$\text{Physiological N or P use efficiency} = \left(\frac{\text{kg of N or P uptake over control}}{\text{kg of N or P applied}} \right) \times 100.$$

Data analysis

Data on biomass accumulation, grain yield and nutrient uptake of maize of the management options at each site were subjected to one way analysis of variance using SPSS statistical package (SPSS, 2008). Mean comparison was done by Tukey test at 5% level of significance.

Results

Response of maize biomass

The time course in biomass accumulation of maize variety HB 520 in the different treatments followed a sigmoid curve with peaks (7-17 t ha^{-1}) observed at 12 weeks across sites and seasons (Figure 1). Treatment effects were noticeable between 8 and 14 weeks after seeding. They were stronger on the Nitisol than on the Acrisol or Ferralsol and more pronounced in the long than in the short rainy season. Irrespective of site and cropping season, significant differences ($P<0.001$) were observed among management options. Mineral fertilizer use resulted in the highest biomass accumulation ranging from 10 to 16 t ha^{-1} on the Nitisol, from 5 to 9 t ha^{-1} on the Acrisol and from 6 to 8 t ha^{-1} on the Ferralsol (Table 2). Lowest biomass was observed consistently in the control with 5-8 t ha^{-1}, 2-3 t ha^{-1} and 2 t ha^{-1} on Nitisol, Acrisol and Ferralsol, respectively.

