Effects of fertilizer on inorganic soil N in East Africa maize systems: vertical distributions and temporal dynamics

Katherine L. Tully,[1,2,6] Jonathan Hickman,[2] Madeline McKenna,[3] Christopher Neill,[4,5] and Cheryl A. Palm[2]

[1]*Department of Plant Science and Landscape Architecture, University of Maryland, College Park, Maryland 20742 USA*
[2]*Agriculture and Food Security Center, The Earth Institute, Columbia University, New York, New York 10025 USA*
[3]*Department of Earth and Environmental Sciences, Columbia University, New York, New York 10025 USA*
[4]*The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts 02543 USA*
[5]*Department of Ecology and Evolutionary Biology, Brown University, Providence, Rhode Island 02912 USA*

Abstract. Fertilizer applications are poised to increase across sub-Saharan Africa (SSA), but the fate of added nitrogen (N) is largely unknown. We measured vertical distributions and temporal variations of soil inorganic N following fertilizer application in two maize (*Zea mays L.*)-growing regions of contrasting soil type. Fertilizer trials were established on a clayey soil in Yala, Kenya, and on a sandy soil in Tumbi, Tanzania, with application rates of 0–200 kg N/ha/yr. Soil profiles were collected (0–400 cm) annually (for three years in Yala and two years in Tumbi) to examine changes in inorganic N pools. Topsoils (0–15 cm) were collected every 3–6 weeks to determine how precipitation and fertilizer management influenced plant-available soil N. Fertilizer management altered soil inorganic N, and there were large differences between sites that were consistent with differences in soil texture. Initial soil N pools were larger in Yala than Tumbi (240 vs. 79 kg/ha). Inorganic N pools did not change in Yala (277 kg/ha), but increased fourfold after cultivation and fertilization in Tumbi (371 kg/ha). Intra-annual variability in NO_3^--N concentrations (3–33 µg/g) in Tumbi topsoils strongly suggested that the sandier soils were prone to high leaching losses. Information on soil inorganic N pools and movement through soil profiles can h vulnerability of SSA croplands to N losses and determine best fertilizer management practices as N application rates increase. A better understanding of the vertical and temporal patterns of soil N pools improves our ability to predict the potential environmental effects of a dramatic increase in fertilizer application rates that will accompany the intensification of African croplands.

Key words: African Green Revolution; fertilizer; Gliricidia sepium; maize; nitrogen variability; sub-Saharan Africa.

Introduction

Across most of the globe, agricultural yields have doubled over the last 50 years because of improved germplasm, increased inorganic fertilizer application, and the expansion of irrigated agriculture (Tilman 2002). Still, hunger and malnutrition persist in many developing countries because of food shortage and food distribution problems. Currently, fertilizer application rates in most farm fields across sub-Saharan Africa (SSA) do not compensate for the nutrients exported through the crop harvest (Sanchez 2002, Vitousek et al. 2009), and only about 4% of cropped lands are irrigated (Wood et al. 2000). As a result, this region suffers from declining soil fertility and low grain yields. Widespread food shortages force the region to rely heavily on food aid, and 214 million people in SSA (about 24% of the population) suffer from chronic undernourishment (FAO et al. 2014).

In 2004, the former UN Secretary General, Kofi Annan called for a uniquely "African Green Revolution"

(AGR; Annan 2004) to rapidly increase agricultural productivity by combining advances in agricultural research with new policy instruments (Sanchez et al. 2009). A key strategy of the AGR is to increase the use of fertilizers, high-yielding seeds, and agricultural extension services (Denning et al. 2009, Sanchez et al. 2009). The Alliance for a Green Revolution in Africa aimed to increase fertilizer use in the region 11-fold, from 7 to 75 kg of fertilizer/ha/yr by 2015 (Hickman et al. 2014). Numerous national government agencies and non-government and international organizations currently support programs that provide agricultural inputs at subsidized rates or through rural credit. Recent studies show that local cereal yields may double or even triple where adoption rates of both improved seeds and fertilizers are high (Sanchez et al. 2007, Denning et al. 2009, Nziguheba et al. 2010, Snapp et al. 2010, Sanchez 2015).

