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ORIGINAL ARTICLE

Nitrogen release and synchrony in organic and conventional farming systems of the Central Highlands of Kenya

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Abstract To match Nitrogen (N) supply to crop N demand, it is essential to understand N release and uptake patterns in different farming systems and crops. To assesses the dynamics of N released in organic and conventional systems and potential synchrony and asynchrony in crop N uptake, a study was conducted over three cropping seasons (potato, maize and leafy vegetables) at two sites in the Central Highlands of Kenya. Mineral-N release and synchrony were monitored in conventional and organic systems at high (recommended N, P, pesticides and irrigation) and low input (low N, P, pesticide use and rainfed) systems. Mineral-N release was assessed using in situ buried bags and N synchrony was measured by the daily differences in N fluxes. The percentage of N applied released during potato (38%) and vegetable (44%) cropping seasons were similar between systems. However, under maize strong temporal N immobilization from inputs occurred, particularly at Thika, related to the poor quality of manure and compost (lignin:N ratio > 13). In all systems, excess-asynchrony of available N was pronounced during vegetative stages and at harvest, while insufficient-asynchrony occurred at reproductive stages. During

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potato cropping season at Thika, Org-High showed highest positive N fluxes (> 20 kg N ha^{-1} day^{-1}) at planting and tuber bulking stage. At early stages of maize and vegetables Org-Low and Org-High experienced up to 5 times larger negative N fluxes (insufficiency) compared to conventional treatments at Chuka site. The study recommends reducing N applications at planting and increasing N dosages at reproductive stages of crops.

Keywords Incubation · Mineralization · Mineral-N release · Synchrony · Organic input quality

Introduction

Most soils in sub-Saharan Africa are highly weathered, have low inherent nutrient stocks and are deficient in nitrogen (N) and phosphorus (P) (Okalebo et al. 2007). This problem is exacerbated by the prevailing climate (Okalebo et al. 2007). N availability is particularly affected by farming system-specific conditions such as tillage, previous fertilization intensity and cropping patterns as well as the chemical, physical and biotic properties of soils (St. Luce et al. 2011). In conventional systems N fertilizer is applied as ammonium (NH_4^+) or nitrate (NO_3^-) based synthetic fertilizers, and/or manure prior to or during planting or as top dressing later, while in organic systems, N is supplied from manure or compost, crop residues, biological N_2 fixation and through crop rotations. The nitrogen availability in organic and integrated systems is therefore dependent on processes that transform N, such as decomposition, mineralization and nitrification (St. Luce et al. 2011). Organic and integrated farming systems are characterized by phases of N building followed by N utilization (Berry et al. 2002). When using synthetic fertilizers N is readily available, but in organic and mixed systems, ensuring the availability of N can be challenging, due to the low N content of some manures, composts and crop residues and/or slow mineralization rates (Berry et al. 2002). Watson et al. (2002) argue that the availability of N in organic farming systems is more dependent on previous fertilization intensities (than is the case with using synthetic fertilizers), with the N that was unavailable and unused in previous seasons being captured in the following seasons. Nett et al. (2012) found that amendment history also influenced the N mineralization of freshly added organic inputs. Crews and Peoples (2005) studied the synchrony of N supply and crop demand from legume cover crop systems and conventional systems. They found that excess-N asynchrony is likely to occur in organic and integrated farming systems due to the continuous release of inorganic N from organic inputs and soil organic matter, and that N deficiencies may occur during periods of N immobilization (Crews and Peoples 2005).

Nitrogen mineralization is affected by macro and microorganisms, the physico-chemical environment and the quality of organic inputs (Swift et al. 1979). Differences in the nature of synthetic fertilizer and organic inputs may affect mineralization trends in conventional and organic systems (Romanyà et al. 2012). In most of sub-Saharan Africa (SSA), manure plays a crucial role in soil fertility, with most farmers using manure, alone or in combination with synthetic fertilizers (Muriuki et al. 2013). Thus, most recommendations on conventional farming systems in this region focus on the integrated use of manure and fertilizer (Muriuki et al. 2013), which have been found to perform well in highly weathered SSA soils. For example, in Kenya, the application of 5 and 10 t ha^{-1} of FYM combined with synthetic fertilizer has been shown to increase maize yields (Mucheru-Muna et al. 2014) in different agro-ecological zones. Organic systems have been shown to have higher microbial activity and diversity (Fließbach et al. 2007), which may result in higher rates of mineralization. The quality of compost and other organic inputs varies seasonally and according to its composition, while manure quality can vary according to its age, how it is handled, the animals' diet and bedding materials (Lekasi et al. 2003). N mineralization of organic resources is mainly affected by N content, the C:N ratio, lignin, the lignin:N ratio and the polyphenol content and these determine the extent to which N is released or immobilized (Vanlauwe et al. 2005). It is estimated that 4–57% of the N (measured in terms of fertilizer equivalency) within fresh or composted cattle and poultry manure is recovered in the first year and 7–18% in the second year, with the differences dependent on the manure type (Muñoz et al. 2008). N release from compost has been reported to be in the range of 5–15% in the first year of application and

2–8% in the following years (Amlinger et al. 2003). Thus, timing of the application of manure, compost and crop residues is essential in order to achieve synchrony between nutrient release and crop demand.

Most mineralization studies have been short-term studies, and hence do not capture the long-term effects of different farming systems. Moreover, most such studies have focused on conventional and integrated nutrient management systems, with little attention to organic farming systems in the SSA. N mineralization in organic farming systems may differ from that of conventional systems due to the farming systems' effects on the chemical and biological (such as microbial biomass and respiration etc.) properties of the soils (Berry et al. 2002; Fließbach et al. 2007). There are few, if any, studies on ways to improve N availability in organic farming systems.

In SSA crops production systems are under low external input (mostly subsistence and rainfed) and high external input systems that rely on high levels of input use and irrigation. In eastern Kenya, research into low external input agriculture (LEIA) has shown similar nutrient depletion problems as conventional farming systems (Tripp 2006); while in western Kenya, research into LEIA has shown increased production with positive N balances (Tambang and Svensson 2008). High input systems have been promoted for agricultural intensification, but there are potential drawbacks with these systems as soil acidification and a decline in SOM sometimes cause initially high yields to decline. These systems can also have negative environmental impacts (Bello 2008). Thus, this study tests the performance of farming systems at low and high input levels, representing existing subsistence and commercial production systems.

The hypothesis of this study was that mineral-N release, N release rates and synchrony between N release and crop N demand differed between conventional and organic systems due to their different sources of nutrients. The objectives of this study were therefore, to determine; i) mineral-N released in conventional and organic farming systems at low and high input levels; ii) the N release rates in conventional and organic farming systems; and iii) the patterns and periods of synchrony or asynchrony of soil mineral-N release and crop N-uptake for different crops.

Materials and methods

Experimental sites

The research was conducted at Chuka and Thika in Kenya as part of the on-going long-term farming systems comparisons trial initiated in 2007 [SysCom; www.system-comparison.fibl.org; (Adamtey et al. 2016)]. The site at Chuka is located at 0°20.864′S latitude, 37°38.792′E longitude and lies at 1458 m above sea level (a.s.l.). It has an annual mean temperature of 20 °C and mean annual rainfall of 1500 to 2400 mm (Jaetzold et al. 2006b). The site at Thika is located at 01°00.231′S latitude, 37°04.747E longitude. It lies at 1518 m above sea level (m a.s.l.) with an annual mean temperature of about 20 °C and mean annual rainfall of 900 to 1100 mm (Jaetzold et al. 2006a). Both sites have a bimodal rainfall distribution that occurs in March–June (long rains, LR) and October–December (short rains, SR). According to the world reference base (IUSS Working Group WRB 2006) the soils at Thika are Rhodic Nitisols and those at Chuka, Humic Nitisols (Adamtey et al. 2016; Musyoka et al. 2017).

Experimental treatments and management

Experimental trials were laid down in a randomized complete block design (RCBD) with plot sizes of 8 × 8 m (net plot size of 6 × 6 m) replicated four times at Chuka and five times at Thika. Four farming systems were compared at each site: Conventional high (Conv-High), organic high (Org-High) (where N and P, pesticides, botanicals and irrigation water were applied at recommended rates for potato, maize and cabbage crops), conventional low (Conv-Low) and organic low (Org-Low) (where N and P, pesticides, botanicals were applied at rates used by local farmers and under rainfed conditions). The trials were based on a two-season, three-year crop rotation (as shown in Table 1; see also Musyoka et al. 2017). In 2012 potato (*Solanum tuberosum* L.) was planted on 16th October at Chuka and 25th October at Thika (SR). In 2013 Maize (*Zea mays* L.) was planted on 27th March at Chuka and 4th April at Thika (LR) and vegetables (cabbage-*Brassica oleracea* var. capitata and kale-*Brassica oleracea* var. acephala intercropped with Swiss chard *Beta vulgaris* subsp cicla) were planted on

Table 1 Crop rotation in of the long-term farming systems comparison trial at Chuka and Thika in the Central Highlands of Kenya. Adopted from Musyoka et al. (2017)

Farming systems	Year 2007, 2010, 2013		Year 2008, 2011, 2014		Year 2009, 2012, 2015	
	LR	SR	LR	SR	LR	SR
Conv-High	Maize		Baby corn		Baby corn	
		Cabbage		French beans		Potatoes
Org-High	Maize/Mucuna[a]		Baby corn/Mucuna		Baby corn/Mucuna	
		Cabbage		French beans		Potatoes
Conv-Low	Maize		Maize/Beans		Maize/beans	
		Collard/Swiss chard		Grain legumes		Potatoes
Org-Low	Maize		Maize/Beans		Maize/beans	
		Collard/Swiss chard		Grain legumes		Potatoes

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low* conventional low input system, *Org-Low* organic low input system, *LR* long rainy season, *SR* short rainy season

[a] *Mucuna pruriens* planted as relay crop four weeks after the maize or baby corn were established. Mucuna biomass was applied in the short rainy season. The shaded region shows the period of data collection in 2012 and 2013

6th and 8th November 2013 at Chuka and Thika site (SR, Table 1).

