Nutrient Cycling in Agroecosystems (2006) 76:171–182
DOI: 10.1007/s10705-005-8314-1

Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya

B Vanlauwe[1,]*, P Tittonell[2] and J Mukalama[1]
*[1]Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), P.O. Box 30677, Nairobi, Kenya; [2]Plant Production Systems, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands; *Author for correspondence (e-mail: b.vanlauwe@cgiar.org; fax: +254-20-7224763)*

Received 21 January 2005; accepted in revised form 25 May 2005

Key words: Limiting nutrient trial, NPK application, Olsen-P, Soil fertility gradients

Abstract

Different fields within a farm have been observed to have different soil fertility status and this may affect the response of a maize crop to applied N, P, and K fertiliser. A limiting nutrient trial was carried out at six farms each, in three districts of Western Kenya. In each of the farms, the following treatments were laid out in three fields with different soil fertility status at different distances from the homestead (close, mid-distance, remote fields): no inputs, application of NPK, NP, NK, or PK fertiliser (urea, triple super phosphate, KCl) to maize. Total soil N decreased at all sites with distance to the homestead (from 1.30 to 1.06 g kg^{-1}), as did Olsen-P (from 10.5 to 2.3 mg kg^{-1}). Grain yields in the no-input control plots reflected this decrease in soil fertility status with distance to the homestead (from 2.59 to 1.59 t ha^{-1}). In the NPK treatments, however, this difference between field types disappeared (from 3.43 to 3.98 t ha^{-1}), indicating that N and P are the major limiting nutrients in the target areas. Response to applied N was related to the soil total N content in Aludeka and Shinyalu, but not in Emuhaia, probably related to the high use of partially decomposed organic inputs with limited N availability. Consequently, response to applied N decreased with distance to the homestead in Aludeka (from 0.95 kg kg^{-1} relative yield to 0.55 kg kg^{-1}) and Shinyalu (from 0.76 kg kg^{-1} to 0.47 kg kg^{-1}), but not in Emuhaia (from 0.75 kg kg^{-1} to 0.68 kg kg^{-1}). Response to applied P was related to the soil Olsen-P content at all sites. While for farms with a relatively high Olsen-P gradient, response to applied P decreased with distance to the homestead (from 0.99 kg kg^{-1} to 0.68 kg kg^{-1}), large variability in Olsen-P gradients across field types among farms within a specific site often masked clear differences in response to P between field types for a specific site. Clear scope for field-specific fertiliser recommendations exists, provided these are based on local soil knowledge and diagnosis. Scenario analysis, using farm-scale modelling tools, could assist in determining optimum allocation strategies of scarcely available fertiliser for maximum fertiliser use efficiency.

Introduction

Although regional and national estimates of nutrient balances are negative for all major nutrient in most of sub-Saharan Africa, large differences in nutrient balances can often be observed between fields within a farm – some field even showing positive balances, resulting in substantial differences in soil fertility status between those fields (Smaling et al. 2002). In a study in Burkina

Faso, West Africa, Prudencio (1993) observed a variation in soil C at farm level from 0.2 to 2.2% from the bush fields to the homestead fields, where different cropping patterns and frequencies of cultivation were generally observed in concentric rings around the village composed of household compounds (ring management system), resulting in concentric gradients with increasing soil fertility status near the village. Gradients in both soil fertility status and in soil nutrient balances have also been reported for 'village fields' and 'bush fields' in central Mali (Dembelé et al. 2000). Typically, smallholder farming systems in Uganda contain three enterprise areas (Woomer et al. 1998): 'outfields' cultivated in cereal-legume intercrops mainly intended for home consumption, 'infields' of market crops, and home sites where livestock are confined, manures and composts accumulated and kitchen gardens cultivated.

Although differences in soil fertility status among fields within a farm are common, less clear is their origin. Since in most of the examples given above, soil fertility tended to decrease with distance from the homestead, the term 'gradients' will be used hereafter. Possible causes underlying these fertility gradients at the farm level are differences in inherent soil properties due to a specific position in the landscape, referred to as soilscapes by Deckers (2002), distance to the homestead, or farmer-induced differences in management of the different fields. In Uganda, crop residues from the 'outfields' are harvested, fed to livestock and manures applied to crops intended for the market, resulting in nutrient mining of 'outfield' soils and the creation of characteristic patches, plots and fields of nutrient-deficient crops (Woomer et al. 1998). In a study in Central Kenya, Murage et al. (2000) reported differences in chemical and biological soil properties of productive and non-productive fields within a farm. Since clay and sand contents did not vary between soil categories in their study, they suggested that these differences in chemical and biological soil properties are not inherent but result from past soil management. Their findings reveal that farmers are more likely to allocate their limited organic resources and fertilisers to higher value crops in more productive areas of the farm than to attempt amelioration of fertility-depleted fields.