Little is known about the fate of these additional nutrients, especially nitrogen (N) in SSA croplands. High rates of N fertilizer use in agroecosystems can lead to a number of environmental impacts including increased concentrations of nitrate (NO_3^-) in ground and surface waters (Carpenter et al. 1998, Galloway et al. 2003) and

increased soil emissions of nitrous oxide (N_2O), a powerful greenhouse gas (Forester et al. 2007). The magnitude and dominant pathways for N loss are strongly controlled by soil type and land use practices, both of which vary widely across SSA (Dixon et al. 2001, Dewitte et al. 2013).

Edaphic factors, such as texture and mineralogy, are important determinants of N storage and loss in soils. Soil texture can influence the rate of water movement and storage, and therefore, the ability of biotic and chemical processes to transform, capture, and/or retain N. Soil mineralogy controls both particle size and the charge distribution that lead to cation exchange capacity (CEC; Brady and Weil 2007), which in turn affect both nutrient storage and loss. In weathered, tropical soils, variable charge 1:1 clay minerals can also develop net anion exchange capacity (AEC) at low pH, which can lead to NO_3^- adsorption and reduction of NO_3^- leaching losses (Berg and Thomas 1959, Ishiguro et al. 1992, Bellini et al. 1996, Katou et al. 1996). When coupled with climatic factors, especially rainfall regimes, soil properties can influence both the magnitude and pathways for N loss. For example, in tropical regions with clayey soils and distinct wet and dry seasons, the onset of rains can result in a pulse of NO_3^- in soil solution caused by rapid mineralization of soil organic matter, often called the Birch effect (Birch 1964). This pulse of NO_3^- has been observed in clayey soils in SSA (Wild 1976, Chikowo et al. 2004) and many other tropical regions (Hardy 1946, Wetselaar 1961). Sandy soils are less likely to show an initial pulse of NO_3^- in the topsoil because soil organic matter content is often low and water tends to infiltrate rapidly, quickly moving solutes down the soil column. Soils with low water-holding capacity also have short water residence time, which may increase N leaching because there is less time for plant or microbial N uptake and the chemical reactions that exchange or immobilize N (Schmidt et al. 2011; T. A. Russo, et al., *unpublished manuscript*).

The type of fertilizer can also influence the fate and magnitude of losses from agricultural systems. Inorganic fertilizers, such as diammonium phosphate (DAP) and urea, are immediately available for plant uptake and susceptible to leaching losses and gaseous emissions once ammonium NH_4^+ has been converted to NO_3^- by nitrification. Organic inputs, on the other hand, must first undergo decomposition and mineralization before plants can assimilate N. Leaching losses will likely be reduced in fields receiving organic compared to inorganic fertilizer because of lower N concentrations in the soil solution as nutrients are released more slowly from organics (Palm et al. 2001). Organic matter can also serve as a source of carbon, promoting nutrient recycling and N immobilization.

We examined the changes in the vertical distribution and temporal dynamics of inorganic N in two maize-based systems in East Africa with contrasting soil types receiving a range of N fertilizer rates. One system (in the western highlands of Kenya) has clayey and the other (in mid-western Tanzania) sandy soils. While Africa's soils are highly diverse, these sites represent the end members of the soil texture spectrum and comprise the dominant soil types for the cultivated humid regions of SSA (Ferralsols and Acrisols). We expected that the sandy soils would have high intra-annual variability in N concentrations in response to precipitation events, that the clayey soils would have a larger total inorganic N pool, and that plots receiving organic inputs (in the form of legume plant material) would have a smaller and less variable inorganic N pool. We use the results to suggest how N applications might be better managed to increase maize productivity, while minimizing expensive and potentially detrimental losses of N to the environment.

MATERIALS AND METHODS

Study sites

This study was conducted at two sites that differed in soil texture, mineralogy, and rainfall: (1) Yala, in the highlands of western Kenya, has sandy clay loams of oxidic mineralogy (Eutric Ferralsol; 37% clay in top 15 cm), and (2) Tumbi, in mid-western Tanzania, has loamy fine sand soils (9% clay in top 15 cm) of mixed mineralogy with small amounts of oxidic minerals (Ferric Acrisol; Table 1). Ferralsols and Acrisols comprise 10.3% and 2.9% of the total land area in SSA (Dewitte et al. 2013, Tully et al. 2015a) and are the dominant soil types across the humid agroecological zones of SSA (Bationo et al. 2012). Soils in Yala have much higher clay content (39%) than Tumbi soils (9%; Table 2). Both total topsoil N and extractable P were generally higher in Tumbi than Yala, but Yala topsoils had higher cation exchange capacity and extractable cations than Tumbi topsoils (Table 3).

