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ORIGINAL ARTICLE

Nitrogen and phosphorus capture and recovery efficiencies, and crop responses to a range of soil fertility management strategies in sub-Saharan Africa

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Abstract This paper examines a number of agronomic field experiments in different regions of sub-Saharan Africa to assess the associated variability in the efficiencies with which applied and available nutrients are taken up by crops under a wide range of management and environmental conditions. We consider N and P capture efficiencies (NCE and PCE, kg uptake kg^{-1} nutrient availability), and N and P recovery efficiencies (NRE and PRE, kg uptake kg^{-1} nutrient added). The analyzed cropping systems employed different soil fertility management practices that included (1) N and P mineral fertilizers (as sole or their combinations) (2) cattle manure composted then applied or applied directly to fields through animal corralling, and legume based systems separated into (3) improved fallows/cover crops-cereal sequences, and (4) grain legume-cereal rotations. Crop responses to added nutrients varied widely, which is a logical consequence of the wide diversity in the balance of production resources across regions from arid through wet tropics, coupled with an equally large array of management practices and inter-season variability. The NCE ranged from 0.05 to 0.98 kg kg^{-1} for the different systems (NP fertilizers, 0.16–0.98; fallow/cover crops, 0.05–0.75; animal manure, 0.10–0.74 kg kg^{-1}), while PCE ranged from 0.09 to 0.71 kg kg^{-1}, depending on soil conditions. The respective NREs averaged 0.38, 0.23 and 0.25 kg kg^{-1}. Cases were found where NREs were >1 for mineral fertilizers or negative when poor

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quality manure immobilized soil N, while response to P was in many cases poor due to P fixation by soils. Other than good agronomy, it was apparent that flexible systems of fertilization that vary N input according to the current seasonal rainfall pattern offer opportunities for high resource capture and recovery efficiencies in semi-arid areas. We suggest the use of cropping systems modeling approaches to hasten the understanding of Africa's complex cropping systems.

Keywords Nutrient use efficiency · Sub-Saharan Africa · Nutrient mining · Fertilizers · Manure · Legumes · Cropping systems modeling

Introduction

Soils with poor nutrient contents, particularly of N and P, are widespread in sub-Saharan Africa (SSA), and this has been widely recognized as one of the pivotal causes of poor agricultural productivity. Compared to other parts of the world were agricultural green revolutions have been stimulated by mechanization and high fertilizer use, SSA soil nutrient balances remain largely negative (Smaling et al. 1997). Where nutrients are applied, albeit often in small doses, their capture and utilization by crops has been poor largely due to nutrient imbalances (Kho 2000). It is well established that efficient nutrient recovery by crops is a function of a multitude of factors that should be in a balanced state (Janssen 1998). Recovery efficiencies of added nutrients depend on soil and plant characteristics, crop management, fertilizer dosage and timing, and season quality. For example, while crop rooting density requirements to remove nitrate from soil is small in relation to that required for less mobile nutrients such as P, nitrate not taken up may be quickly lost through leaching in sandy soils during periods of high rainfall when residence time is short (Cadisch et al. 2004; Chikowo et al. 2003). On the other hand, P availability is often heavily restricted by the iron and aluminum oxides which are common in highly weathered tropical soils (e.g. Vanlauwe et al. 2002; Sanchez et al. 1997). These are the some of the many difficult scenarios that resource-constrained smallholder farmers in Africa have to grapple with in their production systems.

Short-range spatial variability in soils commonly exist within and between farms due to localized differences in parent material and/or management (Tittonell et al. 2005; Mtambanengwe and Mapfumo 2005; Samaké et al. 2006), with major implications on water and nutrient use efficiency. In most cases fields that are poor in N and/or P will give poor returns even when these nutrients are amply supplied through fertilizers, as there would be other nutrients limiting production, beyond N and P (e.g. Vanlauwe et al. 2005; Wopereis et al. 2006; Zingore et al. 2007). Therefore, any fertilization strategy that seeks to optimize resource use efficiency by crops has to recognize the important role of the inherent and distinct capacity of different soils to supply nutrients to the crops.

In the face of limited external resources, the question of how to efficiently target the available nutrients on the farms in a continuum of circumstances becomes critical (Giller et al. 2006). Therefore, a key objective of this study was to analyze nutrient use management options in SSA agriculture and obtain insights on the associated nutrient use efficiencies, a vital step for magnifying cropping systems or system components that offer opportunities for intensification. We illustrate the performance of different cropping systems in the different regions of SSA using data from key publications based on field experiments spanning over the past two decades. The various data in the publications were re-analyzed, taking into account the indigenous nutrient supplying (INS) capacity of the soils, and the fertilizers and organic amendments added to estimate N and P availability and associated nutrient capture efficiencies.

Description of database and data computation

Literature searches were done on various electronic library platforms using key words such as nitrogen, phosphorus or nutrient use efficiency. Relevant articles published from 1990 to date were reviewed and those based on field experiments in SSA were identified. This involved a large array of cropping systems that managed soil fertility in equally varied approaches. The principal cereal crop is maize, but there is a significant component of the small grains (millet and sorghum) in the semi-arid parts of southern Africa and the Sahelian region, and upland and lowland rice in West Africa.

Throughout this study we make reference to two slightly different nutrient use efficiency terms: (1) N and P capture efficiency (NCE or PCE, respectively, for N and P) as the amount of nutrient captured per unit of nutrient availability, and (2) N and P recovery efficiency (NRE or PRE) as the amount of nutrient recovered per unit added through the different fertilization strategies. To compute NCE for the different experiments, N availability was taken as the sum of the external N supply through mineral or organic fertilizers and the indigenous soil N supply.

$$\text{i.e. NCE} = \text{Crop N uptake}/(\text{externally supplied N} + \text{indigenous soil N supply}).$$

Indigenous soil supply of N was estimated from data on N uptake from a treatment in which all other nutrients were amply supplied except for N. Similarly, the indigenous soil P supply was estimated from P uptake in plots where other nutrients had been amply supplied except P. To be included in the database, it was desirable, though not strictly necessary, that the trials contained treatments that resemble this description. Where the treatments were such that this information could not be extracted easily, the soil organic carbon (SOC) content was used to estimate potential N or P availability through mineralization using the transfer functions used in the model QUEFTS, that were derived from experimental data from East Africa (Janssen et al. 1990). In cases where the authors did not provide information on nutrient uptake we assumed an internal N conversion efficiency of 55 kg grain (kg N uptake)$^{-1}$, a value slightly higher than the intermediate between the physiologically possible maximal dilution and maximal concentrations for maize (Janssen et al. 1990). Estimations for other crops were done using their respective average internal N efficiencies, 35 kg kg^{-1} for millet and sorghum, and 55 kg kg^{-1} for rice, given from an extensive review by van Duivenbooden et al. (1996).

Results and discussion

The database

Restricting our scope to SSA excluded a large volume of information on N and P use efficiencies available worldwide. A lot of set backs were encountered during literature retrieval, as many authors only provided information just enough to meet their immediate objectives. As a result many potentially useful articles could not be included in our database. An overview of the literature data grouped into crop responses to N and P fertilizers, legume cover crop/fallow and manure presented as summary statistics reveal the existence of broad ranges in nutrient availability and use efficiencies for the different cropping systems, with the indigenous soil N supply ranging from 10 to 91 kg ha^{-1} (Table 1). The number of experiments testing N fertilizers was considerably larger than for P or manure. When all data from experiments that involved N and P fertilizers with maize were pooled, it was clear that other than N availability, there were other important explanatory variables that explained N uptake (Fig. 1). The description of the cropping systems and of some of the key experiments that constitute the database is given in the following sections.