The highlands of western Kenya support one of the densest rural populations in the world, as a result of large initial settlements attracted by the originally fertile soils in the area. Population growth has led to gradual depletion of nutrients through export in crop products, leaching, and soil erosion, for which farmers have been unable to compensate via imported organic resources or mineral fertilisers (Shepherd and Soule, 1998). Tittonell et al. (2005a) observed on smallholder farms in Western Kenya that soil fertility indicators and nutrient concentrations varied quite consistently between different land quality classes, according to farmers' criteria. Partial N balances were negative in most fields of all farm types, except for the home gardens of the wealthiest farm types. Residue incorporation took place mainly in the home gardens followed by the close fields, however, the wealthiest farm types incorporated most of the crop residues in all fields. The use of organic fertilisers varied clearly for different field types and was strongly affected by distance from the homestead and type of crop.

Various soil fertility management options have been developed to tackle soil nutrient mining and restore the soil fertility status. Nowadays, there is general consensus, both in the research and development community dealing with soil fertility management, that improving soil fertility requires both mineral fertilisers and organic inputs (Vanlauwe et al. 2002a). However, while information on the soil fertility status of different fields within a farm is relatively abundant, information is scanty on the consequences of such soil fertility gradients for the efficiency of different soil fertility management options, in terms of crop yield increases and/or enhancement in soil fertility status, is scanty. Vanlauwe et al. (2000), for instance, reported varying response to P for different positions in the landscape in the Northern Guinea savanna of West-Africa.

The objectives of the current study were (i) to determine maize crop production as affected by differences in soil fertility status for different fields within a farm, (ii) to quantify field-specific responses to applied N, P, and K fertiliser, and (iii) to evaluate relationships between initial soil fertility characteristics and responses to fertiliser N, P, and K. The working hypothesis was that the initial soil fertility status has a significant impact on responses to fertiliser that is large enough to warrant inclusion of information on the soil fertility status in site-specific fertiliser recommendations.

Materials and methods

Target sites and selection of farms

The study was carried out in the Western Province of Kenya, in Emuhaia (0°4′ N; 34°38′ E), Shinyalu (0°12′ N; 34°48′ E), and Aludeka (0°35′ N; 34°19′ E) divisions, in Vihiga, Kakamega and Teso districts, respectively. A detailed description of the study area is given in Tittonell et al. (2005a). Here only the main characteristics are reported. Average annual rainfall is 1850 mm in Emuhaia, 2145 mm in Shinyalu, and 1463 mm in Aludeka, distributed over two cropping seasons: the long rains from March to July and the short rains from August to November. Average altitude is 1640 m asl for Emuhaia, 1820 masl for Shinyalu, and 1180 m asl for Aludeka, while average annual temperatures are 20.4 °C in Emuhaia, 20.8 °C in Shinyalu, and 22.2 °C in Aludeka. Average farm size is 0.7 ha in Emuhaia, 1.3 in Shinyalu, and 2.1 in Aludeka, with population density decreasing from 930 to 310 people km^{-2} in the same order. In Emuhaia and Shinyalu, most farms were concentrated on Nitisols and Ferralsols, whereas in Aludeka, farms were on Acrisols. While in Emuhaia and Shinyalu soil types varied between the crest, slope, and valleys positions in an indulating landscape, soil depth and texture were the main sources of biophysical variability within the farms of Aludeka, due to the relatively flat landscape. Soil organic C values varied between 10.5 and 12.9 g kg^{-1} in Emuhaia, between 17.2 and 18.5 g kg^{-1} in Shinyalu, and between 6.9 and 8.8 g kg^{-1} in Aludeka while pH in water varied between 5.1 and 6.1 in Emuhaia, between 5.2 and 5.7 in Shinyalu, and between 5.2 and 5.8 in Aludeka (Tittonell et al. 2005b). Topsoil silt + clay content varied between 497 and 531 g kg^{-1} in Emuhaia, between 762 and 788 g kg^{-1} in Shinyalu, and between 361 and 443 g kg^{-1} in Aludeka (Tittonell et al. 2005b).

In Emuhaia and Shinyalu the homestead was normally located in the uppermost part of the farm, near the roads that generally run along the top of the ridges in this heavily dissected landscape. Bananas and vegetables intercropped with pulses and cereals were grown around the house. In some farms of Shinyalu, the homestead had been moved to a different place within the farm after about 10 to 15 years, to make use of the accumulated fertility by growing crops. In Aludeka, the homestead was often placed in the centre of the farm and surrounded by banana plants and fruit trees. Maize and groundnuts tended to be grown nearer the house, while cassava and finger millet were mainly found in further fields. In the few farms with cattle, the animals were kept in a boma (stall) during the night (Tittonell et al. 2005a).

In each division, six farms were chosen to include farmers from different social status or resource endowment (two with high, medium, and low access to resources) and gender (Table 1). Farm size of the selected farms varied between 0.4 and 5.0 ha across the divisions and farms contained between 4 and 14 primary production units (PPU) or fields that are usually managed in a uniform way. For most of the farms selected, resource flow analysis, farm transects and soil profile observations, geo-referenced soil sampling and analysis, maize yield estimates, and farmers' classification of soil fertility status were done previously (Tittonell et al. 2005a, b). A third requisite for farm selection was related to securing the results of the experiments, by choosing highly motivated farmers for collaboration in implementing and evaluating the experiments.