Yala, Kenya, receives 1816 mm of precipitation per year on average. The region has two rainy seasons: the long rains typically extend from March to June (about 44% of annual rainfall) and the short rains typically extend from October to November/early December (about 25% of annual rainfall; Fig. 1A). Tumbi, Tanzania receives 928 mm of rainfall per year, but, has one rainy season that extends from November to April (Fig. 1E). The mean annual temperature (across four years) was 23.5°C at both sites (Nziguheba et al. 2010, Palm et al. 2010). Both sites are rain-fed, maize-based systems (Dixon et al. 2001).

The experiments were established on lands owned by the Kenya Broadcasting Corporation, Nyamninia in Yala, Kenya (in January of 2011) and at the Tumbi Agricultural Research Institute (ARI) in Tabora, Tanzania (in November of 2012). The Yala site was converted to agriculture in the 1960s or 1970s. The field was left fallow from 1979 to 1989 and from 1994 to 2007; in

TABLE 1. Study site characteristics for Yala, Kenya, and Tumbi, Tanzania.

Location	Elevation (masl)	Major soil type	Clay content (0–30 cm)	Subsoil mineralogy	Annual rainfall (mm)	Major rainy season	Mean annual Temp (°C)	AEZ†
Tumbi, Tanzania	1160	Acrisols	9.0	Mixed	928 Unimodal	November–April	23	Maize-mixed, dry subhumid
Yala, Kenya	1395	Ferralsols	35.9	Kaolinitic and Oxidic	1816 Bimodal‡	March–August	24	Maize-mixed, subhumid tropics

†AEZ is Agroecological zone (Dixon et al. 2001).
‡40–50% of the rain falls during the long rainy season, similar to the amount of rainfall during the one cropping season in Tumbi.

other years, maize, beans (multiple genera within the *Fabaceae* family), and sweet potatoes (*Ipomoea batatas* (L.) *Lam.*) were grown by local farmers without inorganic fertilizer. Tumbi ARI was established in 1975, and the adjacent miombo woodlands were cleared for maize in 1978. The site was abandoned in 1996 and left fallow until 2003. It was under tobacco from 2003 to 2004 and in natural fallow until the trials were established in November of 2012.

Experimental design

To determine the effect of fertilizer rate on soil N dynamics, experimental plots were established in a randomized complete block design. Plots were amended with six different levels of inorganic fertilizer: 0, 50, 75, 100, 150, and 200 kg N/ha, applied adjacent to the plant. In Tumbi, maize was planted in a ridge-furrow system to conserve rainwater and to follow local practice. Maize is not typically ridged in Yala, so we planted maize on a flat field. In accordance with AGR protocols, we used a split fertilizer application. One-third was applied at planting as DAP in the same hole as the seed. The remaining two-thirds was added 5–6 weeks later (maize growth stage V5-6) as urea within a 15 cm diameter ring around the plant (see Table 4 for fertilizer timetable). In Yala, maize was also cultivated during the short rains, and without fertilizer to follow local practice (Table 4). Yields were not measured. There is no short rainy season in Tumbi, thus only a single crop of maize was planted per year (Table 4).

In Tumbi, we added an additional treatment of *Gliricidia sepium* (Jacq.) Kunth ex Walp, a nitrogen-fixing legume often used in agroforestry systems in the region. Fresh leaves of *Gliricidia* (3.5% N) were collected from outside the experimental area and were added at a rate of approximately 75 kg N/ha (the rate recommended by the AGR) in two applications. We added 8.9 kg of fresh chopped *Gliricidia* leaves and small stems per plot (1.1 kg per ridge, per application; Appendix S1: Eq. S1) at each application. The first organic application occurred two weeks prior to planting and inorganic fertilizer application. We opened the top of the ridge, spread leaves evenly across the top, and covered the leaves with soil. We added the second half of *Gliricidia* leaves at the same time as the second inorganic fertilizer (urea) application (maize growth stage V5-6). In this case, we opened the side of the ridge, spread leaves evenly along mid-ridge, and covered the leaves with soil.