In the organic systems, N was applied in form of compost, *Mucuna pruriens* (Mucuna) biomass, crop residues at planting, with a *Tithonia diversifolia* (Tithonia) mulch added after germination and plant tea for topdressing. P was applied as Minjingu phosphate rock at the time of planting. Well-decomposed farm yard manure (FYM) and fresh FYM were applied in Conv-High and Conv-Low, respectively. In addition, di-ammonium phosphate (DAP) or triple super phosphate (TSP) was applied at planting with calcium ammonium nitrate (CAN) as a top dressing. For the low input systems, the trial aimed to follow common local practices, identified in a survey carried out in 2007 (Adamtey et al. 2016; Musyoka et al. 2017) using N and P rates of 50 kg N ha^{-1} year^{-1} and 26 kg P ha^{-1} year^{-1}, respectively. In the high input systems N and P were applied at 225 kg N ha^{-1} year^{-1} and 124 kg P ha^{-1} year^{-1}, following the recommendations of the Kenyan Ministry of Agriculture and the Japanese International Co-operation Agency (Adamtey et al. 2016; Musyoka et al. 2017).

To ascertain the actual amounts of nutrients applied in each system, FYM, compost, Tithonia, Mucuna and maize stover were analyzed for N and P, which revealed that the nutrients in the FYM and compost varied between the LR and SR. This, coupled with the N applied as Mucuna and crop residue (which were not initially factored in the N and P calculations), explains why the Org-High system received more N than Conv-High. Table 2 shows the N and P levels applied in the different systems during the period of data collection. Pest were managed using an integrated pest management approach (IPM) in the conventional systems and bio-pesticides in organic systems, with a low intensity of pest control in the low input systems (see Supplementary S2). The low input systems were rain-fed while high input systems received supplementary irrigation water through drip irrigation during periods of moisture stress. No irrigation was done during the potato cropping season as the amount and distribution of rainfall was sufficient (Fig. 1). Maize and cabbage received 102 and 209 mm ha^{-1} at Chuka and 287 mm ha^{-1} and 49 mm ha^{-1} at Thika, respectively (the last figure being lower than desired due to constraints in obtaining irrigation water due to a breakdown in the borehole system). The frequency of irrigation was determined by computing the dry spells (days with rainfall of < 1 mm) as described by Adamtey et al. (2016). Thus, maize and cabbage received irrigation water 4 and six times respectively at Chuka while at Thika Maize and cabbage received irrigation water 7 and 8 times respectively. Total rainfall and its distribution during the three cropping seasons is shown in Fig. 1. Other details of the management practices in the farming systems can be

Table 2 Actual total nitrogen (N) and phosphorus (P) contents of the inputs applied during the measurement period in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya. Adopted from Musyoka et al. (2017)

					Input application									
Site	Farming systems	Year	Season	Crop	FYM	Compost[a]	DAP	PR	TSP	CAN[b]	Tithonia mulch[c]	Tithonia tea[b]	Total N applied	Total P applied
					Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Chuka	Conv-High	2012	SR	Potato	10.5	-	-	-	300	200	-	-	160	94
		2013	LR	Maize	3.9	-	200	-	-	100	-	-	113	60
		2013	SR	Cabbage	10.5	-	-	-	200	300	-	-	114	58
	Org-High	2012	SR	Potato	-	22	-	581	-	-	8.2	-	162 (173)[d]	118.5 (36.5)[d]
		2013	LR	Maize	-	22.7	-	364	-	-	5.4	3.9	246	133
		2013	SR	Cabbage	-	22	-	400	-	-	6	6	211 (15)[e]	115 (19)e
	Conv-Low	2012	SR	Potato	2	-	100	-	-	-	-	-	33	27
		2013	LR	Maize	5	-	50	-	-	-	-	-	63	32
		2013	SR	Kale/Swiss Chard	1	-	-	-	50	60	-	-	23	13
	Org-Low	2012	SR	Potato	4.5	-	-	200	-	-	2.72	-	48	45
		2013	LR	Maize	2.2	-	-	100	-	-	1.36	-	35	24
		2013	SR	Kale/Swiss Chard	4.5	-	-	90	-	-	1.2	1.2	21	13
Thika	Conv-High	2012	SR	Potato	14.1	-	-	-	300	200	-	-	124	83
		2013	LR	Maize	7.2	-	200	-	-	100	-	-	84	47
		2013	SR	Cabbage	11	-	-	-	200	300	-	-	184	67
	Org-High	2012	SR	Potato	-	24.4	-	581	-	-	8.2	-	131 (220)[4]	87 (41)[4]
		2013	LR	Maize	-	17.6	-	364	-	-	5.4	3.9	135	81
		2013	SR	Cabbage	-	24.4	-	400	-	-	6	6	290 (25)[5]	100 (2)[5]
	Conv-Low	2012	SR	Potato	2	-	100	-	-	-	-	-	44	25
		2013	LR	Maize	5	-	50	-	-	-	-	-	31	20
		2013	SR	Kale/Swiss Chard	1	-	-	-	50	60	-	-	24	14
	Org-Low	2012	SR	Potato	6.9	-	-	200	-	-	2.72	-	33	37
		2013	LR	Maize	5	-	-	100	-	-	1.36	-	38	24
		2013	SR	Kale/Swiss Chard	6.9	-	-	90	-	-	1.2	1.2	18	13

Conv-Low conventional low input system, *Conv-High* conventional high input system, *Org-Low* organic low input system, *Org-High* organic high input system, *SR* short rainy season, *LR* long rainy season, *DAP* di-ammonium phosphate, *CAN* calcium ammonium nitrate, *TSP* triple superphosphate, *PR* phosphate rock

NB: FYM, compost, *Tithonia* inputs were on a fresh weight basis

[a] Compost was prepared with a similar amount of fresh farm yard manure (FYM) as in Conv-High

[b] *Tithonia diversifolia* plant tea and CAN were applied as top-dressing in two split applications in the high input systems, while in the low input systems the top dressing was done once for specific crops.

[c] Tithonia mulch was applied as an N starter after crop germination

[d] Extra nutrients supplied from other sources such as mulch (2 Mg ha^{-1}), maize stover residues (2 Mg ha^{-1}) and Mucuna (10.3 Mg ha^{-1} at Chuka) and (16.7 Mg ha^{-1} at Thika) during the potato season

[e] N supplied as maize stover residues 2 Mg ha^{-1}

found in Adamtey et al. (2016) and Musyoka et al. (2017).

Preparation of organic inputs

The compost used in Org-High was prepared using the layering heap method (Das 2014) with maize stover (30%), *Lantana camara* fresh and soft twigs (20%) and FYM (50%). Small amounts of wood ash and top soil were sprinkled on top of every layer to support microbial activity. The compost heap was turned once every three weeks until it matured (3 months). In Conv-High and Org-Low, fresh FYM was heaped and allowed to decompose for three months before use. In Conv-Low, fresh FYM was used directly from the cattle shed, following the common farmers' practice in the region. Vegetative organic inputs, such as *Mucuna pruriens* (Mucuna), crop residues and *Tithonia diversifolia* (Tithonia), were chopped into small pieces (of < 5 mm) before use.

Soil sampling and incubation procedure

Soil mineral-N in the topsoil was measured from soil sampled under natural soil-crop interaction at critical stages of the crop. Mineral-N released from applied inputs was studied through field incubation, using the buried bag approach as described by Eno (1960) and modified by Friedel et al. (2000). The soil used was collected from the plough layer (0–0.2 m) of each plot before the input application. The collected soil was sorted by hand to remove debris and big clods and homogenized, taking care to preserve aggregates of 5 mm. The soil was tested in its fresh form without sieving. The properties of the soils at the beginning of data collection (October 2012) are shown in Table 3.

An equivalent weight of 150 g of soil and 150 g of mixed resin beads (dry weight basis) were placed into polyethylene freezer bags (0.235 m × 0.38 m). The freezer bags used in the study were semi-permeable in order to allow an exchange of gases (Friedel et al. 2000).

Organic inputs were applied to the field in fresh form, with the rate of application based on the bulk density of the soil in each system (Supplementary S1). Corresponding inputs were manually mixed with the soil-resin beads mixture, placed into freezer bags and the moisture content adjusted to 60% water holding capacity, using distilled water. The bags were then sealed to avoid water entry and loss of content and then buried in the sampled plots, to ensure the replication of the bags was similar to the trial's layout. The mixed resin beads (Resinex$^{\text{TM}}$ MX-11) were obtained from Clean Water Group (CWG) Technology (GmBH Mannheim, Germany). Resinex$^{\text{TM}}$ MX-11 is a mixture of Resinex$^{\text{TM}}$ K-8 and Resinex$^{\text{TM}}$ A-4 and has a specific gravity of 730 kg m^{-3} and grain size of 0.45–1.2 mm. This study used ion exchange resin beads as these have been shown to prevent the re-immobilization of released N and also mimic the nutrient exchange of plant roots (Friedel et al. 2000).

To assess the mineral-N released from the soil without input application (residual-N) and the mineral-N released from soils amended with inputs, two sets of polyethylene (PE) bags were buried in each experimental plot at a depth of 0.2 m. Twelve bags per replicate were buried at the beginning of the potato cropping season, 16 for maize and 14 for vegetables. This was to ensure that adequate samples were retrieved after 0, 3, 10, 20, 40, 90 days for potato; 0, 3, 10, 20, 41, 61, 122, 157 days for maize; and 0, 3, 10, 26, 41, 69, 109 days for vegetables, which corresponds with the critical development stages of each crop. Four extra bags were installed in each farming system at the beginning of the maize and vegetable cropping seasons to account for the N applied as top dressing during the cropping period. These four bags were retrieved from the maize plots at the V8 leaf stage and tasseling stages and from the cabbage plots at the precupping and head formation stages and the respective top dress inputs added. After that, the bags were buried and sampled during the consecutive sampling dates as indicated above. The positions of bags in each experimental plot were marked with distinct polyvinyl chloride (PVC) pegs to ensure that they remained intact during routine farm management activities. The retrieved bags were placed in air-tight polythene bags, labeled, and transported to the laboratory in ice chests for analysis. The soil mineral-N content was assessed before planting crops and at critical stages of crop development. Soil samples were collected at 0–0.2 m depth, placed in ice chests and transported to the laboratory for analysis.