Treatment structure and trial implementation

In each of the farms, 3 fields (close field, mid-distance field, remote field) were chosen at different distances to the homestead, from all primary production units (PPU) within a farm (Table 1). The criterion of Relative Distance from the Homestead (RDH) related the absolute distance between the PPU and the homestead to the average distance between the furthest fields and the homestead. RDH was used to distinguish field types (RDH's = 0.1–0.3; 0.3–0.6; 0.6–1.0, respectively – Tittonell et al. 2005b), together with the results of resource flow analysis that revealed different patterns of resource allocation and intensity of input use in those fields. Farmers' opinion on the soil fertility status of the different fields was also solicited while choosing fields to be used. Homegardens were excluded as in these fields maize usually grows in association with cassava, sugar cane or banana, quite often in competition with other garden crops. Fields with strong

Table 1. Selected characteristics of the households used in the current study.

Division	Farmer	Gender	Typology[a]	Farm size (ha)	PPU[b] Number
Emuhaia	Joash Mukora	Male	4	0.4	6
	Jairus Lusuli	Male	2	1.4	4
	Sarah Mukabi	Female	3	0.9	5
	Sophia Agoi	Female	5	0.8	4
	Dorcas Nakaya	Male	3	0.7	4
	Refa Oluchina	Female	2	2.7	8
Aludeka	Joseph Ebu	Male	1	1.3	8
	John Obonyo	Male	4	0.7	6
	Kefina Ikaselon	Female	5	0.5	5
	Lazaro Osirom	Male	5	0.9	8
	Joseph Ochudi	Male	3	2.5	8
	Ernest Okitwi	Male	2	5.0	14
Shinyalu	Jane Nyerere	Female	5	0.5	6
	Alpine Shibonje	Male	2	3.0	13
	Lucia Khaukani	Female	5	1.4	8
	Peter Shivayanga	Male	3	2.1	11
	Elphas Lichalus	Male	4	0.9	5
	Rose Analo	Female	2	1.6	5

Data adapted from Tittonell et al. (2005a).

[a] Farmer typologies were defined based on the occurrence of specific production units and availability of labour and off-farm income (Tittonell et al. 2005a). Overall resource endowment of the farmers tends to decrease with increasing typology number.

[b] 'PPU' means 'primary production unit'. A PPU is a crop activity consisting of one or various crops grown deliberately in one field within the farm, taking place over a specific period of time, and managed in a similar way. At the study sites, PPUs are often delineated by hedges or terraces.

impediments (e.g., steep sloops, shallow soils, lots of shade) were also avoided, as were fields that were too remote from the homestead (i.e. difficult to access due to topography or isolated, far from the homestead and prone to theft) and/or difficult to keep under controlled conditions (e.g. unfenced fields prone to be grazed by cattle).

In each of the fields, 5 treatments were laid out on plots of 4.5 by 2.25 m, following a one-farm one-replicate design: a no-input control, a fully fertilised treatment (100 kg N ha^{-1}, 100 kg P ha^{-1}, and 100 kg K ha^{-1}), and three treatments with one of the major nutrients (N, P, or K) missing. Fertilisers were applied as urea, triple super phosphate, and muriate of potash. Between 6 and 14 September during the short rains of 2002, maize (variety Hybrid HB513) was planted at a distance of 75 cm between the rows and 25 cm within the rows and thinned to one plant per hill, about 3 weeks after germination. One third of the N fertiliser and the P and K fertilisers were applied broadcast on the entire plot and incorporated before planting. The plots were hoe-weeded three times during the growing season. At the 5th week after planting, two thirds of the N fertiliser was top dressed by banding urea in the rows of maize. At the same time, insecticide (Bulldock 025EC, granular, active ingredient 25 g l^{-1} beta-cyfluthrin) was applied in the funnels of the maize leaves to control maize stemborer. Whenever a termite attack was visible, insecticide (Gladiator 4TC, liquid, active ingredient 480 g l^{-1} chlorpyrifos) was applied at the base of the maize plants to control this damage. No moisture stress or excess rainfall occurred during the entire season at any of the sites.

Measurements and chemical analyses

Topsoil (0–15 cm) samples were taken with an auger at eight sampling points (4 on each diagonal) per field from the three fields chosen within each farm. Soil samples were air-dried, sieved through 2 mm, stored at room temperature, and analysed for total N and available Olsen-P following standard methods (Anderson and Ingram 1993). Maize was harvested at about 15 weeks after planting (between 23 December 2002 and 13 January 2003) from an area of 3 m by 0.75 m (1 line of 3 m long, containing 12 plants), excluding one border row on each site of the harvested area.