Capture and recovery efficiency of N and P from mineral sources for maize

A wide array of experiments with N and P fertilizers have been carried out both on-station and on-farm with equally varied responses (Tables 2, 3, 4, 5 and 6). In an experiment that was carried out over three seasons in Togo, Wopereis et al. (2006) reported responses of maize to N and P on farmers' fields that had received organic inputs for at least 10 years (infields) and those that did not (outfields). Being on the same soil type, the main difference between infields and outfields on an individual farm was SOC content. Averaged over three seasons at sole 100 kg ha^{-1} N application, NCE was significantly higher on infields compared to outfields (0.52 vs. 0.38 kg kg^{-1}). In a related experiment on degraded and non-degraded soils in Togo, Fofana et al. (2005) also demonstrated that NCE was always superior on a non-degraded soil. Significant improvements in the NRE of applied N and overall NCE on the degraded soil was only realized when N and P were simultaneously applied. Upon application of 40 kg P ha^{-1} on the degraded soil, NCE increased from 0.29 to 0.46 kg kg^{-1} at N rate of 50 kg ha^{-1}, and from 0.29 to 0.38 kg kg^{-1} at 100 kg N ha^{-1} N. As expected, NCE was lower at higher N application rate as N availability increased and its shortage relative to other production resources decreased. The data shows

Table 1 Soil N availability, maize yields, NCE, NRE and summary statistics of the variables for experiments that involved (a) NP fertilizers (b) improved fallows/cover crops and (c) animal manure, in sub-Saharan Africa

Variable/fertility management practice	*n*	Minimum	Maximum	Mean	Median	Standard deviation	Coefficient of variation
(a) NP fertilizers							
Indigenous soil N (kg ha^{-1})	41	10	91	34	30	18	54
Total N availability (kg ha^{-1})	86	13	191	94	100	49	52
Maize yields (Mg ha^{-1})	84	0.29	7.70	2.61	2.1	1.68	64
N uptake (kg ha^{-1})	85	6	136	53	44	32	61
NCE (kg kg^{-1})	64	0.16	0.98	0.53	0.52	0.19	35
NRE (kg kg^{-1})	58	0.05	1.00	0.38	0.35	0.22	56
(b) Improved fallow/cover crops							
Indigenous soil N (kg ha^{-1})	26	12	82	33	30	17	51
N availability (kg ha^{-1})	64	13	400	146	147	86	59
Maize yields (Mg ha^{-1})	69	0.30	8.20	2.14	1.92	1.47	68
N uptake (kg ha^{-1})	68	8	149	48	46	29	61
NCE (kg kg^{-1})	51	0.05	0.75	0.34	0.32	0.19	56
NRE (kg kg^{-1})	51	0	0.66	0.23	0.20	0.17	71
(c) Animal manure							
Indigenous soil N (kg ha^{-1})	10	15	70	36	31	19	54
N availability (kg ha^{-1})	21	25	433	132	115	103	78
Maize yields (Mg ha^{-1})	23	0.40	5.90	2.42	2.1	1.27	52
N uptake (kg ha^{-1})	23	8	107	46	37	26	58
NCE (kg kg^{-1})	15	0.10	0.74	0.37	0.35	0.20	53
NRE (kg kg^{-1})	15	0.0	0.65	0.25	0.19	0.19	77
(d) P relations							
Indigenous soil P (kg ha^{-1})	10	5	18	9	8.5	4.2	47
P availability (kg ha^{-1})	28	5.0	113	49	44	31	62
Maize yields (Mg ha^{-1})	32	0.50	8.4	3.06	2.0	2.3	77
P uptake (kg ha^{-1})	27	2.90	34.0	12.4	11.0	7.7	62
PCE (kg kg^{-1})	22	0.09	0.71	0.25	0.20	0.17	69
PRE (kg kg^{-1})	23	0	0.29	0.16	0.17	0.07	45

Summary statistics for P relations involving experiments with P fertilizers are shown in (d)

n number of publications on the data set

that N fertilization alone significantly increased P uptake by maize and that a moderate P rate of 20 kg ha^{-1} was sufficient for maximum P uptake.

Experiments with N fertilizers and rock phosphate in Mali resulted in NCE ranging between 0.33 and 0.50 kg kg^{-1} for maize over a 4-year period (Bationo et al. 1997; Table 4). In southern and eastern Tanzania, application of a large amount of P fertilizer (80 kg ha^{-1}) across sites with acid P-fixing soils resulted in NCE range of 0.16–0.42 kg kg^{-1} (Msolla et al. 2005). Across four sites, NCE ranged from 0.28 to 0.48 kg kg^{-1} with P fertilizer, and from 0.25 to 0.35 kg kg^{-1} when an equivalent amount of rock P was used. The highly P fixing soils responded poorly to N application, marginally increasing NCE from 0.10 kg kg^{-1} without P to 0.16 kg kg^{-1} when P was applied.

In an experiment that spanned over a 6-year period on two contrasting soils in Zimbabwe, NCE varied between 0.24 and 0.50 kg kg^{-1} on poor farmers' fields, compared with NCE ranging between 0.52 and 0.77 kg kg^{-1} at an on-station site (Waddington and Karingwindi 2001). Despite the annual addition of 18 kg ha^{-1} P, apparent recovery of applied N at on-farms sites was in some

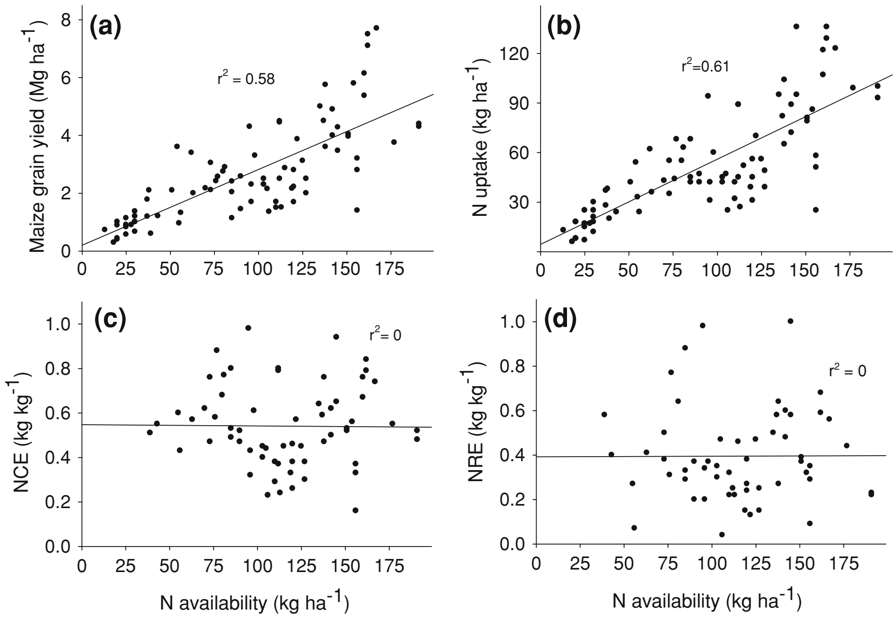

Fig. 1 The relationships between N availability and **a** maize grain yield **b** N uptake **c** N capture efficiency (NCE) and **d** N recovery efficiency (NRE) for experiments that involved N and P fertilizers

cases as low as 0.1 kg kg^{-1}, a scenario that has forced some croplands to be abandoned. This is considered as a classical example of little mileage gained when N and P fertilizers are added to a soil with multiple constraints that may include acute micronutrient deficiencies and soil acidity.

On an Alfisol and Oxisol in Nigeria, average NCE was 0.57 kg kg^{-1} when 45 kg ha^{-1} N and 12 kg ha^{-1} P were annually applied to maize fields over a 10-year period (Kang et al. 1999). Another long-term experiment on a Ferric Lixisol in the same region under ample P supply had average NRE of 0.32 kg kg^{-1} when 120 kg ha^{-1} N was applied, which increased to 0.68 kg kg^{-1} at a reduced N application rate of 60 kg ha^{-1} (Vanlauwe et al. 2005). Application of adequate N and P to five maize varieties in the moist savanna of Nigeria resulted in average NCE of 0.50 kg kg^{-1} and NRE of 0.30 kg kg^{-1} (Oikeh et al. 2003). In Cameroon, application of P fertilizer on two basaltic soils led to variable yield responses by maize (Osiname et al. 2000). Response to P was significant at both sites with grain yield increasing with P rates up to 88 kg ha^{-1} at one site, compared with no additional yield gains beyond an application rate of 22 kg ha^{-1} P at another site, in spite of the low soil P test. Large responses at low rates are encouraging, as it is possible for resource poor farmers to benefit from small amounts of fertilizer P, at the same time avoiding the degradation of soil P status through small maintenance fertilization rates.