Soil and FYM analysis

Soil bulk density was determined in situ using the core method described by Okalebo et al. (2002). Soil cores

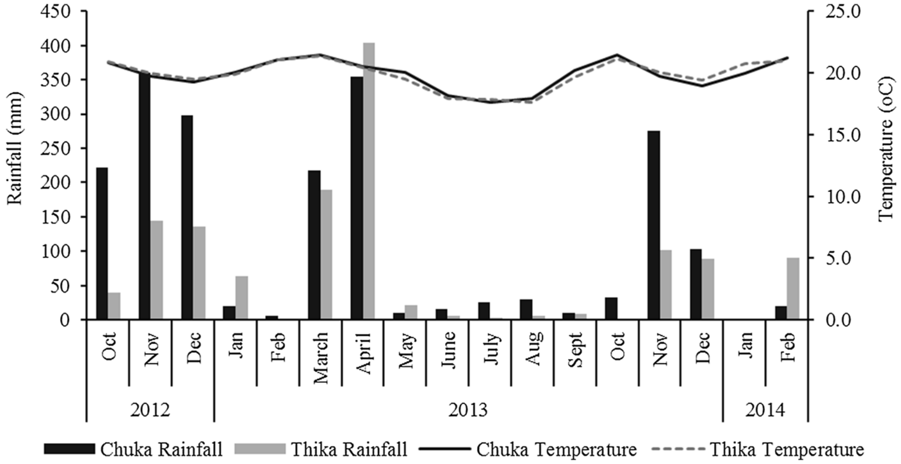


Fig. 1 Cumulative monthly rainfall and average temperatures (from planting to harvesting) during the three cropping seasons in the long-term systems comparison trial at Chuka and Thika in the Central highland of Kenya

(length 0.0503 m; diameter 0.0503 m; and 0.0001 m^3 volume) were driven through undisturbed soil after clearing the surface of plant debris and loose soil. The cores were trimmed to size and closed at both ends, to ensure no loss of soil. They were oven dried at 105 °C to a constant weight. The bulk density was then calculated as the soil dry weight divided by the volume of the core. Soil and FYM pH-H_2O were determined potentiometrically in 2.5:1 and 5:1 water to soil suspensions, while electro-conductivity was determined in a saturated paste extract (Okalebo et al. 2002). Organic carbon was determined using Walkley–Black wet oxidation (Anderson and Ingram 1993). Total N and P in FYM, compost and soil were measured after complete digestion of the samples with a mixture of hydrogen peroxide, sulphuric acid, selenium and salicylic acid, as described by Okalebo et al. (2002). Total N concentration was quantified using a SKALAR segmented flow analyzer at 660 nm wavelength and total P concentration was determined using a spectrophotometer at 400 nm. Potassium, calcium and magnesium were analysed with an atomic absorption spectrophotometer after extraction with ammonium acetate (according to the procedure described by Okalebo et al. 2002). Nitrate-N and ammonium-N were measured using a SKALAR (SKALAR Analytical B.V. Breda, the Netherlands) segmented flow auto analyzer at 540 and 660 nm respectively, after extraction with 0.5 M potassium sulphate. Olsen extractable P was determined after extraction of 2.5 g air-dry soil (sieved through a 2 mm mesh) with 50 mL of 0.5 M sodium bicarbonate and the absorbance of the solution measured at 880 nm wavelength (Okalebo et al. 2002). Lignin in FYM and other organic inputs were determined through the Acid-Detergent Fiber (ADF) method (Anderson and Ingram 1993) while polyphenols were determined using the Folin-Denis method, as described by Anderson and Ingram (1993).

Soil samples collected from each system before applying the inputs, and at different crop growth stages, were analyzed to assess changes in mineral-N in the top soil during crop growth. Soil and soil-resin mixture samples were thoroughly mixed in the laboratory before analysis. Ten grams of freshly sampled soil and soil-resin samples were extracted using 50 mL of 0.5 M K_2SO_4 (at a 1:5 soil solution ratio) shaken for 30 min in an end-to-end mechanical shaker. The content was then filtered through Whatman No. 42 filter paper and stored in the refrigerator. Nitrate and ammonium-N were determined at 540 and 660 nm respectively using a SKALAR segmented flow auto analyzer (SKALAR Analytical B.V. Breda, the Netherlands). The moisture content of the samples were determined using the gravimetric method (Okalebo et al. 2002). At the beginning of each season three samples of unincubated resin were analyzed for nitrate and ammonium-N to determine the nitrogen content in the resin. This was used to correct for the nitrate and ammonium-N levels in the soil plus resin mixtures.

Mineral-N release

Mineral-N released from amended soil or soil alone was calculated on an area basis after consindering bulk

Table 3 Soil chemical characteristics at the beginning of data collection (October 2012) in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya. Adapted from Musyoka et al. (2017)

Site	System	Bulk density (g cm^3)	pH (1:2.5)	Total N (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	OC (g kg^{-1})	C/N ratio	Olsen P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Sand (%)	Clay (%)	Silt (%)
Chuka	Conv-High	0.91	5.36 b	2.3	3.9	3.4	20.0 a	9	59	309	1462	94	18.6	70.8	10.6
	Org- High	0.92	5.83 b	2.4	2.6	3.0	23.9 a	10	31	704	1493	111	17.3	70.7	12.0
	Conv-Low	0.91	5.36 b	2.2	2.7	3.1	20.4 a	9	36	318	1198	80	17.5	73.1	9.4
	Org-Low	0.91	5.35 b	2.1	2.7	3.9	18.6 b	9	34	404	1384	81	18.1	71.4	10.5
Thika	Conv-High	1.09	5.38 b	1.9	17.7	1.9	15.0 bc	8	46	575	1322	92	18.8	74.0	7.2
	Org-High	0.99	6.83 a	2.0	28.6	3.4	17.8 b	9	27	1048	1493	116	17.2	70.8	12.0
	Conv-Low	1.04	5.24 b	1.7	7.0	1.0	14.7 c	9	14	481	669	73	18.2	70.9	10.9
	Org-Low	1.03	5.38 b	1.6	19.9	2.4	14.5 c	9	12	489	809	82	20.3	71.6	8.1
Sources of variations															
System		ns	***	ns	ns	ns	***	ns	ns	***	*	**	*	ns	ns
Site		***	ns	***	***	ns	ns	*	*	***	*	ns	ns	ns	ns
System × site		ns	*	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns

Conv-High conventional high input system, *Conv-Low* conventional low input system, *Org-High* organic high input system, *Org-Low* organic low input system, *pH* pH in water, *OC* organic carbon, *C/N* C to N ratio; a, b, c are comparisons of means, with only significant mean differences shown; K, Ca, and Mg are ammonium acetate extractable bases density in each farming system and the soil depth of the plough layer (0.2 m) and was calculated as the change in mineral-N between sampling dates (1, 2. 3, 4…) (Eqs. 1 and 2 respectively).

$$\text{Mineral-N released}_{\text{amended soil}}\left(\text{kg ha}^{-1}\right) = \text{Mineral-N}_{t+k\ \text{amended soil}} - \text{Mineral-N}_{ti\ \text{amended soil}} \quad (1)$$

$$\text{Mineral-N released}_{\text{soil}}\left(\text{kg ha}^{-1}\right) = \text{Mineral-N}_{t+k\ \text{soil}} - \text{Mineral-N}_{ti\ \text{soil}} \quad (2)$$

where t_i is initial time $I = 0, 1, 2, 3, 4\ldots$ and t_{i+k} is t_i plus k intervals where $k = 1, 2, 3, 4, 5\ldots$

Mineral-N released from the inputs was calculated as the difference between mineral-N released from amended soil at time t_i to t_{i+k} and N released from soil alone at the time t_i to t_{i+k} (Eq. 3).

$$\text{Mineral-N released}_{\text{inputs}}\left(\text{kg ha}^{-1}\right) = \text{Mineral-N released}_{\text{amended soil}} - \text{Mineral-N released}_{\text{soil}} \quad (3)$$

The N release rate was calculated by dividing the mineral-N released from the inputs at each sampling date by the number of incubation days (Loecke et al. 2012). The total mineral-N released from the amended soil and the soil alone was calculated as the sum of the change in soil mineral-N from one sampling date to the next.

Synchrony of released N and plant N uptake

Daily nitrogen flux differences (mineral-N released − plant N uptake, kg ha^{-1} day^{-1}) were used to demonstrate the closeness of the link, or the synchrony, between mineral-N release from the inputs and crop N demand (Loecke et al. 2012). Asynchrony occurs when there is a positive N flux difference [an indication that mineral-N release is larger than the crops' N demand (Crews and Peoples 2005)] or a negative N flux difference [when insufficient N is released to meet the crops' N demand or uptake (Crews and Peoples 2005)]. Daily mineral-N release budgets were constructed by dividing the amount of mineral-N released (kg ha^{-1}) at time t_i to t_{i+k} by the number of days of the incubation period (t_i to t_{i+k}).

Seasonal above-ground N uptake data collected at critical crop growth stages (as outlined in Musyoka et al. 2017) were used to calculate N uptake (Eq. 4). Daily N uptake budgets for each incubation period were as shown in Eq. 5.

$$\text{N uptake}\left(\text{kg ha}^{-1}\right) = \left[\text{N Nuptake}_{\text{crop stage}}(\%) - \text{Crop biomass}_{\text{crop stage}}\left(\text{kg ha}^{-1}\right)\right]/100 \quad (4)$$

$$\text{Daily N uptake}\left(\text{kg ha}^{-1}\ \text{day}^{-1}\right) = \left[\text{N uptaket}_{i+k} - \text{N uptake}_{ti}\left(\text{kg ha}^{-1}\right)\right]/\left[\left(t_{i+k}\right) - ti\right] \quad (5)$$

where ti and $t_{i+\text{k}}$ were days after planting when the N uptake measurement was done.