Maize ears and stover were weighed and subsampled. The sub-samples were dried (65 °C until constant weight) and the grains and inner cobs separated and weighed.

Mathematical and statistical analyses

The relative biomass yield in absence of a specific nutrient (N, P, or K) was calculated as:

$$RY_X = \frac{\text{Aboveground biomass in the treatment without application of } X}{\text{Aboveground biomass in the treatment with N, P, and K applied}} \quad (1)$$

In the above equation, X stands for N, P, or K. RY_X approaches 1 as the response to an applied nutrient X becomes 0.

In the statistical analysis, emphasis was put on overall field characteristics, rather than on differences between specific treatments. Initial soil total N and Olsen-P data, maize grain yields in the control treatment and in the treatment with NPK applied, and RY_X data were analysed using the MIXED procedure of SAS (SAS 1992) and standard errors of the difference (SED) were calculated using the LSMEANS (least square means) option. In the mixed model analysis, 'division', 'field type', and their interaction was used as a fixed factor and 'farm (division)' as a random factor, according to the following linear model:

$$\begin{aligned}\text{Observation}_{ijk} = {} & \text{Mean} + \text{Division}_i \\ & + \text{Field Type}_j + \text{Farm}_{ik} \\ & + \text{Residual}_{ijk} \qquad (2)\end{aligned}$$

with i the number of divisions (3), j the number of field types (3), and k the number of farms used (18).

Means were separated using the PDIFF option of the LSMEANS procedure. Simple regression was used to relate site-specific responses to initial soil total N and Olsen-P contents.

Results

Soil fertility status

Close fields had a significantly higher total N and Olsen-P content than the remote fields for all sites with values for the mid-distance fields falling in between (Table 2). For all field types, soil total N content followed the order: Shinyalu > Emuhaia > Aludeka, while differences in Olsen-P content between sites were not significantly different for all field types (Table 2). For the close fields, however, Olsen-P values varied much between farms at all sites (Aludeka: 1.8–25.1 mg kg^{-1}; Emuhaia: 2.8–29.8 mg kg^{-1}; Shinyalu: 2.6–24.8 mg kg^{-1}). Olsen-P values of the mid-distance and remote fields varied much less between farms. Farmer resource endowment (Table 1) was not observed to have a significant impact on the soil total N nor on the soil Olsen-P content (data not shown).

Maize yields

At the Aludeka and Shinyalu sites, maize grain yields in the control plots (without fertiliser inputs) were significantly larger (1.17–1.30 t ha^{-1}) in the close than in the remote fields (Figure 1a). Differences between the mid-distance and remote fields were not statistically significant. In Emuhaia, yields in the control plots were not significantly different between the different field types. Grain yields were lower in Shinyalu than in both other sites for all field types, but only significantly at the 10% level (Figure 1a). In the NPK treatments, maize grain yields were not significantly different between field types for all sites (Figure 1b). Yields in Aludeka were similar to yields in Emuhaia and significantly higher than in Shinyalu, although not always at the 5% level (Figure 1b).

RY_{N} was significantly lower than 1, indicating response to applied N, for all field types and sites, except for the close fields in Aludeka (Figure 2a). In Aludeka, RY_{N} was significantly higher in the close than in the other two fields, while in Shinyalu, the remote fields had a significantly lower RY_{N} than the other two field types. In Emuhaia, no differences in RY_{N} were observed between the field types. For the same field type, RY_{N} was not significantly different between sites (Figure 2a). RY_{P} was significantly lower than 1, indicating response to applied P, for all fields and sites, except

Table 2. Initial soil total N and Olsen-P content of the three field types.

Division	Field type	Total N (g kg^{-1})	Olsen-P (mg kg^{-1})
Emuhaia	Close fields	1.34	11.10
	Mid-distance fields	1.17	4.83
	Remote fields	1.10	1.72
Aludeka	Close fields	0.88	10.34
	Mid-distance fields	0.62	3.17
	Remote fields	0.62	2.80
Shinyalu	Close fields	1.67	10.05
	Mid-distance fields	1.56	3.80
	Remote field	1.47	2.46
SED(field)[a]		0.09	3.14
SED(site)[a]		0.11	3.40

[a] SED(field) is the Standard Error of the Difference to compare field type for the same division; SED(site) is the Standard Error of the Difference to compare divisions for the same field type.