In Kenya, Probert and Okalebo (1992) showed that under non-N limiting conditions and when extractable P was 8 μg g^{-1}, maize responded to P application but there was no significant difference between three P application rates (20, 40 and 60 kg ha^{-1}) or any tendency for the higher rates to give increased yields of maize. At application rates of 20 kg P ha^{-1}, PRE by maize averaged 0.14 kg kg^{-1} (Table 2). However, in a separate experiment where the same authors employed surface soil management through mulching and tied-ridging, there was a significant response to P inputs as high as 60 kg ha^{-1}. A plausible explanation for this could be that conservation measures resulted in more water retention and thus better root growth and exploitation of P. This is another example on resource interactions and the importance of balanced resource availability for increased resource use efficiency. In southern Malawi, farms usually stretch through three landscape positions, from steep eroded slopes through *dambo* margins to *dambo* valleys, with increasing fertility towards the valley. Phiri et al. (1999) studied the effect of landscape position on the utilization of fertilizer N, and got significantly higher NRE on the *dambo* and *dambo* margin positions (0.46 kg kg^{-1} N) compared with poor recovery (0.22 kg kg^{-1}) on the steep slopes.

Table 2 Indigenous soil P supply (IPS), total P availability, and estimated P capture and apparent recovery efficiencies for experiments that involved N and P fertilizers with maize and millet and rice

Treatment description (ha^{-1})	Soil conditions	IPS ($kg\ ha^{-1}$)	P availability ($kg\ ha^{-1}$)	Grain yields ($kg\ ha^{-1}$)	P uptake ($kg\ ha^{-1}$)	PCE ($kg\ kg^{-1}$ P)	PRE ($kg\ kg^{-1}$ P)	Country and region / climatic conditions	Reference
Maize									
40 kg P	Degraded, 0.4% C	10	50	0.50	3.60			Togo, coastal savana	Fofana et al. (2005)
50 kg Urea-N + 40 kg P			50	1.30	10.0	0.20	0.17		
100 kg Urea-N + 40 kg P			50	1.70	11.9	0.24	0.22		
60 kg N, 43 kg P	Clay, kaolinitic	7	50	1.01	10.1	0.21	0.12	Benin, west Africa	Saïdou et al. (2003)
100 kg P	Vertisols	13	113	3.60	13			Kenya	Sigunga et al. (2002)
100 kg NP			113	5.80	22	0.19	0.09		
100 kg NP + drainage			113	7.70	34	0.30	0.21		
Control	Sandy loam, 0.43% C	11	31	0.59	2.9			Kenya, semi arid	Probert and Okalebo (1992)
90 kg N				3.86	11				
90 kg N + 20 kg P				4.54	13.8	0.19	0.14		
Control (25 kg P)	Kaolinitic, P fixing	5	30	0.80	4	0.13	0	Kenya, humid tropics	Gachengo et al. (1999)
Senna spectabilis			15	1.50	6	0.4	0.2		
Tithonia diversifolia			22	2.00	9	0.41	0.29		
Senna + 25 kg P			40	2.00	8	0.2	0.11		
Tithonia + 25 kg P			47	3.20	12	0.26	0.19		
Millet									
60 kg P	Loamy sand, 0.26% C	7	67	0.90		0.1		Niger, semi arid	Kho (2000)
180 kg N, 60 kg P			67	1.34		0.12	0.19		
90 kg N, 30 kg P			37	1.20		0.2	0.23		
Rice									
100 kg N	Ultisol	5	5	0.75	5			Ivory coast, humid	Sahrawat et al. (1997)
100 kg N + 45 kg P	(Cultivar 1)		55	2.05	9	0.09	0.09		
100 kg N + 90 kg P			95	2.35	12	0.09	0.08		

Table 2 continued

Treatment description (ha^{-1})	Soil conditions	IPS ($kg\ ha^{-1}$)	P availability ($kg\ ha^{-1}$)	Grain yields ($kg\ ha^{-1}$)	P uptake ($kg\ ha^{-1}$)	PCE ($kg\ kg^{-1}$ P)	PRE ($kg\ kg^{-1}$ P)	Country and region / climatic conditions	Reference
100 kg N	(Cultivar 2)	5	5	1.07	5.5				
100 kg N + 45 kg P cv2			55	1.69	10	0.10	0.11		
100 kg N + 90 kg P			95	1.61	11	0.11	0.07		
20 kg P, 50 kg K	Alluvial Vertisols	10–38	44	4.0				Senegal, West Africa	Haefele and Wopereis (2005)
151 kg N 20 kg P			44	7.8			0.11		
151 N, 20 P, 50 kg K			44	8.4			0.18		
Control	Loamy, 0.4% C	18	18	1.80	6			Mauritania, Sahelian	van Asten et al. (2005)
175 kg N			18	5.00	18				
175 kg N, 13 kg P			31	5.60	22	0.71	0.29		
175 kg N, 26 kg P			44	6.10	24	0.55	0.21		
175 kg N, 26 kg P + straw			44	6.20	28	0.64	0.25		

WA west Africa, *EA* east Africa, *SA* southern Africa, *CA* central Africa

Table 3 Indigenous soil N supply (INS), total N availability, and estimated N capture and apparent recovery efficiency for experiments that involved manures, short term fallows, and NP fertilizers on rice in sub-Saharan Africa

Treatment description	General conditions	INS (kg ha^{-1})	N availability (kg ha^{-1})	Grain yields (Mg ha^{-1})	N uptake (kg ha^{-1})	NCE (kg kg^{-1})	NRE (kg kg^{-1})	Country	Reference
100 kg N	Ultisol	15	115	0.75	12	0.11		Ivory coast	Sahrawat et al. (1997)
100 kg N + 45 kg P	(WAB 56–125)		115	2.05	34	0.29	0.22		
100 kg N + 90 kg P			115	2.35	39	0.34	0.27		
100 kg N	(Local CV)		115	1.07	17	0.15			
100 kg N + 45 kg P cv2			115	1.69	28	0.24	0.11		
100 kg N + 90 kg P			115	1.61	26	0.22	0.10		
20 kg P, 50 kg K	Alluvial Vertisols	18–78	44	4.0				Niger	Haefele and Wopereis (2005)
151 kg N, 20 kg P			195	7.8	130	0.66	0.34		
151 N, 20 P, 50 kg K			195	8.4	140	0.71	0.41		
Weed fallow	Alfisol	10	10	0.32	6			Ivory coast	Becker and Johnson (1999)
81 kg Legume fallow[a]			19	1.01	17	0.16	0.12		
Control	Loamy, 0.4% C	39	39	1.80	21			Mauritania	van Asten et al. (2005)
175 kg N			214	5.00	78	0.36	0.32		
175 kg N, 13 kg P			214	5.60	94	0.43	0.41		
175 kg N, 26 kg P			214	6.10	94	0.43	0.41		
175 kg N, 26 kg P + straw			214	6.20	130	0.60	0.52		
Control	0.5% C	25	25	0.97	21			Sierra Leone	Bar et al. (2000)
60 kg N			85	1.33	29	0.35	0.14		
Sesbania rostrata fallow			119	1.36	30	0.25	0.10		
Sesbania + 30 kg N			150	2.14	47	0.31	0.21		

[a] Mean of five legumes (*Calopogonium*, *Canavalia*, *Centrosema*, *Mucuna*, *Pueraria*)