Each treatment was replicated four times, for a total of 24 plots in Yala and 28 plots in Tumbi. Maize was planted in both locations at 30 × 75 cm spacing (Kenya Seed Company WH403 in Yala and Dekalb 8053 in Tumbi). Plots were 18 m^2 (3 × 6 m), with a 0.5-m buffer between each plot in Yala and 1-m buffer between each plot in Tumbi. Each plot contained a total of 80 plants. The outside two rows of maize were considered buffer plants, and all measurements were taken from the center of the plot (10.8 m^2; 24 plants total).

TABLE 2. Soil particle size distribution in Yala, Kenya, and Tumbi, Tanzania, throughout the profile.

Depth (cm)	Yala, Kenya			Tumbi, Tanzania		
	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)
0–15	52.2 (2.4)	12.4 (1.1)	35.2 (2.7)	87.4 (1.2)	3.6 (2.0)	8.9 (0.6)
15–30	52.9 (4.3)	10.3 (0.8)	36.7 (3.5)	88.5 (0.7)	2.4 (0.8)	9.0 (0.5)
30–50	44.6 (1.8)	11.7 (0.8)	43.6 (3.5)	88.9 (0.6)	1.48 (0.0)	9.5 (0.6)
50–100	37.8 (3.2)	9.6 (1.9)	52.5 (4.7)	86.3 (2.2)	2.2 (0.8)	11.4 (3.5)
100–150	39.4	9.6	50.8	90.3	1.8	7.8
150–200	47.4	9.6	42.8	88.3	3.8	7.8
200–250	45.8	9.6	44.5	92.0	0.2	7.8
250–300	43.8	10.3	45.7	92.0	1.8	6.2
300–350	45.4	15.6	38.8	90.4	3.0	6.6
350–400	43.4	17.6	38.8	90.3	1.8	7.8

Notes: Values in parentheses are the standard error of the mean. Samples below 100 cm were composited across plots/blocks, and therefore no standard errors are reported.

TABLE 3. Soil properties (0–15 cm) in Yala, Kenya, and Tumbi, Tanzania.

	Yala, Kenya	Tumbi, Tanzania
pH_{water}	5.97 (0.13)	5.47 (0.32)
P (µg/g)	0.06 (0.005)	0.30 (0.11)
K (mg/g)	50.50 (0.21)	0.71 (0.22)
Ca (mg/g)	19.40 (1.06)	1.13 (0.52)
Mg (mg/g)	2.26 (0.11)	0.30 (0.11)
EC salts (µS/cm)	248.75 (22.89)	18.25 (3.59)
CEC (meq/100 g)	15.40 (0.45)	1.78 (0.58)
Organic C (%)	1.90 (0.08)	2.05 (0.02)
Total N (%)	0.11 (0.00)	0.18 (0.02)

Notes: Values in parentheses are the standard error of the mean.

Maize plants were harvested in mid to late August in 2012 and 2013 in Kenya and in late April in 2013 and 2014 in Tumbi (Table 4). We collected all ears from the inside the buffer area. Total stalks and ears were weighed in the field. Subsamples of grains, stalks, and shelled cobs were weighed fresh within 24 h of sampling. Subsamples were then oven dried at 60°C for 48 h and re-weighed to determine moisture content. The fresh:dry ratios were used to calculate the total plot harvested dry weight (Hickman et al. 2015). Subsamples of grain, cob, and stalks were ground to 2-mm mesh and analyzed for total C and N content using elemental analysis (ICRAF Laboratories, Nairobi Kenya). Nutrient concentrations in maize plant tissues were used to calculate the quantity of N taken up by maize. As stalks were left in the field after harvest, the amount of N exported was calculated as the amount in maize grains alone.