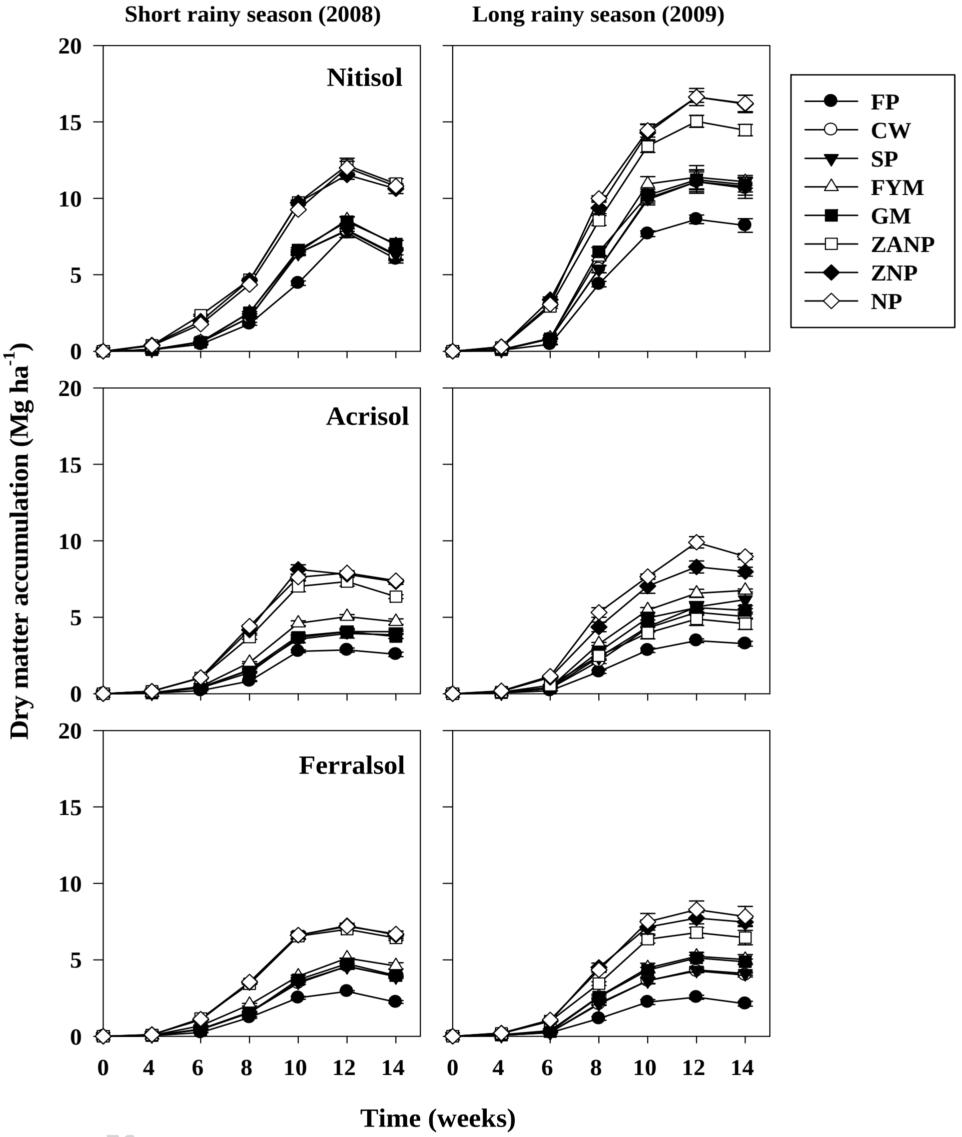

Figure 1. Variation in dry matter accumulation of maize variety HB 520 on three contrasting soil types in Western Kenya during the short rainy season of 2008 and the long rainy season of 2009. Bars are standard error of the means (n=4). CW=clean weeding, SP=seed priming, FYM=farmyard manure, GM=green manure, ZANP=zero tillage combined with the use of a cover crop, ZNP=zero tillage combined with mineral fertilizer use, NP=mineral fertilizer, FP=Control, actual farm yield in farmers' fields.

Response of maize grain yield

Maize grain yield differed significantly ($P<0.001$) among management options on the three experimental sites (Table 3). Mineral fertilizer application had the largest effect on maize grain yield (>200% increase above the control) on the Acrisol and Ferralsol. The reduced tillage options also provided generally significant yield gains. The only exception was observed in zero tillage combined with the use of a cover crop on Acrisol during the long rainy season where maize yield response was not significantly different from the control. Grain yield responses to green manure were stronger on the Nitisol than on the Acrisol or Ferralsol with 40 and 60% increments over the farmer practice in the long and short rainy seasons, respectively. Farmyard manure significantly increased maize grain yield at all sites but the effect was most pronounced (1.6 t ha^{-1} more than the control) on the Acrisol. Seed priming resulted in slight increases in maize grain yield that were significant only in some sites and seasons and the effects were generally less than with other management options. Clean weeding procured a significant increase above the control only during the long rainy season and on the Ferralsol. Irrespective of site and season, maize grain yield was consistently lowest in the control (less than 3 t ha^{-1}).

Table 3. Effects of management options on final biomass accumulation of maize variety HB 520 on a Nitisol, Acrisol and Ferralsol in Western Kenya. Trials were conducted in the short rainy season of 2008 and the long rainy season of 2009. Values are means of 4 replicates.

[a]Management option	Nitisol (t ha^{-1})		Acrisol (t ha^{-1})		Ferralsol (t ha^{-1})	
	[b]SR08	[c]LR09	SR08	LR09	SR08	LR09
FP (control)	5.4^{b}	7.9^{c}	2.3^{e}	3.1^{f}	2.1^{d}	2.0^{c}
CW	5.6^{b}	10.4^{b}	3.6^{d}	5.0^{de}	3.7^{c}	3.9^{b}
SP	5.7^{b}	10.5^{b}	3.7^{d}	6.1^{dc}	3.8^{c}	4.1^{b}
FYM	6.4^{b}	11.0^{b}	4.6^{c}	6.7^{bc}	4.4^{b}	5.0^{b}
GM	6.5^{b}	10.9^{b}	3.4^{d}	5.4^{de}	3.9^{bc}	4.8^{b}
ZANP	10.3^{a}	14.2^{a}	6.1^{b}	4.5^{e}	6.2^{a}	6.8^{a}
ZNP	10.1^{a}	16.0^{a}	7.0^{a}	7.9^{ab}	6.4^{a}	7.3^{a}
NP	10.2^{a}	16.1^{a}	7.1^{a}	8.7^{a}	6.5^{a}	7.7^{a}

Means in a column with the same letter are not significantly different by Tukey ($P<0.05$).

[a] FP=farmers' practice, CW=clean weeding, SP=seed priming, FYM=farmyard manure, GM=green manure, ZANP=zero tillage combined with a cover crop, ZNP=zero tillage combined with mineral fertilizer use, NP=mineral fertilizer.