Table 4 Indigenous soil N supply (INS), total N availability, and estimated N capture and apparent recovery efficiencies for experiments that involved manures, short term fallows, and NP fertilizers on sorghum in sub-Saharan Africa

Treatment description	General conditions	INS (kg ha^{-1})	N availability (kg ha^{-1})	Grain yields (Mg ha^{-1})	N uptake (kg ha^{-1})	NCE (kg kg^{-1})	NRE (kg kg^{-1})	Country/ region	Reference
Control	Sandy loam	45	45	1.54	43			Niger	Zaongo et al. (1997)
Mulch			45	2.10	60				
50 kg N ha^{-1}			95	2.37	67	0.71	0.45		
50 kg N ha^{-1} + mulching			95	2.49	71	0.75	0.52		
Control		48	48	1.68	48	1.00		Uganda	Hagedorn et al. (1997)
112 kg N (Tephrosia)			160	1.87	53	0.33	0.04		
52 kg manure N			100	2.76	79	0.79	0.59		
Control (site 1)	Lixisol	33	33	1.16	33			Burkina Faso	Ouédraogo et al. (2001)
65 kg compost N (site 1)			98	1.68	48	0.49	0.23		
Control (site 2)	Ferric Lixisol	15	15	0.40	11				
130 kg compost N (site 2)			142	1.38	39	0.27	0.21		
Control	Average 0.7% C	28	35	0.86–1.04				Mali	Bationo et al. (1997)
7 kg N + 11 kg P				1.24–1.92	35–54	>1	>1		
12 kg N + 27 kg P rock phosphate				1.16–2.21	33–63	0.64–1.0	>0.5		
Control	Ferric Lixisol	35	31	1.10				Burkina Faso	Zougmoré et al. (2004)
50 kg Urea-N			81	2.10	60	0.74	0.58		
50 kg compost-N			81	2.27	65	0.80	0.68		
Control (year 2)		35	31	1.16	33	1.07			
50 kg Urea-N (year 2)			81	1.40	40	0.49	0.14		
50 kg compost-N (year 2)			81	2.38	68	0.84	0.70		
65 kg N + 10 kg P only	Ferric Lixisol (year 1)	30	95	1.12	32	0.33		Burkina Faso	Mando et al. (2005)
10 t cattle manure + 65 kg N + 10 kg P			205	2.53	72	0.35			
65 kg N + 10 kg P only	Ferric Lixisol (year 2)		95	0.62	18	0.19			

Table 4 continued

Treatment description	General conditions	INS (kg ha^{-1})	N availability (kg ha^{-1})	Grain yields (Mg ha^{-1})	N uptake (kg ha^{-1})	NCE (kg kg^{-1})	NRE (kg kg^{-1})	Country/ region	Reference
10 t cattle manure + 65 kg N + 10 kg P			205	2.35	67	0.32			
60 kg P	Loamy sand, 0.26% C	25	25	0.90	25			Niger	Kho (2000)
180 kg N, 60 kg P			205	1.34	43	0.32	0.19		
90 kg N, 30 kg P			115	1.20	30	0.31	0.23		
Control	Sandy	12	12	0.37	10			Niger	Rockström and de Rouw (1997)
5 t Manure			82	0.52	15	0.18	0.07		
30 kg N, 13 P kg P fertilizer			42	0.65	18	0.44	0.28		
13 kg N + 22 kg P fertilizer	Sandy (0.2–0.6% C)	20	33	0.41–0.97	11–27	0.48–0.78	0.33–0.47	Mali	Bationo et al. (1997)
23 kg N +27 kg P rock phosphate			43	0.35–0.96	10–27	0.28–0.64	0.05–0.41		
Control	Sandy, 0.13% C, low P	25	25	0.58	25			Niger	Sangaré et al. (2002)
3 t Low quality manure			83	0.88	37	0.45	0.21		
3 t High quality manure			98	0.92	39	0.39	0.19		
3 t Low quality manure + mulch			92	1.15	49	0.53	0.36		
3 t High quality manure + mulch			106	1.41	58.5	0.55	0.41		
Control (crest)	0.2% C, 85% sand	15	15	0.36	12			Niger	Brouwer and Powell (1998)
1.5 t manure (crest)			46	0.81	27	0.59	0.48		
8.5 t manure (crest)			183	0.97	32	0.18	0.12		
Control (concave)			15	0.24	8.1				
2.9 t manure (concave)			74	0.35	12	0.16	0.07		
Control	>90% sand (nitisols)	20	20	0.48	16			Niger	Gandah et al. (2003)
3.53 t manure			74	1.10	36	0.49	0.38		

A range indicates data is derived from multiple seasons

Table 5 Indigenous soil N supply (INS), total N availability, and estimated N capture and apparent recovery efficiencies for experiments that involved manures, short term fallows, and NP fertilizers on millet in sub-Saharan Africa

Treatment description	General conditions	INS (kg ha^{-1})	N availability (kg ha^{-1})	Grain yields (Mg ha^{-1})	N uptake (kg ha^{-1})	NCE (kg kg^{-1})	NRE (kg kg^{-1})	Country/ region	Reference
60 kg P	Loamy sand, 0.26% C	25	25	0.90	25			Niger	Kho (2000)
180 kg N, 60 kg P			205	1.34	43	0.32	0.19		
90 kg N, 30 kg P			115	1.20	30	0.31	0.23		
Control	Sandy	12	12	0.37	10			Niger	Rockström and de Rouw (1997)
5 t Manure			82	0.52	15	0.18	0.07		
30 kg N, 13 P kg P fertilizer			42	0.65	18	0.44	0.28		
13 kg N + 22 kg P fertilizer	Sandy (0.2–0.6% C)	20	33	0.41–0.97	11–27	0.48–0.78	0.33–0.47	Mali	Bationo et al. (1997)
23 kg N +27 kg P rock phosphate			43	0.35–0.96	10–27	0.28–0.64	0.05–0.41		
Control	Sandy, 0.13% C, low P	25	25	0.58	25			Niger	Sangaré et al. (2002)
3 t Low quality manure			83	0.88	37	0.45	0.21		
3 t High quality manure			98	0.92	39	0.39	0.19		
3 t Low quality manure + mulch			92	1.15	49	0.53	0.36		
3 t High quality manure + mulch			106	1.41	58.5	0.55	0.41		
Control (crest)	0.2% C, 85% sand	15	15	0.36	12			Niger	Brouwer and Powell (1998)
1.5 t manure (crest)			46	0.81	27	0.59	0.48		
8.5 t manure (crest)			183	0.97	32	0.18	0.12		
Control (concave)			15	0.24	8.1				
2.9 t manure (concave)			74	0.35	12	0.16	0.07		
Control	>90% sand (nitisols)	20	20	0.48	16			Niger	Gandah et al. (2003)
3.53 t manure			74	1.10	36	0.49	0.38		

A range indicates data is derived from multiple seasons

Table 6 Indigenous soil N supply (INS), total N availability, and estimated N capture and apparent recovery efficiencies by maize in experiments that involved manure application (with or without NP fertilizers) in sub Saharan Africa