To assess N synchrony, the partial balances between plant N uptake and mineral-N released from the amended soils per day at each sampling date (Eq. 6) were constructed and modified from those reported by Loecke et al. (2012).

$$\text{N flux}\left(\text{kg N ha}^{-1}\ \text{day}^{-1}\right) = \text{Mineral-N released}_{\text{inputs}}\left(\text{kg N ha}^{-1}\ \text{day}^{-1}\right) - \text{Daily N uptake}\left(\text{kg N ha}^{-1}\ \text{day}^{-1}\right) \quad (6)$$

Data analysis

N release data were statistically analyzed using a linear mixed-effect model with *lmer* function from the *lme4* package in R statistical software (Bates et al. 2013). Sites were treated as fixed effects since they were selected based on the basis of prior knowledge of the weather, soil organic carbon and pH. Systems were also treated as a fixed effect while replicates were treated as random effect. Analysis was done after assessing for data normality using *Shapiro.test* and a homogeneity test using *Bartlett.test*. Mean separation was done using adjusted Tukey's method, implemented using "*multicompView package*" *for cld* function as developed by Graves et al. (2015) in R software version R3.1.1 (R Development Core Team 2014) after calculation of the least mean square, using *lsmeans* package.

Results

The characteristics of the organic inputs applied

The characteristics of FYM, compost, plant and crop residues applied in the different farming systems at the beginning of every season are shown in Table 4. The quality of compost and FYM differed, both showing seasonal and site variations, with that made at Chuka having a higher N content than that from Thika. During the maize cropping season, a higher C:N ratio was observed at Thika than Chuka while lignin content was higher at Chuka.

The effects of farming systems on mineral-N released from soil and applied inputs

Potato

Expressed as a percentage of the total N applied, the mineral-N released showed no significant difference between systems, sites and their interactions.

Maize

There was no significant differences between the systems or within the sites on mineral-N released (expressed as a percentage of total N applied). However, a significant system × site interaction effect ($P < 0.05$) on mineral-N released was observed (Table 5). More mineral-N was released in the two low input systems at Chuka than in the same systems at Thika.

Vegetables

There were no significant differences in mineral-N released from inputs, expressed as a percent of total N applied (Table 5).

Rates of N released from inputs during the cropping seasons

Potato

Rates of N release from inputs were significantly higher ($P < 0.001$) at 0 to 14 days of incubation (corresponding to nutrient application and early potato growth stages) in all the farming systems (Fig. 2). Thereafter the rate declined. At Thika, significantly higher N release rates were observed during the initial 3 days of incubation (DOI, corresponding to the germination stage) in Conv-High and Org-High than in Conv-Low and Org-Low. This difference disappeared by 44 DOI (corresponding to tuber initiation), and there were no longer any discernible differences between the high and the low input systems (Fig. 2).

Maize

There was a strong net immobilization of N from the applied inputs at Chuka during the initial 10 days of incubation (corresponding to the maize seedlings stage) in the Org-High system. This was followed by a net N release rate at 20–41 DOI (corresponding to the vegetative growth stage i.e., V5-V12 leaf stage), although this difference declined thereafter to close to zero (Fig. 2). At Thika, there was a high N release rate in Conv-High at 0–7 days after planting (germination stage of maize).

Vegetables

At Chuka, significantly higher ($P < 0.001$) net N release rates from the added inputs were observed at 2 DOI in the low input systems than in the high input systems (Fig. 2). N immobilization was observed at 48 days of incubation (corresponding to the pre-cupping stage of cabbage and development of harvestable vegetative plant parts and harvesting stages in kale and Swiss Chard) in all the farming systems at both sites (Fig. 2). Similar trends were observed at Thika except that the rate of N release was lower at 2 DOI.

The effects of farming and cropping systems on seasonal N fluxes

Potato

More mineral-N was released from amended soil, which exceeded N uptake at all potato growth stages at both sites (Fig. 3a). From 30 days after sowing (DAS), mineral-N release in Org-High was significantly higher than in all the other systems (except at maturity for Conv-High). At Chuka, soil mineral-N (SMN) was higher in all systems at 20–30 and 93 DAS (the vegetative and harvesting stage) of potato than at planting (Fig. 3a) although Conv-Low had a significantly lower ($P < 0.001$) SMN than the other systems (Fig. 3a) at 0–33 DAS (planting and vegetative stages). Soil mineral-N declined after 49 DAS (tuber initiation stage) in all the systems and increased significantly at the time of harvest (Fig. 3a) in Conv-High and Org-High, which had a significantly higher ($P < 0.05$) SMN than Conv-Low and Org-Low. Similar trends were observed at Thika (Fig. 3a).

Maize

Large amounts of mineral-N were released from amended soil which exceeded the crop's N uptake between 0 and 40 DAS (corresponding planting and vegetative stage) in all the farming systems at both sites. At Chuka, the mineral-N released at 73 to 155 DAS (tasselling to harvesting stages) in the low input systems also exceeded maize's N uptake (Fig. 3b). By contrast, mineral-N released at Thika at 29–43 and 159 DAS (vegetative and harvesting stages) in all four systems was less than N uptake (Fig. 3b). A decline in mineral-N released from the amended soils was observed at 40 DAS at Thika and at 60 DAS at Chuka. At Chuka the SMN in the topsoil was high at the time of planting maize, but this declined to 20 kg ha^{-1} at 28–73 DAS (vegetative and reproductive stages). Soil mineral-N, increased slightly at 159 DAS (corresponding to the harvest). At Thika, SMN remained below 40 kg ha^{-1} at 29–159 DAS (vegetative to harvesting stages) in all the systems except Org-High and Conv-Low, where SMN increased slightly at the silking stage of maize (94 DAS).

Vegetables

Mineral-N released in the low input systems at both sites exceeded N uptake in kale and Swiss chard (Fig. 3c). At 0 to 69 DAS (corresponding to planting to the development of harvestable vegetative plant parts of kale and Swiss chard) mineral-N released exceeded cabbage N uptake in the high input systems (Fig. 3c). The SMN was significantly higher ($P < 0.001$) at day 0 (before input application) for cabbage in the high input systems than in the low input systems at Chuka but declined to 4 kg ha^{-1} at 43 DAS (pre-cupping stage, Fig. 3c). An increase in SMN was also observed at 71 DAS (head formation stage of cabbage) with Org-High showing appreciably higher SMN than the other systems. The SMN at Thika was significantly lower ($P < 0.001$) on day 0 (at before input application) than at Chuka. Soil mineral-N increased in all the systems at 25–44 DAS (vegetative and pre-cupping stages of cabbage and the development of harvestable vegetative plant parts for kale and Swiss chard) except in Org-High, where there was a decline at 44 DAS (pre-cupping stage of cabbage). Soil mineral-N was similar for all the systems at 83–114 DAS (corresponding to the head formation of cabbage and development of harvestable vegetative plant parts of kale and Swiss Chard and harvesting stages) at Thika.

The effects of farming and cropping systems on patterns and degree of N synchrony

Potato

N fluxes during potato growth period ranged from − 5.7 to 14 kg ha^{-1} day^{-1} at Chuka and − 11 to 41 kg ha^{-1} day^{-1} at Thika. Positive N flux differences were observed at 3–12 DAS (corresponding to planting and germination stages) of potato in all the farming systems (Fig. 4). At Chuka, negative N flux differences (immobilisation) were observed at 44–63 DAS (tuber initiation and bulking stages) in Conv-High and Org-High; and at 44 and 93 DAS (tuber initiation and harvesting stages) in Conv-Low and Org-Low. At Thika the positive N flux differences in Conv-High and Org-High followed a similar pattern. They were observed at 3–12 DAS (planting and germination). Negative N flux differences at Thika were observed in Conv-High at 63 DAS (Tuber initiation) and in Org-High at 106 DAS. At 63 DAS (tuber bulking stage), the Org-High system at Thika exhibited a positive N flux difference, in contrast to the negative N flux differences in all the other farming systems ($P < 0.002$).

Maize

N flux differences during the maize cropping period ranged between − 60 and 23 kg ha^{-1} day^{-1} (Fig. 4). At Chuka, the two organic systems showed a higher ($P < 0.002$) negative N flux difference at 7 DAS (the germination stage) than the two conventional systems. In addition, a negative N flux difference was observed at 28–61 DAS (the vegetative to tasselling stages). The

Table 4 Quality of organic inputs used in different farming systems during the three different seasons in the long-term system comparison trials at Chuka and Thika in the Central Highlands of Kenya