[b] SR=Short rainy season (September-December).

[c] LR=long rainy season (March-July).

Effect of treatments on maize yield gaps

Maize yield gaps were slightly larger in the short than in the long rainy season. The yield gaps were 4.0-5.3 t ha^{-1}, 6.0-6.2 t ha^{-1} and 6.1-6.5 t ha^{-1} on the Nitisol, Acrisol and Ferralsol, respectively. The share of these yield gaps closed by management options differed widely with sites and season (Figure 2). Mineral fertilizer treatments were most effective in closing maize yield gaps across sites, with strongest effect (about 80%) observed on the Nitisol during the long rainy season. The reduced tillage options could close 25-60% of the yield gap on Acrisol and Ferralsol, with the exception of zero tillage combined with the use of a cover crop that performed poorly (less than 10%) on the Acrisol during the long rainy season. Farmyard manure showed strongest response (60%) in closing maize yield gap on the Nitisol and less (25-26%) on the Acrisol and Ferralsol (25%). Irrespective of the cropping season, green manure and seed priming performed better in closing maize yield gaps on Nitisol (18-65%) than in Acrisol and Ferralsol (less than 25%). Clean weeding was an effective measure to close the maize yield gap (17%) only on Ferralsol during the long rainy season and less so in the short rainy season and on the other sites where weed infestation was less.

Effect of treatments on nutrient uptake by maize

Nutrient N and P uptake by maize showed different trends across sites (Table 4). Generally, N uptake by maize followed the order Nitisol>Ferralsol>Acrisol while P uptake was in the order Nitisol> Acrisol>Ferralsol. The soil N supplying capacity (N uptake by maize in the no-input farmer practice) was about 25 kg N ha^{-1} on the Acrisol and Ferralsol and about four times higher on the Nitisol. The soil P supplying capacity was lowest on the Ferralsol (approximately 4 kg ha^{-1}) and highest on the Nitisol (approximately 15 kg ha^{-1}). Significant differences ($P<0.001$) in N and P uptake by maize were also observed among management options (Table 4). On the Nitisol, the application of mineral fertilizer stimulated highest nutrient uptake by maize with an increase of more than 100% in N uptake and 200% in P uptake over the control. Application of farmyard and green manure enhanced N uptake by 25-50% and P uptake by 30-75%. Seed priming and clean weeding significantly increased P uptake only in the long rainy season. On the Acrisol, all treatments significantly increased maize N and P uptake in both cropping seasons above that of the control (Table 4). However, the application of mineral fertilizer had the largest effect in all soil types (Table 4).