Treatment description	General conditions	INS (kg ha^{-1})	N availability (kg ha^{-1})	Grain yields (Mg ha^{-1})	N uptake (kg ha^{-1})	NCE (kg kg^{-1})	NRE (kg kg^{-1})	Country	Reference
Control	Loamy sand	25	25	1.15	25			Zimbabwe	Nyamangara et al. (2003)
12 t manure			142	2.20	49	0.35	0.20		
12 t manure + 60 kg N			202	3.51	78	0.38	0.29		
37 t manure			373	3.19	71	0.19	0.13		
37 t manure + 60 kg N			433	4.05	90	0.20	0.15		
17 t manure	Poor sandy	15	148	0.40	15	0.10	0.08	Zimbabwe	Chikowo et al. (2004)
17 t manure + 40 kg N			188	1.60	25	0.13	0.12		
2 t manure	Degraded soil	18	58	1.40	34	0.58	0.40	Tanzania	Baijukya et al. (2006)
2 t manure + 50 kg N			108	2.30	63	0.58	0.50		
Control	Sandy loam	20		0.40	8			Mali	Kaya and Nair (2001)
10 t manure				1.12	20				
Control	Alfisol	30	30	1.58	25			Ethiopia	Lupwayi et al. (1999)
3 t manure			117	2.00	32	0.28	0.08		
40 kg N, 30 kg P			127	2.15	33	0.26	0.19		
Control (site 1)	Humic nitisols, acidic	69	69	2.30	42			Kenya	Smaling et al. (1992)
5 t manure			144	4.50	82	0.56	0.53		
Control (site 2)	Clayey, moderate fertility	70	70	3.20	58				
5 t manure			145	5.90	107	0.74	0.65		
Control (site 3)	Sandy loam, low NPK	32	32	1.60	29				
5 t manure			107	1.20	21	0.20	0		
Control	(Semi-arid)		37	1.78	37			Tanzania	Jensen et al. (2003)
7.5 t manure (site 1)	Sandy loam	37	104	2.17	44	0.42	0.10		
7.5 t manure (site 2)	Sandy	45	115	3.46	69	0.60	0.32		

Low-lying areas with Vertisols can constitute locally productive soils in otherwise largely unproductive areas. However, these soils are often not fully exploited due to excess water problems during periods of high rainfall, as their high content of expansive clays prevents the rapid drainage of excess water. Sigunga et al. (2002) investigated the effect of improved drainage on N and P utilization efficiencies on such soils using 0.4–0.6 m deep furrows. At 100 kg ha^{-1} N and P fertilizer application, drainage increased NCE from 0.56 to 0.74 kg kg^{-1} N and PRE from 0.09 to 0.21 kg kg^{-1} P (Table 2).

Capture and recovery efficiency of N and P with rice, millet and sorghum

Rice is an important crop in West Africa, with various alternatives currently being proposed towards its intensified production. Becker and Johnson (1999) investigated the role of several legume accessions on rice yields when grown for 6 months during the dry season, under a range of hydrological and soil conditions. Overall, legumes increased rice yields by 0.23 Mg ha^{-1}, while some five selected legumes raised rice yields from 0.32 to 1 Mg ha^{-1} (Table 3). In Mauritania, application of N fertilizer increased rice yields, and addition of straw had a positive effect, independent of fertilizer dose or soil type (van Asten et al. 2005). On neutral soils, NRE ranged from 0.32 kg kg^{-1} in the absence of P to 0.41 kg kg^{-1} when P was added, and further increased to 0.52 kg kg^{-1} in the presence of rice straw. On alkaline soils the NRE was lower and the range was 0.20–0.42 kg kg^{-1}. Recovery of P ranged between 0.1 and 0.35 on both alkaline and neutral soils, but was high and confined between 0.21 and 0.29 kg kg^{-1} on neutral soils (Table 2). Haefele and Wopereis (2005) demonstrated the significance of localized soil variability to nutrient use efficiency in rice on a 3 ha experimental farm. They reported NRE ranging from 0.34 to 0.41 kg kg^{-1} N, and PRE ranging from 0.11 to 0.19 kg kg^{-1} P, depending on K addition and the indigenous soil N or P supply. The suitability of *Sesbania rostrata* as green manure in combination with N fertilizer for lowland rice production was evaluated in Sierra Leone (Bar et al. 2000). Rice recovered 0.14 kg kg^{-1} N added as urea, while NCE was 0.35 kg kg^{-1}. Recovery of *Sesbania* N alone was 0.10 kg kg^{-1}, and overall recovery efficiency doubled when 30 kg urea-N was added as top dressing.

A summary of calculated capture and recovery efficiencies of N by millet and sorghum for various systems is presented in Tables 4 and 5. Among the important findings was that mulching alone significantly increased yields in dry environments. Millet and sorghum experiments with small doses of N fertilizers and rock phosphate in Mali resulted in NCE ranging between 0.05 and 0.41 kg kg^{-1} for millet and at least 0.50 kg kg^{-1} for sorghum over a 4-year period (Bationo et al. 1997). On a ferric Lixisol in Burkina Faso, Zougmoré et al. (2004) reported large sorghum yield increase from either urea or compost application in 1 year, with urea NRE of 0.58 kg kg^{-1}, but poor NRE of only 0.14 kg kg^{-1} for urea during the following season that was linked to in-season dry spells.

Capture and recovery efficiency of N from animal manure

Animal manure is an important resource on smallholder farms, as nutrients are concentrated from common rangelands. Animal ownership is therefore a strong determinant for farm SOC and N management. The potential and pitfalls for efficient utilization of N through crop-livestock systems have been recently reviewed (Rufino et al. 2006). We summarize results of experiments with manure in Table 6. Some early experiments with cattle manure in several agroecological zones in Kenya showed that maize response to manure application was different across sites (Smaling et al. 1992). At a site with P-fixing soils, manure was shown to be particularly effective in increasing maize yields, with application of 5 Mg ha^{-1} increasing yields from 2.3 to 4.5 Mg ha^{-1}. Contrasting results across sites were also found in Tanzania, where at one site NRE was only 0.1 kg kg^{-1} compared with 0.32 kg kg^{-1} at the other site, when 7.5 Mg manure of similar quality were applied to maize (Jensen et al. 2003). In Zimbabwe, NRE ranged between 0.15 and 0.29 kg kg^{-1} when manure was applied alone or in combination with N fertilizer (Nyamangara et al. 2003), while on a degraded sandy soil application of 17 Mg ha^{-1} poor quality manure alone could not supply sufficient nutrients to a maize crop (Chikowo et al. 2004). Mando et al. (2005) reported the long-term effects of tillage and manure application on sorghum in the Sudano-Sahelian conditions. The increase in yields was associated with increased N availability due to manure and greater water availability that improved the efficiency of use of the applied fertilizer.

Capture and recovery efficiency of N and P in fallow/cover crop-cereal crop sequences

Inputs of N from N_2-fixation in tropical cropping systems are limited by both the small proportion of legumes actually grown and by the restrictions placed on the fixation rate by drought and nutrient deficiencies (Giller 2001). Nitrogen cycling through leguminous shrubs has had mixed fortunes on many smallholder farms, with N recovery from organic materials on light textured soils found to be pitifully poor in some cases and promising in others (e.g. Chikowo et al. 2004; Mafongoya and Dzowela 1999; Mtambanengwe and Mapfumo 2006). Carsky et al. (1999) showed that many legumes accumulated large amounts of N, but there also were large N losses during the long dry season resulting in poor translation into improved rotational maize yields. In contrast to these results, Sanginga et al. (1996) estimated *Mucuna pruriens* N fertilizer replacement value of 120 kg N ha^{-1} in a derived savanna where the dry season is only 3 months long. So far, the general experience with the cover crops is that they have to be targeted on fields that are not yet extremely depleted and acidic, to be able to produce acceptable biomass of at least 2 Mg ha^{-1}.

In Kenya, Stahl et al. (2002) reported the contribution of 22-month fallows of *Sesbania* sesban and *Calliandra* on two subsequent maize crops. The immediate post-fallow maize crop suffered from drought, resulting in poor N recovery. During the more favorable second season, *Sesbania* more than doubled maize yields, with similar effects as 60 kg ha^{-1} fertilizer N. Nitrogen recovery efficiency with *Calliandra* was comparatively poor, in line with its low quality. In eastern Zambia, Kwesiga and Coe (1994) demonstrated that maize yields following 2-year *Sesbania* fallows were equivalent to application of 112 kg N ha^{-1}. Mafongoya and Dzowela (1999) also showed *Sesbania* as a promising improved fallow species on Alfisols in Zimbabwe, though research on sandy soils (Chikowo et al. 2004) indicated that *Sesbania* produced very little biomass and was therefore unsuitable.