In an undisturbed part of the field in Yala (between the blocks), we measured bulk density with a slide hammer using a stacked-ring method (core volume of 205.9 cm³; Core Sampler Complete, AMS, American Falls, Idaho, USA). This method allowed for multiple samples to be taken in a small area with minimal disturbance to crops, in contrast to the pit and carving methods. In Tumbi, we excavated a 2-m pit and inserted aluminum rings (100 cm³) into the side of the pit in a vertical array and used the carving method to determine bulk density (Gradwell 1972). We used one measurement of bulk density for Yala and one for Tumbi at each depth across all plots.

Soil profile sampling

In Yala, the experimental treatments and maize crops had already been in place for one year prior to the first vertical profile collection. The profile was collected in the unfertilized plots on 23–24 April of 2012, 18 d after planting the second long rain maize crop. In Tumbi, soils were sampled before the fertilizer trial was established from four blocks of the experimental field on 12–13 November 2012, 25 d before planting the first year of maize. In both sites, soils were collected to 400 cm using a 7-cm bucket auger at ten depths: 0–15, 15–30, 30–50, 50–100, 100–150, 150–200, 200–250, 250–300, 300–350, and 350–400 cm. We randomly selected four locations per plot/blocks, and drilled to 15 cm, and composited all four samples (samples were thoroughly mixed in the field). We then randomly selected two of the four holes and drilled three separate depths (15–30, 30–50, and 50–100 cm) and composited each depth. We selected at random one of the holes and drilled six separate depths to 400 cm or until we hit a restriction in the soil profile.

Two additional vertical soil profiles were collected in Yala (in May, 2013 and September, 2014) and one in Tumbi (in May, 2014; Table 4). Soils were collected to 400 cm as described previously and samples were taken within 15 cm of a maize plant, the area where fertilizer was applied. In Yala, soils were collected from the unfertilized plots and the plots receiving 200 kg N/ha/yr. In Tumbi, soils were collected in (1) the unfertilized plots, (2) plots receiving 200 kg N/ha/yr, (3) plots
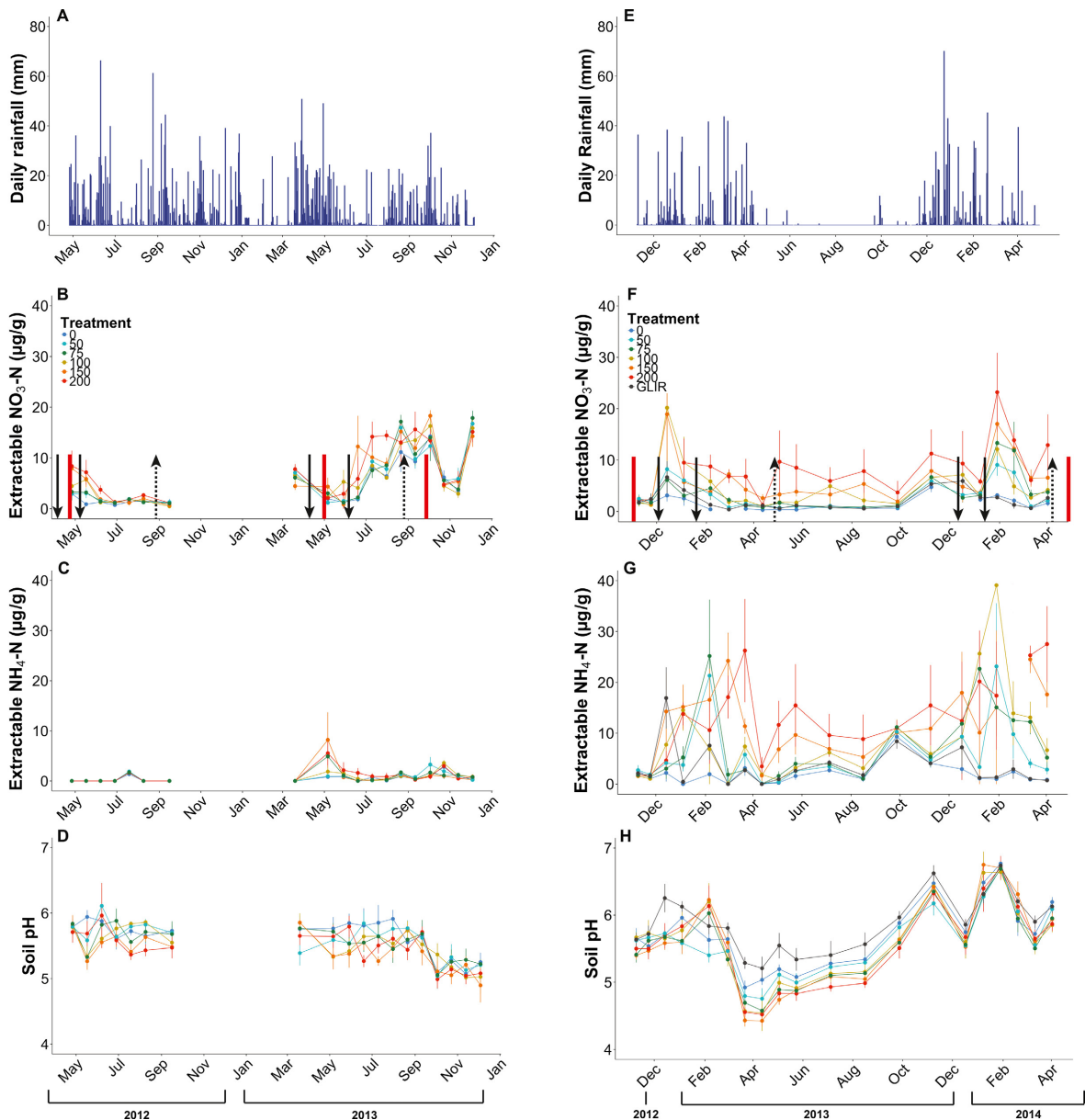
Fig. 1. Precipitation, soil inorganic N, and pH (0–15 cm) in fertilizer trials in Yala, Kenya, (A–D) and Tumbi, Tanzania (E–H). Daily precipitation (A and E), mean concentrations of (B and F) NO_3^--N and (C and G) NH_4^+-N and (D and H) pH in soils collected during the second and third maize growing season (Kenya) and the first and second growing season (Tanzania). Error bars are standard error of the mean. Black down-facing arrows indicate fertilizer additions (first addition was added at planting). Black, dashed, up-facing arrows indicate maize harvest. Red lines indicate timing of soil profiles (Kenya, April 2012 and May 2013, Tanzania: November 2012 and May 2014).