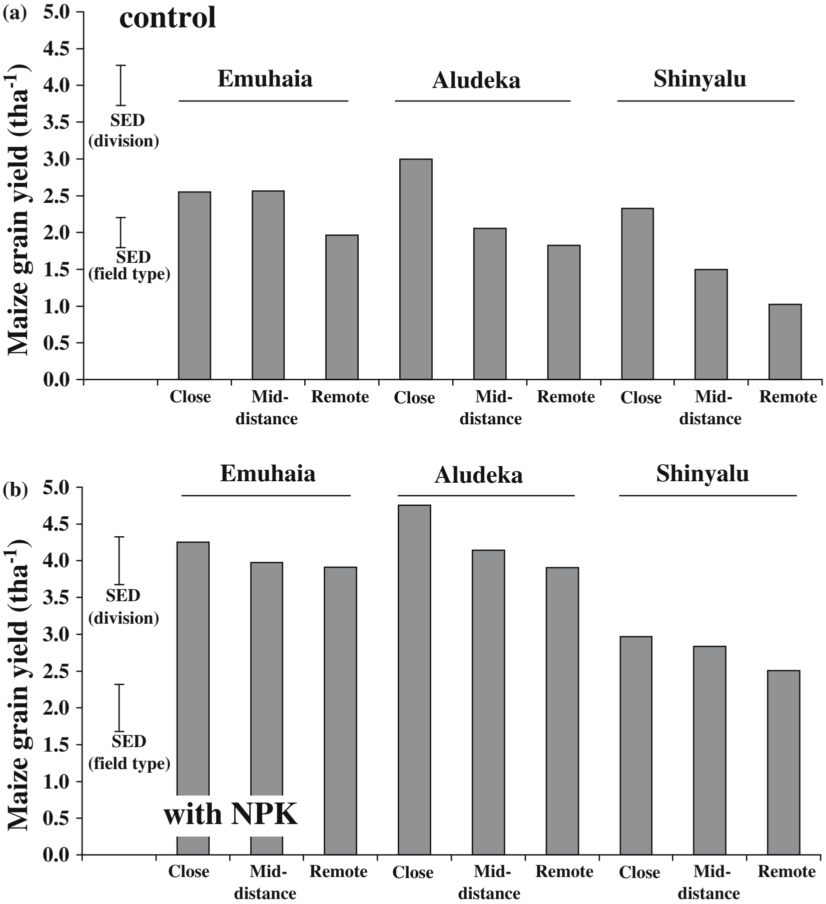

Figure 1. Grain yield in the no-input control plots (a) and in the plots with N, P, and K fertiliser added (b) for the different field types and divisions ($n = 6$). The error bars are Standard Errors of the Difference.

for the mid-distance fields in Emuhaia and the close fields in Shinyalu (Figure 2b). In Emuhaia, RY_P in the mid-distance fields was significantly higher than in the remote fields, while in Shinyalu, RY_P was significantly higher in the close than in the two other field types. In Aludeka, no