In western Kenya Gachengo et al. (1999) reported increased N uptake and NRE when the *Senna spectablis* or *Tithonia* where applied in combination with P fertilizer. Highest yields were obtained with *Tithonia* plus P fertilizer treatment. Overall, PRE ranged from 0.11 to 0.29 kg kg^{-1}. The range of plant materials with critical total P concentrations of 2.4 g kg^{-1} with the propensity to cause net P release is narrow and a soil fertility strategy that involves replenishing soil P with plant materials alone seems to be bound to failure in many African cropping systems (Kwabiah et al. 2003; Palm et al. 2001). When all data from experiments that involved improved fallows and cover crops were pooled, only a weak relationship between N availability and N uptake could be established, while a general tendency for reduced NRE with increased N availability existed (Fig. 2).

Resource capture and recovery efficiencies in grain legume-cereal rotations

Grain legumes fortify food security in many rural communities in SSA through strengthening sustainable production of cereals grown in sequence. For example, a review by Mpepereki et al. (2000) indicates that promiscuous soybean varieties with low N harvest indices have been successfully grown in rotation with maize over years by smallholder farmers in southern Africa. The benefits to the rotational cereal crop have also been demonstrated, e.g. Osunde et al. (2003) and Sanginga et al. (2002) in West Africa (Table 7). However, the reasons for the increased rotational maize yields are often not straight forwardly related to the N balances as a result of the legume N fixation. For example, in the Guinea savanna zone of Nigeria, Osunde et al. (2003) showed that despite a cumulative negative N balance of 147 kg N ha^{-1} after two successive cropping of soybean with stover exported, maize yields were at least 2 Mg ha^{-1} (45 kg ha^{-1} N uptake) compared with 0.5 Mg ha^{-1} (11 kg ha^{-1} N uptake) for the fallow plots (Table 7). Also, in the moist savanna, Sanginga et al. (1996, 2002) used five soyabean lines and investigated their residual effects on maize. Soybean net N input from fixation ranged from −8 to 43 kg ha^{-1} N, and the rotational effects on maize were all positive with soyabean N contribution

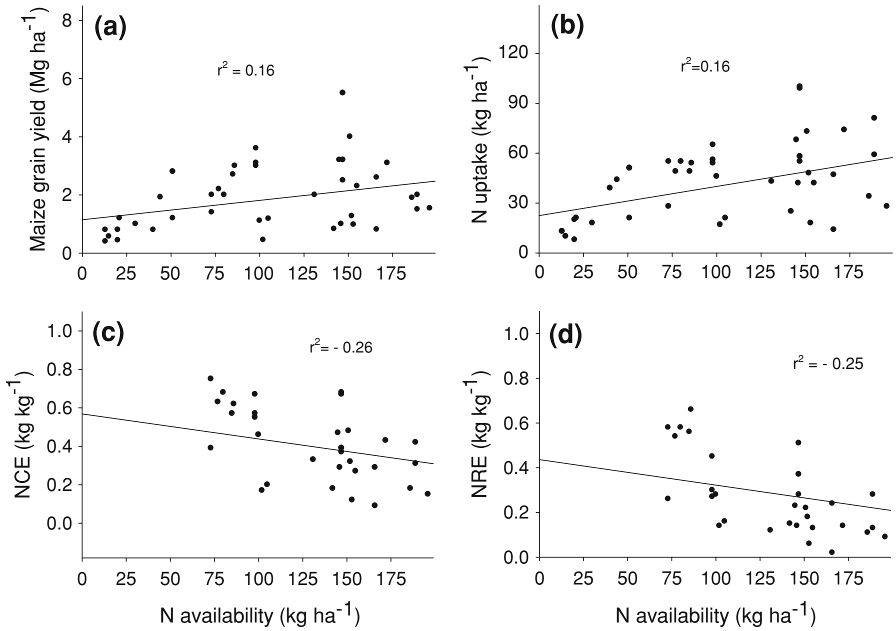

Fig. 2 The relationships between N availability and **a** maize grain yield **b** N uptake **c** N capture efficiency (NCE) and **d** N recovery efficiency (NRE) for experiments that involved improved fallows/ cover crops

to maize N uptake ranging from 16 to 27 kg ha^{-1} N, again in spite of net N depletion by one of the soybean lines. However, in Benin, Ogoke et al. (2003) showed that only modest positive N contributions of up to 10 kg ha^{-1} N are attainable in a soyabean-cereal cropping system, this only possible when the soybean variety is late maturing, some P is applied and all the soybean residues are retained in the field. In principle, N balances are often used to estimate potential impact on the in-coming crop, but there seems to be no direct link when grain legumes are involved. Therefore, an analysis of N capture efficiency by maize following grain legumes, based on estimated net-N contribution and N balance approach alone, is not sufficient as it fails to capture the other positive 'rotational effects' that result in increased maize yields in cases were N balances are negative. Other than open statements, we are yet to come across publications where the 'sparing effects' of grain legumes have been quantitatively given for different environments. An attempt towards this objective will be useful for the development of useful algorithms for modeling grain legume-cereal sequences.

Nutrient capture and soil water relations

Nitrogen and P utilization in experiments that span across several cropping seasons were found to be variable, and arguably one of the factors responsible for this variability is rainfall. A fragmented approach in which the focus is on single elements of the farming systems such as nutrient supply or soil and water conservation will likely fail to generate substantial impact in semi arid areas, where crop production is equally limited by soil water availability and nutrients. High water losses are associated with poorly managed soil surfaces in hot environments with high evaporative demand. For example, in rain-fed millet in West Africa, Wallace (2000) reported that soil evaporation losses constituted 30–45% of rainfall, runoff and drainage constituted 40–50%, while only 15–30% of the rainfall was available for transpiration. In fields where farmers establish sparse crop stands as a management strategy under poor fertility, evaporation losses are likely to be higher. Generally, the high runoff losses are a result of infrequent but intensive rainfall, and the tendency of sandy soils to form crusts with low infiltration rates. To manage variable rainfall environments, Piha (1993) devised and successfully tested a flexible system of fertilization, in which theoretically optimum rates of phosphorus, potassium and sulfur fertilizers are applied based on yield potential in an average rainfall season, while N is applied as a series of split applications, which are adjusted during the season according to the degree of water stress

Table 7 Estimated net N input from N_2-fixation, continuous or rotational cereal grain yields, total N uptake, and the legume contribution to maize N uptake for grain legume-cereal sequences in sub-Saharan Africa

Treatment description/crop sequences	General conditions	Net N input from N_2-fixation (kg ha^{-1})	Grain yields (Mg ha^{-1})	N uptake (kg ha^{-1})	Legume contribution to cereal N uptake (kg ha^{-1})	Country	Reference
Fallow	Guinea savanna		0.50	10		Nigeria	Osunde et al. (2003)
Soyabean (promiscuous)—maize		−65	2.10	38	28		
Soyabean (specific variety)—maize		−47	2.60	47	37		
Continuous maize	Alfisol, savanna soil		1.22	41		Nigeria	Sanginga et al. (2002)
Soybean variety 1- maize		−8	1.54	57	16		
Soybean variety 2- maize		11	2.42	68	27		
Soybean variety 3- maize		15	3.02	67	26		
Soybean variety 4- maize		30	1.45	58	17		
Soybean variety 5- maize		43	1.98	64	23		
Continuous maize	Loamy sand (site 1)		0.38	8		Zimbabwe	Kasasa et al. (1999)
Soybean (promiscuous)—maize		13	1.59	30	22		
Soybean (specific variety)—maize		7	1.11	23	15		
Continuous maize	Loamy sand (site 2)		0.36	7			
Soybean (promiscuous)—maize		26	1.62	36	30		
Soybean (specific variety)—maize		−7	1.17	25	18		
Maize–maize	Sandy soil		0.20	6		Zimbabwe	Chikowo et al. (2004)
Soybean-maize		8	0.50	15	7		
Continuous millet	0.16–0.5% C		0.94	26		Niger	Bagayoko et al. (2000)
Cowpea –millet		Not given	1.26	36	10		
Continuous sorghum			0.40	12			
Cowpea—sorghum		Not given	0.56	16	4		
Continuous maize	Loamy sand		2.46	44		Zimbabwe	Waddington and Karingwindi (2001)
Groundnut-maize		Not given	4.61	84	40		

observed. This system optimized resource use efficiency during good rainfall seasons, while ensuring minimum losses in case of drought due to the reduced fertilizer inputs.