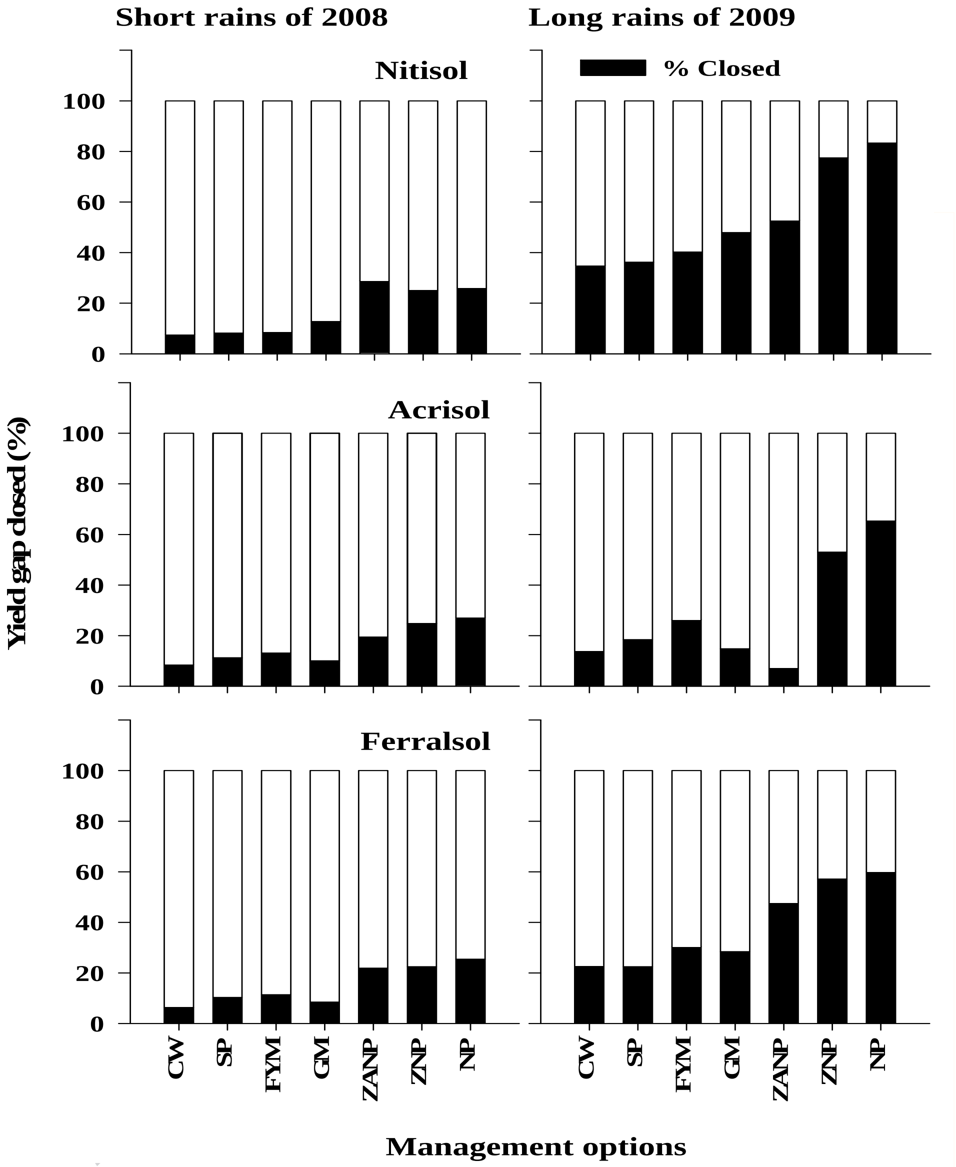

Figure 2. Percentages in maize (HB 520) yield gap closed by management options (MO) on three contrasting soil types in Western Kenya in the short rainy season of 2008 and the long rainy season of 2009. Yield gap closed=[(yield MO-control) / (yield Max-control)]×100. Values are means of 4 replicates. CW=clean weeding, SP=seed priming, FYM=farmyard manure, GM=green manure, ZANP=zero tillage combined with the use of a cover crop, ZNP=zero tillage combined with mineral fertilizer use, NP=mineral fertilizer.

Table 4. Effects of management options on the grain yield of maize variety HB 520 on a Nitisol, Acrisol and Ferralsol in Western Kenya. Trials were conducted in the short rainy season of 2008 and the long rainy season of 2009. Values are means of 4 replicates.

[a]Management option	Nitisol (t ha^{-1})		Acrisol (t ha^{-1})		Ferralsol (t ha^{-1})	
	[b]SR08	[c]LR09	SR08	LR09	SR08	LR09
FP (control)	1.7^{c}	3.0^{c}	0.8^{d}	1.0^{d}	0.9^{c}	0.5^{c}
CW	2.0^{c}	4.4^{b}	1.3^{c}	1.8^{bcd}	1.3^{bc}	2.0^{b}
SP	2.1^{c}	4.4^{b}	1.5^{c}	2.1^{bc}	1.5^{b}	2.0^{b}
FYM	2.2^{c}	4.6^{b}	1.6^{bc}	2.6^{b}	1.6^{b}	2.5^{b}
GM	2.4^{bc}	4.9^{b}	1.4^{c}	1.9^{bcd}	1.4^{bc}	2.3^{b}
ZANP	3.2^{a}	5.1^{b}	2.0^{ab}	1.4^{cd}	2.2^{a}	3.6^{a}
ZNP	3.0^{ab}	6.1^{a}	2.3^{a}	4.2^{a}	2.3^{a}	4.2^{a}
NP	3.1^{a}	6.3^{a}	2.5^{a}	4.9^{a}	2.4^{a}	4.4^{a}

Means in a column with the same letter are not significantly different by Tukey ($P<0.05$).