Site	Cropping period	System	Inputs	pH	EC (S m^{-1})	org C (%)	NO$_3$-N (mg kg^{-1})	NH$^+$-N (mg kg^{-1})	N (%)	P (%)	K (%)	Lignin (%)	Polyphenols (%)	C:N ratio	Lignin:N ratio
Chuka	Potato	Conv-High	FYM	8.40±0.04	0.28±0.005	24.7±3	nd	nd	1.50±0.04	0.32±0.00	1.19±0.06	10.6±0.8	nd	16±1.6	7±0.7
		Org-High	Compost	8.56±0.01	0.28±0.014	19.5±1.2	nd	nd	1.29±0.02	0.33±0.01	1.19±0.13	14.8±0.8	0.04±0.05	15±0.3	16±3.9
			Mulch	6.58±0.03	nd	54.5±1.9	nd	nd	1.92±0.03	0.26±0.01	1.85±0.04	19.5±0.3	0.90±0.1	28±1.8	10±0.6
			Maize	7.58±0.06	nd	46±1.14	nd	nd	1.46±0.09	0.21±0.01	0.64±0.12	5.9±0.6	1.48±0.1	25±0.6	3±0.8
			Mucuna	5.41±0.08	nd	47±1.92	nd	nd	2.9±0.13	0.07±0.02	0.47±0.12	8.9±0.5	0.36±0.1	16±0.9	7±0.5
			Tithonia	6.58±0.03	nd	nd	nd	nd	4.37±0.18	0.43±0.05	1.72±0.11	nd	1.10±0.1	nd	nd
		Conv-Low	FYM	8.59±0.00	0.13±0.001	24.5±2	nd	nd	1.46±0.03	0.36±0.01	0.29±0.07	12.8±0.6	0±0.2	17±1.7	9±0.6
		Org-Low	FYM	8.97±0.00	0.24±0.005	19.8±0.1	nd	nd	1.07±0.01	0.43±0.00	0.96±0.02	9.5±0.4	0	19±0.3	9±0.4
	Maize	Conv-High	FYM	7.23±0.01	0.16±0.001	20.1±2.6	nd	nd	2.37±0.02	0.5±0.013	0.93±0.02	19.4±0.4	nd	8±1.0	8±0.1
		Org-High	Compost	8.78±0.14	0.15±0.005	10.3±1.3	nd	nd	1.45±0.03	0.37±0.00	1.11±0.00	14.1±0.3	nd	7±1.1	10±0.1
		Conv-Low	FYM	8.58±0.19	0.27±0.009	25±1.7	nd	nd	2.26±0.09	0.45±0.01	1.95±0.03	21.7±1.0	nd	11 ±1.2	10±0.1
		Org-Low	FYM	7.77±0.08	0.11+0.014	20.3±0.1	nd	nd	2.28±0.02	0.49±0.01	0.92±0.00	18.9±0.8	nd	9±0.1	9±0.3
	Vegetable	Conv-High	FYM	9.03±0.08	nd	18.6±4.9	80±2	63±3	1.13±0.05	0.27±0.05	1.32±0.14	13.7±0.4	0.2±0.01	16±3.8	12±0.1
		Org-High	Compost	8.32±0.18	nd	43.8±2.6	121±4	53±18	1.11±0.03	0.4±0.02	1.99±0.14	12.4±0.4	0.2±0.01	40±5.1	11±0.2
			Stover	nd	nd	nd	nd	nd	2.25+0.26	0.03+0.01	0.28±0.06	nd	0.9+0.1	nd	nd
			Tithonia	nd	nd	nd	nd	nd	4.37+0.04	0.43+0.02	1.72+0.2	nd	1.1+0.5	nd	nd
		Conv-Low	FYM	8.76±0.01	nd	36.2±1.2	141±1	55±2	1.53±0.03	0.33±0.01	1.71±0.18	18.6±1.1	0.4±0.2	24±1.4	12±0.4
		Org-Low	FYM	9.04±0.08	nd	26±5.0	136±11	58±1	1.14±0.11	0.38±0.03	1.59±0.13	12.7±0.7	0.2±0.2	23±1.3	11±0.5
Thika	Potato	Conv-High	FYM	7.85±0.28	0.27±0.005	19.7±4	nd	nd	0.66±0.07	0.19±0.00	0.97±0.09	9.5±1.9	nd	30±3.2	15±1.7
		Org-High	Compost	8.38±0.02	0.26±0.005	14.5±0.6	nd	nd	1.51±0.02	0.25±0.01	0.83±0.07	8.21±1.2	nd	10±1.4	5±0.3
			Maize	7.38±0.04	nd	47.3±1.1	nd	nd	3.01±0.02	0.12±0.01	0.51±0.26	nd	nd	16±1.7	nd
			Mucuna	5.57±0.06	nd	49.6±1.0	nd	nd	3.96±0.04	0.15±0.01	0.51±0.04	nd	nd	13±1.3	nd
			Tithonia	6.43±0.03	nd	nd	nd	nd	3.03±0.13	0.41±0.03	6±0.72	nd	nd	nd	nd
		Conv-Low	FYM	8.20±0.00	nd	33.9±1.3	nd	nd	2.54±0.06	0.25±0.00	1.02±0.04	9.9±0.2	0.4±0.1	13±0.2	4±0.1
		Org-Low	FYM	7.79±0.02	0.32±0.002	13.3±1.6	nd	nd	1.47±0.10	0.22±0.00	1.31±0.14	13.8±0.8	nd	10±7.2	10±3.0
	Maize	Conv-High	FYM	8.21±0.03	0.38±0.022	47.6±4	440±28	95±27	0.95±0.18	0.27±0.04	1.56±0.00	13.1±1.3	3.2±0.3	55±5.9	15±2.2
		Org-High	Compost	7.89±0.03	0.36±0.003	26.7±4.2	311±9	53±11	0.80±0.07	0.2±0.006	1.24±0.02	11.3±0.8	2.1±0.3	32±2.6	14±0.6
		Conv-Low	FYM	8.25±0.04	0.13±0.015	40.4±2.6	58±29	147±12	0.96±0.03	0.19±0.00	0.78±0.03	13.5±0.4	2.3±0.0.1	42±1.6	14±0.1
		Org-Low	FYM	7.34±0.10	0.26±0.008	21.5±2.9	352±20	192±65	0.89±0.09	0.24±0.00	1.08±0.08	11.6±1.0	2.3±0.2	27±5.0	13±0.3
	Vegetable	Conv-High	FYM	8.39±0.04	nd	20.1±3	247.1±84	6±1	0.88±0.06	0.17±0.00	0.83±0.16	13.0±0.1	0±0. 1	24±3.8	16±0.5
		Org-High	Compost	8.48±0.02	nd	12.9±1.1	225±49	24±7	0.66±0.04	0.14±0.00	0.72±0.03	9.0±0.7	nd	20±2.1	14±0.2
			Stover	nd	nd	nd	nd	nd	1.87±0.07	0.03±0.00	0.20±0.01	nd	nd	nd	nd
			Tithonia	nd	nd	nd	nd	nd	4.36±0.10	0.22±0.03	3.5±0.80	nd	2.0±0.8	nd	nd
		Conv-Low	FYM	8.81±0.02	nd	20.2±3	164±24	311±57	1.26±0.04	0.36±0.00	1.41±0.01	14.1±0.6	0.3±0.1	17±2.9	11±0.9
		Org-Low	FYM	7.79±0.13	nd	14.1±2.4	301±15	35±2	0.43±0.03	0.1±0.004	0.19±0.01	5.9±1.0	nd	33±5.6	16±3.5

Conv-Low conventional low input system, *Conv-High* conventional high input system, *Org-Low* organic low input system, *Org-High* organic high input system negative N difference was significantly more pronounced ($P < 0.001$) in the high input systems than the low input systems. By contrast, positive N flux differences were observed at 73–157 DAS (the silking and harvesting stages) in all the systems. At Thika, negative N flux differences were observed at 28–41 and 159 DAS (corresponding to the germination, vegetative and harvesting stages of maize crop) in all the farming systems. Positive N flux differences were observed at 70–94 DAS (corresponding to the tasselling and silking stages).

Vegetables

N flux differences during the growth periods for cabbage, kales and Swiss chard ranged from − 25 to 8.5 kg ha^{-1} day^{-1}. At Chuka (Fig. 4), a lower positive N flux ($P < 0.001$) was observed in Conv-High than in the other systems at 69 DAS (head formation stage of cabbage) and at 109 DAS (harvest), The negative N flux differences were significantly higher ($P < 0.01$) in the high input systems than the low input systems. Positive N flux differences were observed at 9 and 69 DAS (vegetative and heading stage) of the cabbage and kale/Swiss chard intercrop and negative N flux differences were observed at 41 DAS (the precupping stage of cabbage and the development of harvestable vegetative plant parts for kale and Swiss chard).

At Thika, positive N flux differences were observed at 9 to 26 DAS (the vegetative stage) and at 117 DAS (harvest) stages in all the systems except in Org-High (at the vegetative stage) and Conv-High and Org-Low (at harvest), when a positive N flux difference was observed. At 74 DAS (head formation stage of cabbage), Conv-High and Org-High showed negative N flux differences while Conv-Low and Org-Low had significantly positive N flux differences ($P < 0.001$).

Discussion

The effects of farming systems on the synchrony of N supply to uptake

Potato

The higher rates of N release and positive N fluxes in amended soil during the early growth stages of potato in all the farming systems can be attributed to the provision of additional sources of carbon and materials with a low C:N ratio (e.g. FYM and compost) as well as the residual effects of previously applied inputs. Additions of fresh carbon sources are associated with increases in microbial biomass (Wang et al. 2015) that enhance rapid decomposition (El-Sharkawi 2012). During decomposition, the low C:N ratio materials could be expected to supply sufficient N to meet the N needs of the decomposing organisms (El-Sharkawi 2012). This led to a net release and build-up of mineral-N in the soil (mineralization) and, hence, the high mineral-N observed at the early growth stages of potato. On the other hand, the use of organic inputs with high lignin content at Chuka could account for the low rates of N release at the initial stages of incubation (compared to the N released at Thika). The variation in the lignin content of the inputs may also account for the variations in the N release rates during potato growing period. Vanlauwe et al. (2005) investigated the relationship between the lignin:N ratio of materials and N release and concluded that there was a negative correlation between materials with a high lignin content (Class A) and N release. These reasons, coupled with the residual effects of previously applied inputs, were responsible for the major increase in N availability, in all the farming systems, before the crop was fully established.

High positive N flux differences observed in Org-High throughout the potato growth period at Thika indicate that large amounts of mineral-N were released in this system. This can be attributed to the application of Mucuna biomass (on average 7.3 t ha^{-1}) which was expected to supply 211 kg N ha^{-1} compared to 3.3 t ha^{-1} applied at Chuka (with a potential to supply 127 kg N ha^{-1}). Kaizzi et al. (2004) reported that Mucuna accumulates 170 and 350 kg N ha^{-1} in low and high potential agro-ecological zones, respectively. The resulting asynchrony observed at the planting and vegetative stages (3–33 DAS) of potato is in line with the findings of Lynch et al. (2008) who reported increases in mineral-N concentrations 30–35 days after planting potato. The negative N flux differences observed at the tuber initiation and bulking stages in Conv-High and Org-High at Chuka, and in Conv-High and Conv-Low at Thika were due to higher crop N demand which exceeded the mineral-N supply from the inputs. At this stage the crop was likely to derive extra N from lower soil layers, as shown by a lowering of NO_3^--N at a depth of 0.2–0.4 m (Musyoka et al. 2019). The positive fluxes observed in the high input systems at Chuka could have been due to a reduction in N uptake, due to the effect of late blight (*Phytophthora infestans*) disease which affected potato at this site. The result runs contrary to the observations of Nyiraneza and Snapp (2006), who reported synchrony of N release which matched potato N uptake throughout its growth period under cover crops, poultry manure and fertilizer application. The similarity in the pattern of N synchrony and the degree of N fluctuation in all the farming systems contradicts earlier reports by Kirchmann et al. (2008) that nutrient release in conventional systems always meets crop N demand, which is not the case in organic systems. The difference in our results can be attributed to the difference in the quality of organic inputs and their N release rates as well as the integrated application of synthetic fertilizer and FYM in our conventional systems.