Conclusions and future perspectives

This study is an exhibit of research carried out on soils that have been degraded and run-down over years due to lack of soil fertility investments and therefore decades of nutrient mining. Cases of naturally fragile soils and tropical ecosystems e.g. extremely sandy soils and P-fixing acid soils, also presented challenges to increased nutrient use efficiency. The complexity of systems across Africa calls for complementary exploration with modeling tools. Recently, the NUANCES modeling framework, which recognizes the heterogeneity between farmers and within farming systems, allowing the exploration of trade-offs between different options, has been developed and tested (Tittonell et al. 2008, 2009).

The study has been an ambitious project to define N and P use efficiencies in cropping systems across SSA as we endeavor to have an in depth understanding of the systems. This work indicated that N and P use efficiencies in SSA cropping systems are diverse, being a logical consequence of poor correlation between yields and N or P availability in environments with other multiple constrains. For example, NCE ranged from as little as 0.05 to >0.70 kg kg^{-1}. Numerous examples were found in which response to nutrients applied were meager when other resources were limiting. Flexible systems of fertilization that vary N input according to the current seasonal rainfall pattern offer opportunities for high resource capture and recovery efficiencies in semi-arid areas. In much of our work, we employ integrated soil fertility management (ISFM) as a gateway to increased resource use efficiencies, in the process strongly subscribing to the need to balance nutrient inputs for efficient use as discussed in 'Efficient use of nutrients—an art of balancing' (Janssen 1998).

This study will probably direct some readers into a 'so what' mode. In the years ahead, scientists working across SSA will continue to re-design and execute their experimental research programs that will produce extra scientific information. Those as optimistic as us will continue to hope that strides are being made towards the coveted Green revolution for Africa in the light of the many challenges we have highlighted in this paper. Undoubtedly, there is another constituency of scientists who are getting weary and frustrated by what they perceive as an extremely slow sub-continent.

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References

Bagayoko M, Buerkert A, Lung G, Bationo A, Romheld V (2000) Cereal/legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes. Plant Soil 218:103–116

Baijukya FP, de Ridder N, Giller KE (2006) Nitrogen release from decomposing residues of leguminous cover crops and their effect on maize yield on depleted soils of Bukoba district, Tanzania. Plant Soil 279:77–93

Bar AR, Baggie I, Sanginga N (2000) The use of Sesbania (*Sesbania rostrata*) and urea in lowland rice production in Sierra Leone. Agrofor Syst 48:111–118

Bationo A, Ayuk E, Ballo D, Koné M (1997) Agronomic and economic evaluation of Tilemsi phosphate rock in different agroecological zones of Mali. Nutr Cycl Agroecosyst 48:179–189

Becker M, Johnson DE (1999) The role of legume fallows in upland rice-based systems of West Africa. Nutr Cycl Agroecosyst 53:71–81

Brouwer J, Powell JM (1998) Increasing nutrient use efficiency in West-African agriculture: the impact of micro-topography on nutrient leaching from cattle and sheep manure. Agric Ecosyst Environ 71:229–239

Cadisch G, de Willigen P, Suprayogo D, Mobbs DC, van Noordwijk M, Rowe EC (2004) Catching and competing for mobile nutrients in soils. In: van Noordwijk M, Cadisch G, Ong CK (eds) Below-ground interactions in tropical agroecosystems: concepts and models with multiple plant components. CAB International, Wallingford, pp 171–191

Carsky RJ, Oyewole B, Tian G (1999) Integrated soil management for the savanna zone of W. Africa: legume rotation and fertilizer N. Nutr Cycl Agroecosyst 55:95–105

Chikowo R, Mapfumo P, Nyamugafata P, Nyamadzawo G, Giller KE (2003) Nitrate-N dynamics following improved fallows and spatial maize root development in a Zimbabwean sandy clay loam. Agrofor Syst 59:187–195

Chikowo R, Mapfumo P, Nyamugafata P, Giller KE (2004) Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agric Ecosyst Environ 102:119–131

Fofana B, Tamelokpo A, Wopereis MCS, Breman H, Dzotsi K, Carsky RJ (2005) Nitrogen use efficiency by maize as affected by a mucuna short fallow and P application in the coastal savanna of West Africa. Nutr Cycl Agroecosyst 71:227–237

Gachengo CN, Palm CA, Jama B, Othieno C (1999) Tithonia and senna green manure and inorganic fertilizers as phosphorus sources for maize in Western Kenya. Agrofor Syst 44:2–36

Gandah M, Bouma J, Brouwer J, Hiernaux P, van Duivenbooden N (2003) Strategies to optimize allocation of limited nutrients to sandy soils of the Sahel: a case study from Niger, West Africa. Agric Ecosyst Environ 94:311–319

Giller KE (2001) Nitrogen fixation in tropical cropping systems, 2nd edn. CAB International, Wallingford

Giller KE, Rowe EC, de Ridder N, van Keulen H (2006) Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric Syst 88:8–27

Haefele SM, Wopereis MCS (2005) Spatial variability of indigenous supplies of N, P and K and its impact on fertilizer strategies for irrigated rice in West Africa. Plant Soil 270:57–72

Hagedorn F, Steiner KG, Sekayange L, Zech W (1997) Effect of rainfall pattern on nitrogen mineralization and leaching in a green manure experiment in south Rwanda. Plant Soil 195:365–375

Janssen BH (1998) Efficient use of nutrients: an art of balancing. Field Crops Res 56:197–201

Janssen BH, Guiking FCT, van der Eijk D, Smaling EMA, Wolf J, van Reuler H (1990) A system for quantitative evaluation of tropical soils (QUEFTS). Geoderma 46:299–318

Jensen JR, Bernhard RH, Hansen S, McDonagh J, Moberg JP, Nielsen NE, Nordbo E (2003) Productivity in maize based cropping systems under various soil-water-nutrient management strategies in a semi-arid, Alfisol environment in East Africa. Agric Water Man 59:217–237

Kang BT, Caveness FE, Tian G, Kolawole GO (1999) Long-term alley cropping with hedgerow species on an Alfisol in southwestern Nigeria—effect on crop performance, soil chemical properties and nematode populations. Nutr Cycl Agroecosyst 54:145–155

Kasasa P, Mpepereki S, Musiiwa K, Makonse F, Giller KE (1999) Residual nitrogen fixation benefits of promiscuous soybeans to maize under smallholder field conditions. Afr Crop Sci 7:375–382

Kaya B, Nair PKR (2001) Soil fertility and crop yields under improved fallow systems in southern Mali. Agrofor Syst 52:1–11

Kho RM (2000) On crop production and the balance of available resources. Agric Ecosyst Environ 80:71–85

Kwabiah AB, Stoskopf NC, Palm CA, Voroney RP (2003) Soil P availability as affected by the chemical composition of plant materials: implications for P-limited agriculture in tropical Africa. Agric Ecosyst Environ 100:53–61

Kwesiga FR, Coe R (1994) The effect of short rotation Sesbania sesban planted fallows on maize yield. For Ecol Manag 64:199–208

Lupwayi NZ, Haque I, Saka AR, Siaw DEKA (1999) Leucaena hedgerow intercropping and cattle manure application in the Ethiopian highlands II. Maize yields and nutrient uptake. Biol Fertil Soil 28:196–203

Mafongoya PL, Dzowela BH (1999) Biomass production of tree fallows and their residual effects on maize in Zimbabwe. Agrofor Syst 47:139–151