[a] FP=farmers' practice, CW=clean weeding, SP=seed priming, FYM=farmyard manure, GM=green manure, ZANP=zero tillage combined with a cover crop, ZNP=zero tillage combined with mineral fertilizer use, NP=mineral fertilizer.

[b] SR=Short rainy season (September-December).

[c] LR=long rainy season (March-July).

Effects of treatments on nutrient use efficiency of maize

Applied nutrients were generally used more efficiently in the long than in the short rainy season (Table 5). The only exception was in the zero tillage treatment on the Acrisol where the use of a cover crop negatively affected N and P use efficiency. Generally, the application of mineral fertilizer tended to enhance agronomic N use efficiency by 1 to 12 kg grain kg^{-1} above that observed with organic amendments (Table 5). On the Nitisol, green manure application led to the highest N use efficiency. Similarly, the agronomic P use efficiency was generally higher with organic amendments (39-154 kg grain kg^{-1}) than with mineral fertilizer (12-39 kg grain kg^{-1}), regardless of site and season. The physiological use efficiencies followed similar trends across sites (Table 5), whereby N showed the largest response with mineral fertilizer treatments (50-167%) and P with organic amendments (14 to 119 %).

Table 5. Total nitrogen (N) and phosphorus (P) uptake by maize variety HB 520 as affected by management options on a Nitisol, Acrisol and Ferralsol in Western Kenya. Trials were conducted during the short rainy season of 2008 and the long rainy season of 2009. Values are means of 4 replicates.

Soil type	[a]Management option	N uptake (kg ha^{-1})		P uptake (kg ha^{-1})	
		[b]SR 08	[c]LR 09	SR 08	LR 09
Nitisol	FP	81.7^{c}	106.3^{d}	14.8^{d}	20.6^{d}
	CW	84.5^{c}	139.1^{c}	15.3^{cd}	27.0^{d}
	SP	86.0^{c}	141.3^{c}	17.5^{bcd}	34.7^{c}
	FYM	110.0^{b}	158.1^{c}	19.8^{bc}	35.9^{c}
	GM	102.8^{bc}	159.0^{c}	21.6^{b}	41.1^{c}
	ZANP	173.1^{a}	232.3^{b}	39.3^{a}	62.3^{b}
	ZNP	187.2^{a}	273.1^{a}	38.8^{a}	73.0^{a}
	NP	192.2^{a}	268.3^{a}	39.0^{a}	72.7^{a}
Acrisol	FP	21.4^{e}	27.8^{d}	5.47^{f}	7.1^{c}
	CW	33.0^{d}	44.5^{c}	8.4^{e}	11.3^{c}
	SP	34.7^{d}	54.4^{bc}	10.6^{d}	18.5^{b}
	FYM	45.3^{c}	66.1^{b}	12.9^{c}	20.3^{b}
	GM	33.4^{d}	52.0^{c}	10.2^{de}	17.7^{b}
	ZANP	61.7^{b}	44.5^{c}	19.2^{b}	17.9^{b}
	ZNP	78.1^{a}	113.1^{a}	22.4^{a}	31.1^{a}
	NP	78.7^{a}	121.4^{a}	23.6^{a}	35.4^{a}
Ferralsol	FP	24.6^{e}	23.0^{d}	5.0^{c}	4.3^{c}
	CW	43.6^{d}	44.0^{cd}	8.9^{b}	11.7^{b}
	SP	44.0^{d}	45.4^{cd}	9.5^{b}	12.1^{b}
	FYM	51.3^{c}	73.1^{c}	11.1^{b}	14.7^{b}
	GM	45.2^{cd}	67.2^{c}	10.4^{b}	15.4^{b}
	ZANP	93.6^{b}	116.3^{b}	18.5^{a}	24.1^{a}
	ZNP	95.8^{a}	124.5^{a}	18.7^{a}	25.6^{a}
	NP	101.6^{a}	130.8^{a}	19.5^{a}	26.5^{a}

Means in a column with the same letter are not significantly different by Tukey ($P<0.05$).