Maize

Even though there was high residual mineral-N in the top-soil (due to poor N uptake by the preceding potato crop caused by late blight disease) at planting, there were negative rates of N release and negative N fluxes in the amended soil at the beginning of maize cropping season in the high input systems at Chuka. This indicates that immobilization occurred at the initial growth stages (from planting to the V8 leaf stage of maize). This can be attributed to the effects of the applied organic inputs with a high lignin content ($> 15\%$) at Chuka. The application of these organic inputs stimulated microbial growth and development, with the microbes making additional demands on the available N in the soil in order to decompose the applied organic inputs, resulting in N immobilization (Chen et al. 2014; Mooshammer et al. 2014). With time, the available carbon sources become exhausted, resulting in the death of the microbes and the release of N that they contain (Kuzyakov 2010), which probably explains the high N release (mineralization) observed at 60–120 DAS (tasselling and silking stages).

The decline in mineral-N released from amended soil and soil alone between the V8 leaf and silking stages of maize (41–100 DAS) indicates the possibility of NO_3^--N being desorbed from the resin and assimilated by soil microbes (microbial immobilization) due to the long period (100–158 days) that the resin bags were deployed. Giblin et al. (1994) found that short deployment periods (44 days) of resins resulted in higher mineral-N release than long (whole season) deployment periods. There is also the possibility of N loss through denitrification on the resin films, possibly during periods of low oxygen availability. Therefore, it appears advisable not to incubate resins for extended periods in future studies. The duration at which the resin is kept as a sink is further dependent on the exchange capacity of the resin, nutrient availability and the conditions of the soil at the time of burial (Qian and Schoenau 2002).

The significantly insufficient N asynchrony observed in Org-High at the germination stage at Chuka can be attributed to immobilization caused by the reasons discussed above. Insufficient-asynchrony, which mainly occurred at the vegetative stage of the maize crop (28 to 61 DAS), in all farming systems at both sites, can be attributed to low mineral-N release from the amended soil which was unable to meet the crop's high N demand. The high crop N demand during this period could have been partly met by the crop deriving N from lower soil layers. This also indicates that the supply of available N needs to be enhanced at these critical stages. One practical way would be to reduce the amount of N applied at the planting stage and increase the N supplied as a top dressing during the reproductive stages (V8 to silking stages of maize) to match the high N demand by the crop. This can be achieved by using CAN in conventional systems and the use of plant teas (prepared from leaves and soft twigs of Tithonia) in organic systems (Chikuvire et al. 2013; Adamtey et al. 2016). By contrast, there was an excess of N at the silking and harvesting stages (70–94 and 157 DAS) in all the farming systems, which can be explained by an increase in mineral-N release from both the residual and new inputs applied as top dressing in high input systems and crop failure in the in the low input systems at Thika, which affected N uptake (Musyoka et al. 2017). One implication of this is the likelihood of more N leaching into the environment. Our companion paper (Musyoka et al. 2019) confirms this assertion.

Table 5 Mineral-N released from soil alone, soil amended with inputs, inputs alone and percentage of applied N released in the long-term farming systems comparison trials at Chuka and Thika in the Central Highlands of Kenya

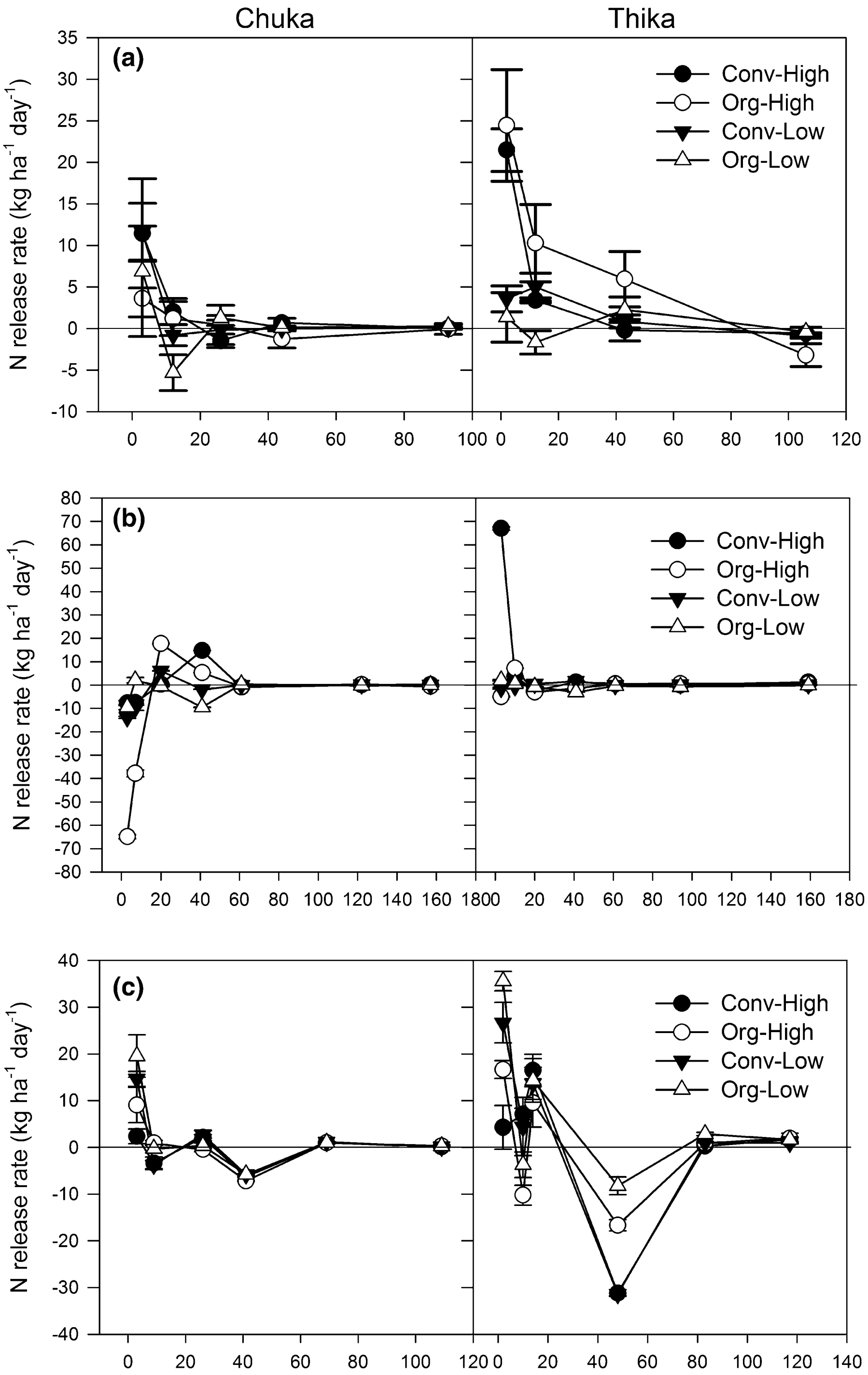
		Potato cropping season				Maize cropping season				Vegetables cropping season			
		Mineral-N released from soil (kg ha^{-1})	Mineral-N released from soil + Inputs (kg ha^{-1})	Mineral-N released from Input (kg ha^{-1})	N released as % of N applied[a] (%)	Mineral-N released from soil (kg ha^{-1})	Mineral-N released from soil + Inputs (kg ha^{-1})	Mineral-N released from Input (kg ha^{-1})	N released as % of N applied[a] (%)	Mineral-N released from soil (kg ha^{-1})	Mineral-N released from soil + Inputs (kg ha^{-1})	Mineral-N released from Input (kg ha^{-1})	N released as % of N applied[a] (%)
Systems	Conv-High	176	231ab	55	40	118	120ab	2	5	112ab	180ab	68ab	44
	Org-High	219	312a	93	27	150	127a	− 23	− 16	133a	250a	118a	41
	Conv-Low	125	141b	16	39	95	96b	1	20	97b	122b	25b	49
	Org-Low	128	152b	24	45	103	95b	− 8	− 19	105b	129b	24b	43
Site	Chuka	152	178b	26	31	115	141a	26a	38	74b	108b	35	45
	Thika	173	240a	67	44	118	78b	− 37b	− 68	150a	233a	83	43
Chuka	Conv-High	131bc	186	55	34	102b	145	43	38abc	75	114	39	34
	Org-High	219ab	231	12	4	170a	166	− 5	− 2abcd	102	165	63	28
	Conv-Low	133bc	141	8	25	100b	129	29	46ab	58	68	11	47
	Org-Low	124c	154	30	61	97b	122	25	71a	60	85	25	71
Thika	Conv-High	221a	277	56	45	134ab	94	− 40	− 47cde	149	246	97	53
	Org-High	219ab	393	174	50	129ab	89	− 40	− 30bcde	164	335	171	54
	Conv-Low	118c	141	23	52	90b	63	− 27	− 85de	135	176	41	50
	Org-Low	132bc	150	18	28	108b	67	− 41	− 109e	150	173	22	15
Source of variations													
System		***	***	ns	ns	***	***	ns	ns	*	***	**	ns
Site		ns	*	ns	ns	ns	***	***	***	***	***	ns	ns
System × Site	*	ns	ns	ns		ns	ns	**		ns	ns	ns	

Conv-Low conventional low input system, *Conv-High* conventional high input system, *Org-Low* organic low input system, *Org-High* organic high input system, *ns* not significant

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

[a] N released expressed as a percentage of the total N applied

Fig. 2 Net mineral-N release rates of applied inputs in different farming systems during **a** potato **b** maize and **c** vegetable cropping periods at Chuka and Thika (N released from inputs = N mineralized from amended soil − N mineralized from soil alone; negative values represent N immobilization). *Note*: Bars for the standard error of means are only shown when they are larger than the symbols



Vegetables

N release rates were high during the initial 10 days after incubation in the amended soils. This can be attributed to the application of fresh carbon sources with relatively low N, C:N ratio and lignin content of < 15% (class III, Gachengo et al. 2004) which resulted in short term mineralization. However, application of these materials could also have resulted in increasing the microbial population which would