Mando A, Ouattara B, Somado AE, Wopereis MCS, Stroosnijder L, Breman H (2005) Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions. Soil Use Manag 21:25–31

Mpepereki S, Javaheri F, Davis P, Giller KE (2000) Soyabeans and sustainable agriculture: promiscuous soyabeans in southern Africa. Field Crop Res 65:137–149

Msolla MM, Semoka JMR, Borggaard OK (2005) Hard Minjingu phosphate rock: an alternative P source for maize production on acid soils in Tanzania. Nutr Cycl Agroecosyst 72:299–308

Mtambanengwe F, Mapfumo P (2005) Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. Nutr Cycl Agroecosyst 73:227–243

Mtambanengwe F, Mapfumo P (2006) Effects of organic resource quality on soil profile N dynamics and maize yields on sandy soils in Zimbabwe. Plant Soil 281:173–191

Nyamangara J, Bergström LF, Piha MI, Giller KE (2003) Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. J Environ Qual 32:599–606

Ogoke IJ, Carsky RJ, Togun AO, Dashiell K (2003) Effect of P fertilizer application on N balance of soybean crop in the guinea savanna of Nigeria. Agric Ecosyst Environ 100:153–159

Oikeh SO, Carsky RJ, Kling JG, Chude VO, Horst WJ (2003) Differential N uptake by maize cultivars and soil nitrate dynamics under N fertilization in West Africa. Agric Ecosyst Environ 100:181–191

Osiname OA, Meppe F, Everett L (2000) Response of maize (Zea mays) to phosphorus application on basaltic soils in Northwestern Cameroon. Nutr Cycl Agroecosyst 56:209–217

Osunde AO, Bala A, Gwam MS, Tsado PA, Sanginga N, Okogun JA (2003) Residual benefits of promiscuous soybean to maize grown on farmers' fieds around Minna in the southern Guinea savanna zone of Nigeria. Agric Ecosyst Environ 100:209–220

Ouédraogo E, Mando A, Zombré NP (2001) Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. Agric Ecosyst Environ 84:259–266

Palm CA, Gachengo CN, Delve RJ, Cadisch G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ 83:27–42

Phiri ADK, Kanyama-Phiri GY, Snapp S (1999) Maize and Sesbania production in relay cropping at three landscape positions in Malawi. Agrofor Syst 47:153–162

Piha MI (1993) Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp Agric 29:405–415

Probert ME, Okalebo JR (1992) Effects of phosphorus on the growth and development of maize In: Probert ME (ed) A search for strategies for sustainable dryland cropping in semi-arid Kenya. Proceedings of a symposium held in Nairobi, Kenya, 10–11 December 1990. Canberra, Australia, ACIAR proceedings No. 41

Rockström J, de Rouw A (1997) Water, nutrients and slope position in on-farm pearl millet cultivation in the Sahel. Plant Soil 195:311–327

Rufino MC, Rowe EC, Delve RJ, Giller KE (2006) Nitrogen cycling efficiencies through resource-poor African crop-livestock systems. Agric Ecosyst Environ 112:261–282

Sahrawat KL, Jones MP, Diatta S (1997) Direct and residual fertilizer phosphorus effects on yield and phosphorus efficiency of upland rice in an Ultisol. Nutr Cycl Agroecosyst 48:209–215

Saïdou A, Janssen BH, Temminghoff EJM (2003) Effects of soil properties, mulch and NPK fertilizer on the maize yields and nutrient budgets on ferralitic soils in southern Benin. Agric Ecosyst Environ 100:265–273

Samaké O, Smaling EMA, Kropff MJ, Stomph TJ, Kodio A (2006) Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. Agric Ecosyst Environ 109:335–345

Sanchez PA, Sherperd KD, Soule MJ, Place FM, Buresh RJ, Izac AM, Mokunywe AU, Kwesiga FR, Ndiritu CG, Woomer PL (1997) Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51 ASA and SSSA, Madison

Sangaré M, Rernández_Rivera S, Hiernaux P, Bationo A, Pandey V (2002) Influence of dry season supplementation for cattle on soil fertility and millet (*Pennisetum glaucum* L.) yield in a mixed crop/livestock production system of the Sahel. Nutr Cycl Agroecosyst 62:209–217

Sanginga N, Ibewiro B, Houngnandan P, Vanlauwe B, Okogun JA, Okobundu IO, Versteeg M (1996) Evaluation of symbiotic properties and the nitrogen contribution of mucuna to maize grown in the derived savanna of West Africa. Plant Soil 179:119–129

Sanginga N, Okogun J, Vanlauwe B, Dashiell K (2002) The contribution of nitrogen by promiscuous soybeans to maize based cropping in the moist savanna of Nigeria. Plant Soil 241:223–231

Sigunga DO, Janssen BH, Oenema O (2002) Effects of improved drainage and nitrogen source on yields nutrient, uptake and utilization efficiencies by maize (*Zea mays* L.) on Vertisols in sub-humid environments. Nutr Cycl Agroecosyst 62:263–275

Smaling EMA, Nandwa SM, Prestele H, Roetter R, Muchena FN (1992) Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. Agric Ecosyst Environ 41:241–252

Smaling EMA, Nandwa SM, Janssen BH (1997) Soil fertility in Africa is at stake. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. SSSA Publication 51 SSSA and ASA, Madison, pp 47–61

Stahl L, Nyberg G, Högberg P, Buresh RJ (2002) Effects of planted tree fallows on oil nitrogen dynamics, above ground and root biomass, N2-fixation and subsequent maize crop productivity in Kenya. Plant Soil 243: 103–117

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ 110:166–184

Tittonell P, Corbeels M, van Wijk MT, Vanlauwe B, Giller KE (2008) Targeting nutrient resources for integrated soil fertility management in smallholder farming systems of Kenya. Agron J 100:1511–1526

Tittonell P, van Wijk MT, Herrero M, Rufino MC, de Ridder N, Giller KE (2009) Beyond resource constraints—Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agric Syst 101:1–19

van Asten PJA, van Bodegom PM, Mulder LM, Kropff MJ (2005) Effect of straw application on rice yields and nutrient availability on an alkaline and a pH-neutral soil in a Sahelian irrigation scheme. Nutr Cycl Agroecosyst 72:255–266

Van Duivenbooden N, de Wit CT, van Keulen H (1996) Nitrogen, phosphors and potassium relations in five major cereals reviewed in respect to fertilizer recommendations using simulation modelling. Fertil Res 44:37–49

Vanlauwe B, Diels J, Lyasse O, Aihou K, Iwuafor ENO, Sanginga N, Merckx R, Deckers J (2002) Fertility status of soils of the derived savanna and northern guinea savanna and the response to plant nutrients, as influenced by soil type and land use management. Nutr Cycl Agroecosyst 62:139–150

Vanlauwe B, Diels J, Sanginga N, Merckx R (2005) Long-term integrated fertility management in South-western Nigeria: crop performance and impact on the soil fertility status. Plant Soil 273:337–354

Waddington SR, Karingwindi J (2001) Productivity and profitability of maize + groundnut rotations compared with continuous maize on smallholder farms in Zimbabwe. Exp Agric 37:83–98

Wallace JS (2000) Increasing agricultural water use efficiency to meet future food production. Agric Ecosyst Environ 82:105–119

Wopereis MCS, Tamélokpo A, Ezui K, Gnakpénou D, Fofana B, Breman H (2006) Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crop Res 96:355–362

Zaongo CGL, Wendt CW, Lascano RJ, Juo ASR (1997) Interactions of water, mulch and nitrogen on sorghum in Niger. Plant Soil 197:119–126

Zingore S, Murwira HK, Delve RJ, Giller KE (2007) Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric Ecosyst Environ 119:112–126

Zougmoré R, Mando A, Stroosnijder L, Ouédraogo E (2004) Economic benefits of combining soil and water conservation measures with nutrient management in semiarid Burkina Faso. Nutr Cycl Agroecosyst 70:261–269