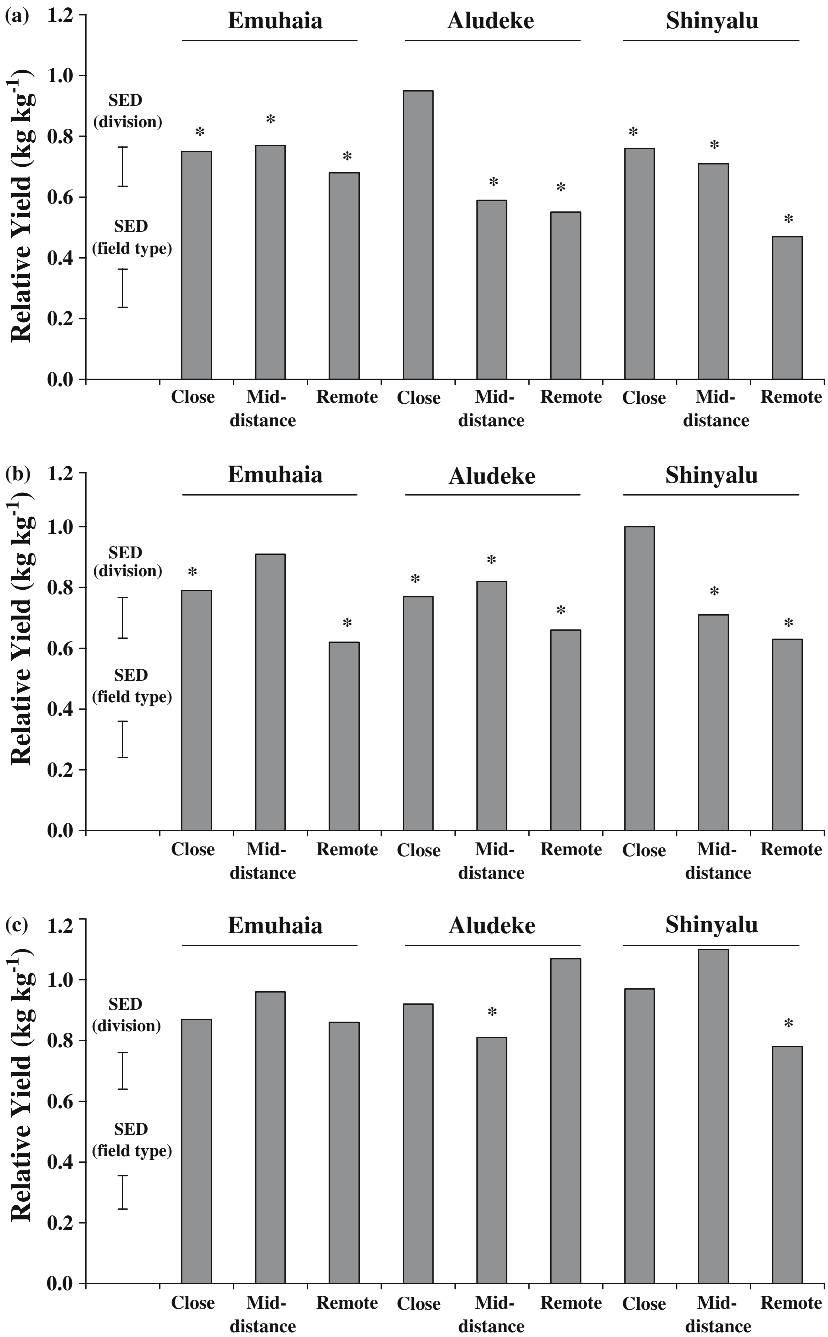

Figure 2. Relative total aboveground biomass yields in absence of N (a), P (b), and K (c) for the different field types and divisions (n = 6). 'SED' means 'Standard Error of the Difference'. Bars indicated with '*' are significantly different from 1 at the 5% level. The lowest bars indicate the strongest response to the missing element.

differences in RY_P between field types were observed. For the same field type, RY_P was not significantly different between sites (Figure 2b). When considering the farms with relatively large differences in Olsen-P content between the close and remote fields, the close fields had a significantly

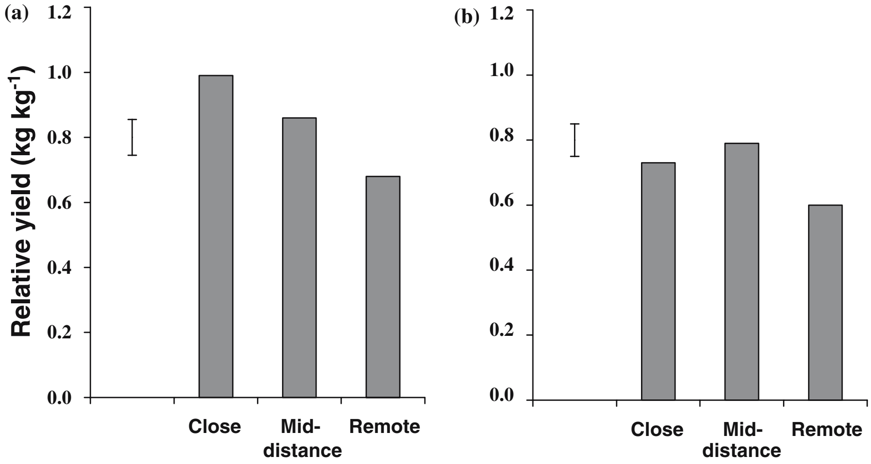

Figure 3. Relative total aboveground biomass yields in absence of P for the fields with the highest Olsen-P gradients across the three field types (difference in Olsen-P > 5 mg kg^{-1}) across the 3 sites (8 farms) (a) and those with the lowest Olsen-P gradients across the three field types (difference in Olsen-P < 5 mg kg^{-1}) across the three sites (10 farms) (b). The error bars are Standard Errors of the Difference.

larger RY_P than the other two field types (Figure 3a) while for the other farms, no differences in RY_P between field types were observed (Figure 3b). RY_K was significantly lower than 1, indicating response to applied K, only for the mid-distance fields in Aludeka and the remote fields in Shinyalu (Figure 2c). For the mid-distance fields, RY_K was significantly higher in Shinyalu then in Aludeka, while the reverse was true for the remote fields (Figure 2c).

Relationships between responses to applied nutrients and soil fertility status

RY_N was significantly related to the initial soil total N content in Aludeka and Shinyalu but not in Emuhaia (Figure 4a). For the same level of soil total N, RY_N was higher in Aludeka than in Shinyalu, indicating less response to applied N at Aludeka (Figure 4a). RY_P tended to reach a plateau for Olsen-P values above 8 mg kg^{-1} and to decrease with further increases in Olsen-P. No differences in relationships between RY_P and Olsen-P contents were observed between the three sites (Figure 4b). As most fields did not show response to applied K, no attempts were made to relate RY_K to the initial soil K status.