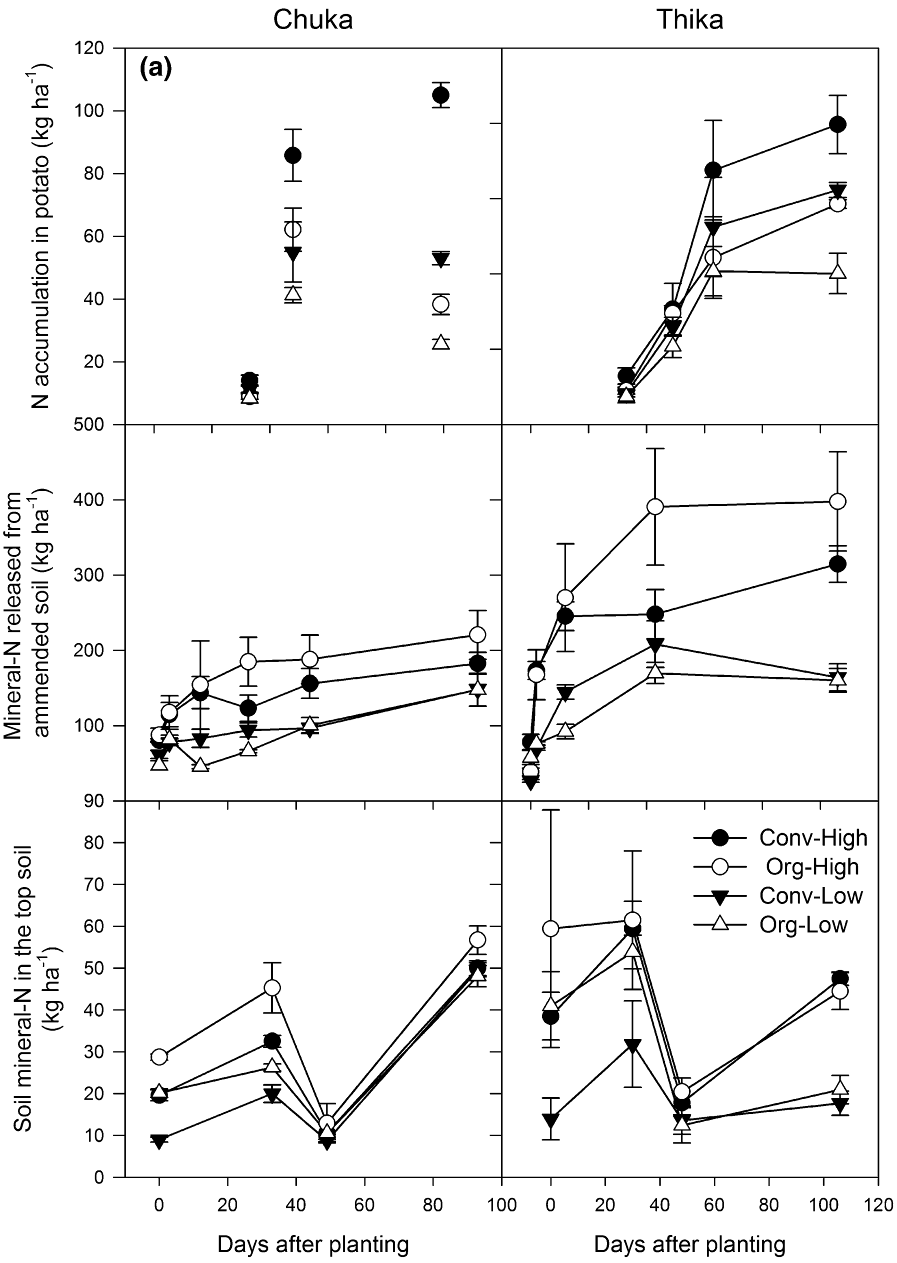
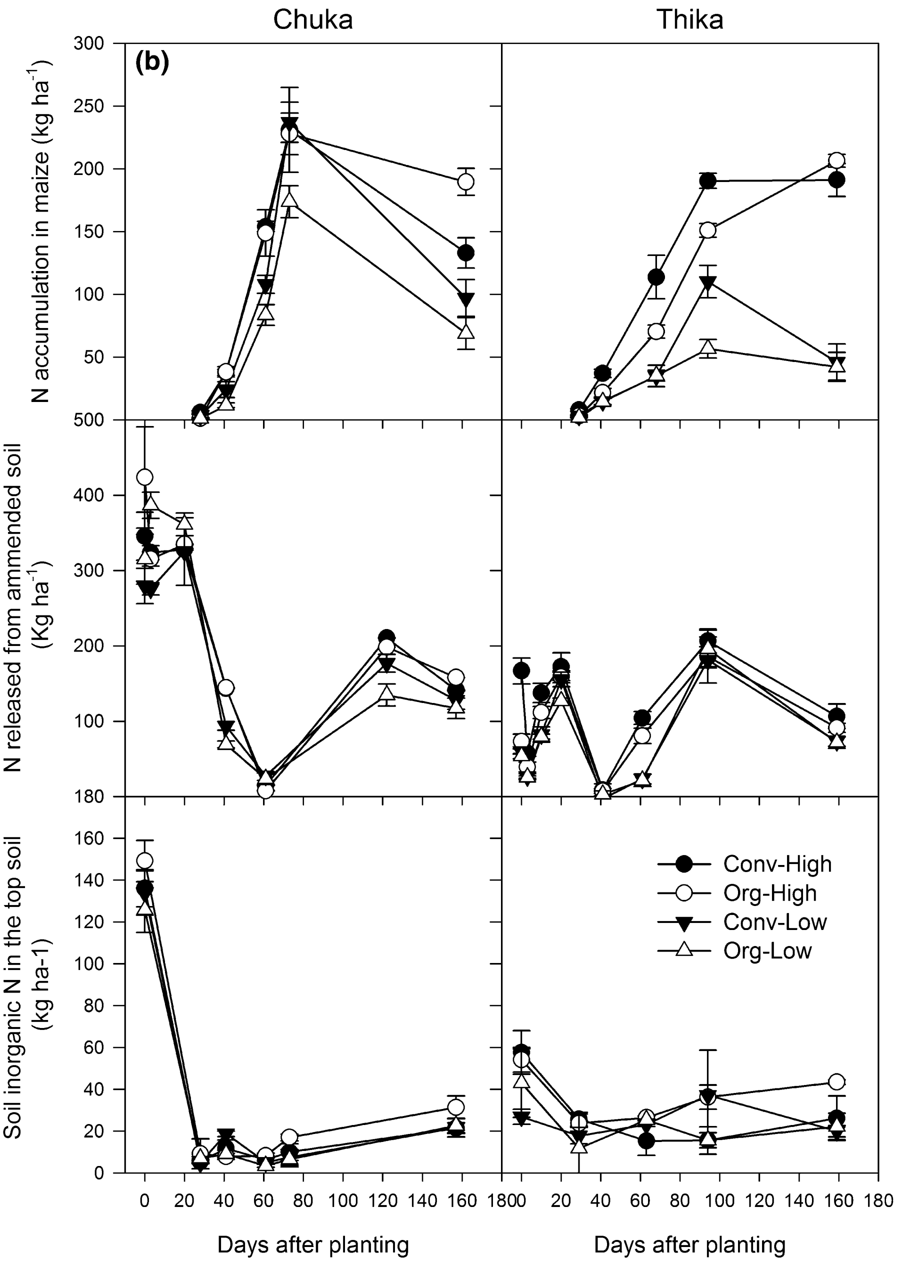


Fig. 3 **a** N uptake, cumulative N released from the amended soils (buried bags) and soil mineral-N (under natural soil-crop interaction) in different farming systems at different growth stages of potato at Chuka and Thika in the Central Highlands of Kenya. *Note*: Bars for the standard error of means are only shown when they are bigger than the symbols. **b** N uptake, cumulative N released from amended soil (buried bags) and soil mineral-N in different farming systems at different stages of maize at Chuka and Thika. *Note*: Bars for the standard error of means are only shown when they are bigger than the symbols. **c** N uptake, cumulative N released from amended soil (buried bags) and soil mineral-N (0–20 cm) (under natural soil-crop interaction) in different farming systems at different stages of vegetables at Chuka and Thika sites. *Note*: Bars for the standard error of means are only shown when they are bigger than the symbols

have taken up much of the available N in the soil to meet their N requirements (El-Sharkawi 2012; Wang et al. 2015). This may explain the short period of immobilization observed at the vegetative and reproductive stages of vegetables in both the high and low input systems at both sites. The increase in N release rates at the pre-cupping and heading stages of cabbage and the development of harvestable vegetative plant parts for kale and Swiss chard (40–70 DAS) in all the systems can be explained by the top dressings of CAN or Tithonia tea that were applied. Insufficient-N asynchrony was observed during the vegetative and pre-cupping stages of cabbage and development of harvestable vegetative plant parts for kale and Swiss chard (26–41 DAS at Chuka and 48 DAS at Thika) in all the systems and at harvest (107 DAS) in the high input systems. This is an indication that the top dressings were inadequate to meet crop N demand and points to the need to increase the N application rate at this stage. By contrast, the excess asynchrony during