[a] FP=farmers' practice, CW=clean weeding, SP=seed priming, FYM=farmyard manure, GM=green manure, ZANP=zero tillage combined with a cover crop, ZNP=zero tillage combined with mineral fertilizer use, NP=mineral fertilizer.

[b] SR=Short rainy season (September-December).

[c] LR=long rainy season (March-July).

Table 6. Effects of management options on the agronomic and physiological N and P use efficiencies of maize variety HB 520 on three contrasting soil types in Western Kenya. Nutrient use efficiency was calculated from applied N and P, nutrient N and P uptake and grain yield of maize during the short rainy season of 2008 and the long rainy season of 2009. Values are means of 4 replicates.

Soil type	[c]Management option	[a]A-NUE (kg kg^{-1})		A-PUE (kg kg^{-1})		[b]P-NUE (%)		P-PUE (%)	
		[d]SR08	[e]LR09	SR08	LR09	SR08	LR09	SR08	LR09
Nitisol	FYM	8	27	39	123	47	86	38	119
	GM	17	35	21	56	50	96	20	60
	ZANP	15	21	15	21	91	126	25	42
	ZNP	13	31	13	31	105	167	24	53
	NP	14	33	14	33	110	162	24	52
Acrisol	FYM	13	27	62	123	40	64	57	102
	GM	16	17	18	26	32	47	14	30
	ZANP	12	4	12	4	40	17	14	11
	ZNP	15	32	15	32	57	85	17	24
	NP	17	39	17	39	57	94	18	28
Ferralsol	FYM	12	33	54	154	44	93	46	80
	GM	15	36	15	53	62	95	16	33
	ZANP	13	31	13	31	69	99	13	20
	ZNP	14	37	14	37	71	107	14	21
	NP	15	39	15	39	77	113	15	22

[a] Agronomic N / P use efficiency (A-NUE/A-PUE)=[(kg of grain yield increase over control)/(kg of N or P applied)].

[b] Physiological N / P use efficiency (P-NUE/P-PUE)=[(kg of N uptake over control)/(kg of nutrient applied)] × 100.

[c] FP=farmers' practice, CW=clean weeding, SP=seed priming, FYM=farmyard manure, GM=green manure, ZANP=zero tillage combined with a cover crop, ZNP=zero tillage combined with mineral fertilizer use, NP=mineral fertilizer.

[d] SR=Short rainy season (September-December).

[e] LR=long rainy season (March-July).

Discussion

This study was conducted over two cropping seasons and thus provides only a short-term assessment of maize production and nutrient use efficiency in smallholder farming systems in Western Kenya. The assessment was facilitated by strong differences in the response due to the large diversity in biophysical conditions among the study sites. In general, soil physical and chemical properties, agronomic management and seasonal rainfall availability are key factors regulating crop productivity and nutrient use efficiency in smallholder farming systems (Liu and Wiatrak, 2011; Tittonell et al., 2007).

Soil type effects

Soils differ in their chemical and physical properties that can influence moisture availability, nutrient supplying capacity and microbial activities (Brady and Weil, 2002). Soils with high inherent fertility are seen to positively affect maize production in smallholder farms (Ngome et al., 2011a; Vanlauwe et al., 2000). This is supported by the higher maize productivity and nutrient use efficiency observed on the Nitisol than on the Acrisol or Ferralsol in the current study. Whereas the experiment on the Nitisol was conducted on a research farm with a history of fertilizer application, field experiments on the Acrisol and Ferralsol were conducted in farmers' fields with lower inherent soil fertility. Furthermore, the Acrisol was sandy while the Nitisol and Ferralsol were clay soils. Sandy soils have a low water holding capacity (Brady and Weil, 2002) that can negatively influence maize performance especially where rainfall is variable with frequent short dry spells within cropping seasons (Barron and Okwach, 2005). Thus, in the cover crop treatment on Acrisol with relatively low organic matter content, the rainfall-related drought stress was exacerbated by the sandy soil texture that possibly also enhanced nutrient losses by leaching (Brady and Weil, 2002; Tisdale et al., 1993) as reflected in low N use efficiencies. These finding suggest a need to associate mineral fertilizer use with the addition of manure to increase crop productivity, particularly on the sandy soils in Western Kenya.