Discussion

Maize grain yield (Figure 1) and total biomass production (data not shown) in the absence of fertiliser inputs decreased with increasing distance to the homestead and related decreasing soil fertility status (Table 2) at all sites, although the decline in yields was less steep in Emuhaia. In Northern Nigeria, Carsky et al. (1998) equally observed that compound fields close to the homestead produced substantially larger amounts of maize than fields further away. Important to note is that the relative area of each of the field types is not equal for a specific farm, with the close fields with high soil fertility status often occupying only a marginal area of the total farm (Tittonell et al. 2005b). With NPK fertiliser additions, differences in maize grain yield between field types were smaller than for the control soils, indicating that low soil available N, P, and/or K are the most limiting factors to maize production. An implication is that different amounts of fertiliser inputs are needed to achieve similar yields on the different field types, indicating that the response to applied inputs or their agronomic use efficiency is likely to decrease with increasing soil fertility status. Using ^{15}N labelled urea under on-farm conditions in Southern Benin and Northern Nigeria, Vanlauwe et al. (2004) observed contrasting relationships

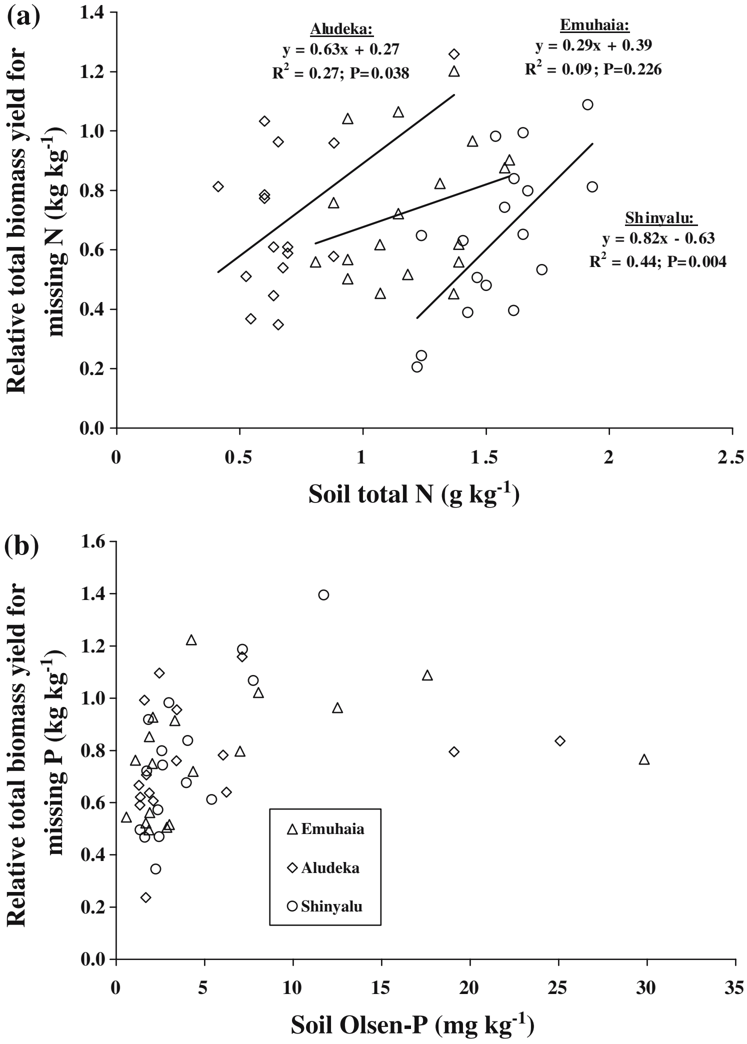

Figure 4. Relationships between relative yields without N and the initial soil total N content (a) and between the relative yields without P and the soil Olsen-P content (b). Y-axis values of 1 indicate no response to applied N or P fertiliser. The number of observations is 18 for Emuhaia (no missing values), 16 for Aludeka (2 missing values due to unrealistically low yields in the NPK treatment caused by within field variability), and 17 for Shinyalu (1 missing values due to crop failure caused by livestock browsing).

between N fertiliser recovery and the soil organic matter status of different fields at the two sites. While total recoveries of urea-N covered the same range in both areas (between 20 and 45%), in Benin, recovery of applied urea-N was positively related with soil organic C content while in Nigeria a negative relationship was observed. Although the reasons underlying these different trends were not clear, one could hypothesize that the major function of the soil organic matter pool in Benin was to alleviate one or more specific constraints to crop growth besides N, while in Nigeria, soil organic matter supplied N to the growing crop, in competition with the N fertiliser applied. In the latter case, N released from the soil organic matter pool may be better synchronized with plant demand for N than applied fertiliser N.