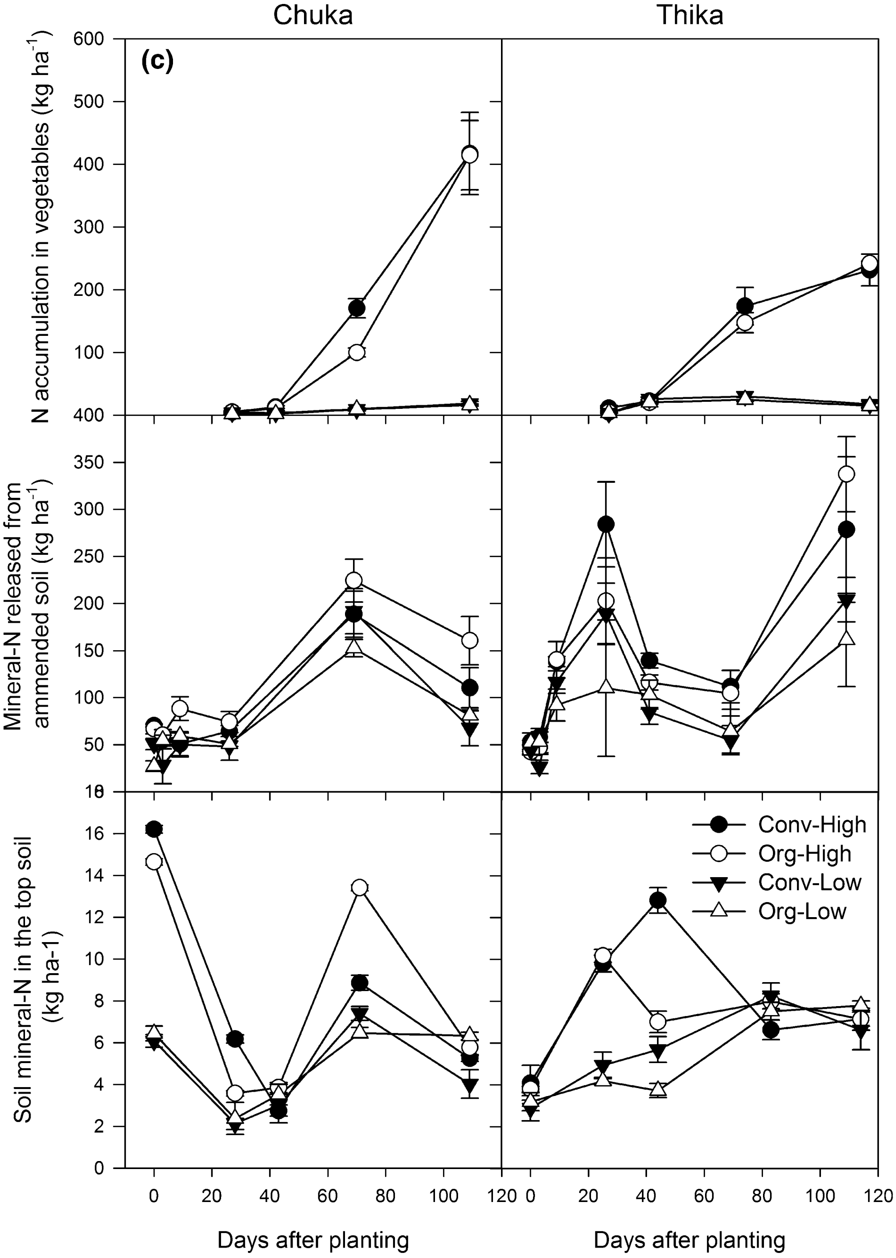
Fig. 3 continued



the head formation stages of cabbage (69 DAS) in both high input systems at Chuka can be attributed to higher mineral-N release from the inputs as a result of the 2nd top-dressings with CAN and Tithonia tea. We also observed excess asynchrony at the development of harvestable leaves stage (69 DAS) of kale and Swiss chard in both low input systems at both sites. This was probably due to the effect of drought which led to low N uptake (Musyoka et al. 2017).

Research has shown that 4–57% of N applied as manure or compost can be released in the year following application (Muñoz et al. 2008). In our case, 4 to 71% of total N applied was released during the potato (three months) and vegetable (three months) cropping periods in the four different systems. The differences in mineral-N released can be attributed to variations in the quality of inputs used. The observed excess and insufficient asynchronies during the three

Fig. 3 continued



cropping periods could have been higher if root N demand was also considered.

The effects of the environment on the synchrony of N supply and uptake

The effects of the environment on mineral-N release were mainly associated with the quality of FYM and composts used at each site. The farm yard manure available at Chuka site was from a zero-grazing unit, while the one for the Thika site was from free-grazing cows and goats, which may explain the difference in FYM and compost quality at the two sites. Seasonal variations in FYM quality were probably due to the seasonality of fodder available for the livestock. The C:N ratios of compost and FYM (7–55) were within the range of 5–81 obtained from manures and composts sampled from Central Highlands of Kenya by

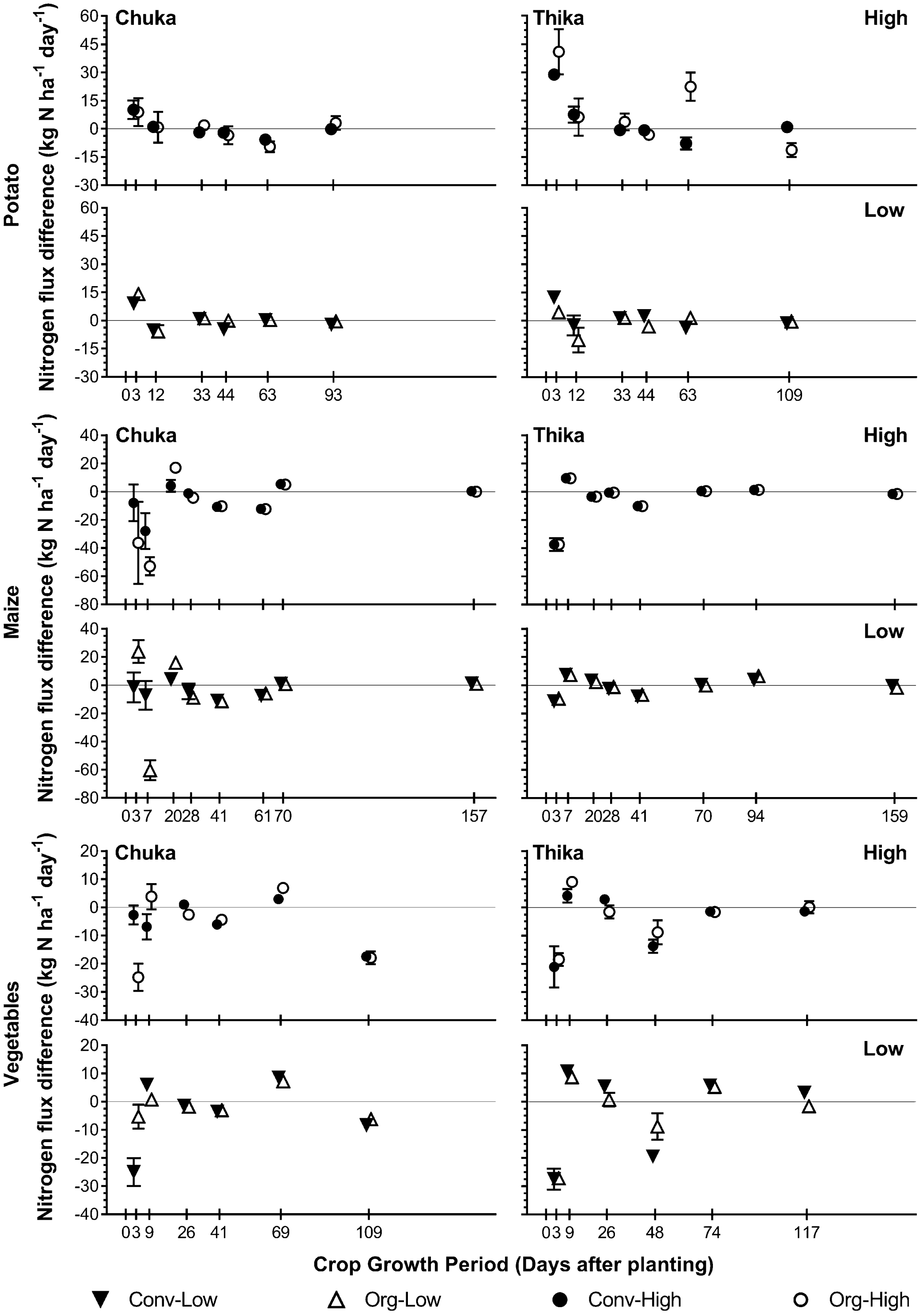


Fig. 4 Nitrogen flux differences (calculated per day) between N release and N uptake (amended soil) under potato, maize and vegetable based conventional and organic farming systems at different input intensities at Chuka and Thika in the Central Highlands of Kenya. *Note*: Bars for the standard error of means are only shown when they are bigger than the symbols

Lekasi et al. (2003). Nitrogen levels in the FYM and compost used in the study ranged from 0.43–2.54%, which was higher than the 0.33–1.91% reported by the same authors. The organic input qualities that mostly affected mineral-N release were N and the C:N and Lignin:N ratios. This is in line with the findings of other authors (Vanlauwe et al. 2005) who found that C, N, C:N ratio, Lignin, Lignin:N ratios influence decomposition and N release rates. The low C:N ratio of the compost is a result of the high proportion of N rich Lantana biomass and FYM used as composting material whilst that of FYM may be due to management effects such as the use of carbon rich materials as bedding material for livestock and the handling of FYM during collection. The differences between N fluxes observed at Chuka and Thika can also be partly attributed to differences in soil characteristics and mineralogy (Adamtey et al., unpublished), total active bacteria and archaea population (Karanja et al., unpublished), and the amount and distribution of rainfall (with Thika being drier).

Conclusions

N release rates were high at the initial stages of the potato and vegetable crops, indicating high N availability at the time of low crop N demand. As a result, this N may be susceptible to being lost. Mineral-N release and release rates were highly variable and dependent on the quality of inputs (which varied between the seasons). This means that organic farmers need to carefully assess the quality of organic inputs that they use, and the timing of application, if they are to supply sufficient (and not excessive) N to the crop. The study also revealed that the conventional and organic farming systems exhibited similar periods of N excess and insufficient-asynchrony. Excess-asynchrony was pronounced during early crop stages and at harvest while insufficient-asynchrony occurred at peak N demand stages of the crop in all the systems. This indicates the need to delay N application to coincide with periods of high N demand in order to achieve synchrony at the early stages of the crop. Thus, there is a need to reduce N application at early crop growth stages and increase N supplementation at the reproductive stages to more closely align N supply with crop N demand. Further research is needed on more accurate N synchrony estimates as crop root N was not included in this study. There is also a need to further study the temporal dynamics of N immobilization/remobilization by microbes of complex organic inputs which could have led to underestimations of fluctuations mineral-N release.

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