receiving 75 kg N/ha/yr, and (4) plots receiving *Gliricidia* clippings at a rate of approximately 75 kg N/ha/yr.

On the same day as collection, field-moist soils were extracted in duplicate using 2 mol/L potassium chloride (KCl; 25:100 soil to solution) and extracts were immediately frozen until they could be analyzed. Also the same day as collection, field-moist soils were weighed and then dried for 48 h at 105°C and re-weighed to determine moisture content. We transported frozen extracts to the

Marine Biology Laboratory in Woods Hole, Massachusetts, USA, for analysis. Inorganic NO_3^- in the KCl extract was analyzed on a LACHAT QuikChem (LACHAT Instruments, Loveland, Colorado, USA) using cadmium-reduction. Ammonium -N was determined in extracts by indophenol-blue method (Solorzano 1969) and analyzed on a spectrophotometer at 640 nm (Shimadzu UV- 1601, Kyoto, Japan). In Yala, the third set of soil profiles was collected in September 2014 in the

TABLE 4.   Farm management activities in Yala, Kenya, and Tumbi, Tanzania during the field study.

	Yala, Kenya	Tumbi, Tanzania
Study year 1		
Planting and first fertilizer application	5-April-12	8-December-12
First vertical profile (unfertilized plots only)	23-April-12	12-November-12
Second fertilizer application	7-May-12	22-Janary-13
Maize harvest	28-August-12	28-April-13
Maize crops per year	2	1
Rainfall during growing season (mm)	1162	715
Study year 2		
Planting and first fertilizer application	10-April-13	10-December-13
Second fertilizer application	8-May-13	5-January-14
Maize harvest	16-August-13	30-April-14
Second vertical profile (fertilized and unfertilized plots)	1-May-13	6-May-14
Third vertical profile (fertilized and unfertilized plots)	25-September-14	…
Maize crops per year	2	1
Rainfall during growing season (mm)	760	739