Zooming in on the specific lack of available N, P, and K across the different field types, the following could be observed: (i) most fields responded to applied N and P fertiliser, (ii), in Aludeka and Shinyalu, the response to applied N tended to increase with distance to the homestead (Figure 2a), and in Emuhaia and Shinyalu, this was also true for the response to applied P (Figure 2b), and (iii) response to applied K fertiliser was scarce at all sites, although not completely absent (Figure 2c). Shepherd et al. (1997) equally observed that N and P were the main limiting nutrients in food crop production in western Kenya. The increase in N response with distance from the homestead in Aludeka and Shinyalu, reflected in the decline in RY_{N}, was related to the decline in soil total N with distance from the homestead (Table 2, Figure 4a), although the relationship between both parameters only explained 27 to 44% of the variation. It is commonly known that total N or organic C are weak indicators for soil N availability although a wider range in soil total N values included usually results in a stronger correlation with crop yield (Carsky et al. 1998). The larger intercept for the Aludeka soils, compared with the Shinyalu soils (Figure 4a), reflected the higher soil clay and silt content in Shinyalu, resulting in stronger protection of the soil organic matter and lower N mineralisation potential (Vanlauwe et al. 2002b). The intermediate position of the Emuhaia points in Figure 4a reflects their intermediate clay and silt content and consequently intermediate protective capacity of the soil organic matter pool. The lack of correlation between crop dry matter production and soil total N content for the Emuhaia soils might be associated with the quality of the soil organic matter pool as the range in soil total N values between the close and the remote fields is similar (0.24 g kg^{-1}) as for the other two sites (0.20–0.26 g kg^{-1}). In Emuhaia, relatively more organic inputs are used, mostly in the form of compost and/or animal manure (2.9 t ha^{-1}, averaged across all farm types – Tittonell et al. 2005a) than in Shinyalu (0.3 t ha^{-1}) or in Aludeka (0.0 t ha^{-1}), and application rates decrease with distance to the homestead (Tittonell et al. 2005b). Such organic resources have undergone a decomposition phase, either in the rumen of cattle and/or in a compost heap, and their N is usually less available than fresh organic resources of a similar biochemical quality (Vanlauwe et al. 2002c), which form the likely bulk of inputs in the other sites through crop residues (roots, cereal stover, etc). Consequently, the differences in total soil N values between the three field types may represent in fact smaller differences in soil available N, compared to the other two sites, consequently resulting in less difference in response to N applied between the three field types.

Due to the high variability in Olsen-P of the close fields, differences in Olsen-P among fields within a farm varied widely at all sites, potentially masking some of the impacts of field type on P response. When considering all farms, in farms with relatively high Olsen-P gradients, clear differences in P response between fields were observed and close fields were observed to be non-responsive to P (Figure 3a). The relatively low RY_{P} values for the close fields in Emuhaia and Aludeka (Figure 2b) reflect the declining trend in RY_{P} for Olsen-P values ranging from 10 to 30 mg kg^{-1} (Figure 4b). The reasons behind this trend are not clear and could be related to the occurrence of limitations in nutrients that react with soil and/or fertiliser P, e.g., Zn. As for K, continuous cultivation and consequent extraction of available K from the soil reserves may induce K deficiencies in the medium to long term, especially in areas with relatively low base cation status. Shepherd et al. (1997) equally observed that N and P were the main limiting nutrients in food crop production in western Kenya, although K deficiencies were locally important.

Our findings highlight the need, in areas where management has induced often substantial differences in soil fertility status among fields, for site-specific fertiliser recommendations, especially in sub-Saharan Africa, where fertiliser is either relatively expensive and/or scarce. In Western Kenya (Kitale), for instance, transport costs nearly double the cost of one bag of di-ammonium phosphate to about 17 USD a bag (IFDC 2003). However, in order to formulate site-specific recommendations, it will be essential to base the diagnostic part on local soil quality assessment schemes, as formal soil analysis currently is beyond the financial reach of most small-scale farmers. Fortunately, farmers are often aware of within-farm soil fertility gradients and use local terms for the different soil quality levels of their fields. According to Murage et al. (2000) farmer's criteria for distinguishing productive and non-productive fields include crop performance, ease of tillage, soil moisture retention, soil colour and presence of weeds and soil invertebrates. Tittonell et al. (2005b) showed agreement between farmers classification and soil fertility status and maize yields; and management intensity varied accordingly (e.g. planting date; fields with a higher fertility status were usually planted earlier than fields with lower fertility) from the fertile to the poor fields.

As farms in the target areas do contain fields with different soil fertility status and as this soil fertility status was shown to affect responses to applied fertiliser (mainly N and P), targeting of external inputs within this heterogeneity is a research question worth addressing. Due to the complexity of this question and the many potential combinations of management options, tools for evaluation of various scenarios will be required. An example of such farm-level modelling framework is the NUANCES (Nutrient Use in ANimal and Cropping systems – Efficiency and Scales) framework (Giller et al. 2005). The NUANCES modelling framework aims at analysing tradeoffs in technology adoption for mixed crop/livestock systems, which includes nutrients, labour and economic balances, and effects on environmental services. Scenarios could be evaluated under constant availability of resources, to assess whether alternative resource allocation strategies might result in enhanced resource use efficiency at the farm level, or under increased availability of resources, to derive optimum allocation strategies for these additional resources. The former exercise could be regarded as an evaluation of current farmer knowledge and practices while the latter exercise is likely to generate information beyond the current farmer knowledge.

Acknowledgements

We acknowledge the Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) for providing the necessary financial support in the framework of the project on ‘Improving integrated nutrient management practices on small-scale farms in Africa’. We also thank Isaac Ekise (TSBF) and Walter Munyuere (Kenya Rural Extension Service) for their skilled assistance with the field activities. Helen Wangechi and Wilson Ngului are acknowledged for the laboratory analyses.

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