Crop management effects

Agronomic management options affect directly (or indirectly) the availability of nutrients. In smallholder farming systems in East Africa, nutrient deficiencies in croplands are wide-spread because of continuous cultivation without nutrient replenishment (Ngome et al., 2012; Okalebo et al., 2006). In the current study, the application of mineral fertilizer was observed to improve maize production across the study sites, as was also reported from other studies in Western Kenya (Anyanzwa et al., 2010; Kwabiah et al., 2003). Conversely, seed priming and green manuring appeared promising in closing the maize yield gap on the Nitisol than on the Acrisol or Ferralsol largely due to higher inherent fertility of the Nitisol. The poor performance of zero tillage combined with a cover crop in closing maize yield gaps on the Acrisol demonstrated that the technology appears not well adapted to sandy soils with low water-holding capacity, particularly when rainfall is low. Some scientists earlier observed that there is variability in crop response to zero tillage combined with a mulch (conservation agriculture), which is due to the interacting effects of soil, crop requirements and climate (Giller et al., 2009; Giller et al., 2011). These scientists further reported that the adoption by farmers of crop residues as mulch in parts of Africa is limited by other conflicting uses for crop residues such as feed for animals. In such environments, farmyard manure appears to be the most appropriate option for low income farmers to improve farm productivity.

Nutrient recovery and use efficiencies in croplands are affected by the quality and the timing of application of organic and mineral fertilizer (Barber, 1984; Cassman et al., 1996). While mineral nitrogen is immediately available for plant uptake, organic N requires mineralization by microorganisms (Barber, 1984). Mineral N in the current study was split applied, probably increasing the synchrony between maize N demand and N supply (Cassman et al., 1998). However, the high physiological N use efficiencies, particularly on Nitisol and Ferralsol, suggest that other N sources may have been exploited that were not considered in the current study. These sources may include (i) residual N from the previous maize crop and (ii) N supply from subsoil (Tisdale et al., 1993).

The high P use efficiencies of maize associated with the application of farmyard manure probably indicated that (i) the amount of P supplied by farmyard manure may not have been sufficient to meet crop demand (Wang et al., 2010) and (ii) that P was possibly made available from sorption/ fixation sites following the application of organic amendments (Kwabiah et al., 2003), particularly on the acidic P-fixing Ferralsol. Conversely, a low P use efficiency in the mineral fertilizer treatments could indicate that the amount of P applied was exceeding the crop requirement, possibly leading to P accumulation in the soil (Tisdale et al., 1993).

Seasonal rainfall effects

Seasonal rainfall availability moderates the effectiveness of agronomic management options such as mineral fertilizer use, green manure and cover crop fallow technologies to enhance crop yields (Becker, 1999; Carsky et al., 2001; Ma et al., 2012). In Western Kenya, total rainfall is generally lower and more variable in the short than in the long rainy season (Jaetzold et al., 2006). This seasonal difference in rainfall possibly contributed to the higher maize yields observed in all treatments in the long rainy season, apart from the control in the Ferralsol where weed infestation largely reduced maize yields.

In the past, most farmers in Western Kenya planted maize only in the long rainy season and an occasional crop of beans or vegetables in the short rainy season. However, in response to the soaring demand for maize due to population pressure in Kenya, farmers in Western Kenya are now growing maize both in the long and in the short rainy seasons. As the amount of rainfall during the short rainy season is frequently insufficient to sustain maize growth, alternative strategies to supplement rainfall such as run-off water harvesting (Barron and Okwach, 2005) or water conservation by tied-ridging (Jensen et al., 2003) have been recommended for Western Kenya but their effectiveness may differ by soil type.

It may be concluded that the application of mineral fertilizer remains vital for increasing maize production, particularly in soils with low inherent fertility, while organic amendments appear promising on inherently fertile soils of Western Kenya. However, the addition of organic or mineral inputs should balance plant nutrient demand to avoid excess accumulation of nutrients or soil nutrient mining. As soil type and crop management differentially affected maize productivity and nutrient use efficiency, there is a need to target agricultural technologies to specific farm types to boost maize production particularly in smallholder farming systems of Western Kenya.

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