unfertilized and 200 kg N/ha/yr plots. Soils were composited by fertilizer treatment and bulked into the following depth categories for analysis: 0–50, 50–100, 100–200, 200–300, 300–400 cm. Thus, there were no replicates at the plot-level. These samples were shipped on ice to the wet chemistry laboratory at the International Center for Tropical Agriculture (CIAT, Nairobi, Kenya) for KCl extraction and analysis on a UV spectrophotometer (Thermo Fisher Scientific, Helios Delta, USA) for NO_3^- and NH_4^+. We used NO_3^--N and NH_4^+-N concentration in dry weight equivalent soil and bulk density to calculate inorganic N pools in kg/ha for the different depths (Eq. 1).

pH/EC/TDS/temperature probe, HI 98129, Woonsocket, RI). Sub-samples from each depth in the initial profiles were analyzed for texture using the hydrometer method (Gee and Bauder 1986).

Longitudinal surface soil sampling (0–15 cm)

Every three weeks during the growing season, soils from each plot were collected from 0 to 15 cm using a 2.2 cm diameter soil probe. Samples were collected from eight random locations in each plot and composited for a total of 24 samples per sampling date in Yala and 28 samples per sampling date in Tumbi. Soils were not col-

$$N\,\mathrm{stock} = N\,\mathrm{concentration} \left(\frac{\mathrm{g}}{\mathrm{g}} \right) * \mathrm{bulk\ density} \left(\frac{\mathrm{g}}{\mathrm{cm}^3} \right) * \mathrm{sample\ depth\,(cm)} * \left(\frac{10^3 \mathrm{g}}{\mathrm{kg}} \right) * \left(\frac{\mathrm{ha}}{10^8 \mathrm{cm}^2} \right). \qquad (1)$$

Because soil depths were of variable thickness (0–15 cm compared to 50–100 cm), we also examined the vertical distribution of inorganic N pools normalized for 15 cm of soil at each depth (Jobbágy and Jackson 2001). We calculated a normalized soil N pool by replacing the sample depth in Eq. 1 with a standard depth of 15 cm (Appendix S1: Fig. S1).

A subsample of the top 15 cm of the initial profiles in Yala and Tumbi were measured for total N (modified Kjeldhal digestion and analysis on photometric analyzer; Thermo Scientific, Aquakem 200), and soil organic matter (Walkey Black using a UV-Vis [Shimadzu, UV-1240 Thermo Fisher Scientific, USA]). Available soil P, K, Ca, Mg, and Na was determined using a Mehlich III extraction (Mehlich 1984) and analyzed on an inductively coupled plasma mass spectrometer (ICP-MS Thermo Fisher Scientific, iCAP 6300, USA). Cation exchange capacity (CEC) was determined by summation of Ca, K, Mg, and Na. Soil pH was determined by a 1:2 soil to water slurry on all samples (Hanna combination

lected between 6 September, 2012 and 19 March, 2013 in Kenya (short rain season). In subsequent short rain seasons in Kenya (2014) and the dry season in Tumbi, samples were collected every six weeks. Soil samples were extracted for inorganic N using 2 mol/L KCl and analyzed on the colorimeter and spectrophotometer for NO_3^--N and NH_4^+-N, respectively.

Statistical approach

When necessary, we used Box–Cox (Box and Cox 1964) and log transformations prior to analysis to satisfy the assumptions of the statistical model. We used a linear mixed-effects (LME) model (lme4 package for R; Bates et al. 2013) to examine the differences in concentrations of NO_3^--N and NH_4^+-N, and pH between locations (Yala and Tumbi), depths, and fertilizer treatments. As the experiments were established as randomized complete block designs, blocking was included as a random effect in all models. To examine the effect of location and depth

on initial soil characteristics, blocks were nested within location and we used Tukey *post hoc* tests (multcomp package for R; Hothorn et al. 2008) to examine the differences in soil characteristics among depths. To test the effect of N fertilizer application and maize cultivation (second vertical profiles; Yala- May, 2013; and Tumbi-May, 2014) on soil characteristics, we included location, depth, and treatment (0 and 200 kg N/ha/yr) as fixed effects in the LME with blocks nested within location and fertilizer treatments nested within blocks as random effects. We then subset the data by location to more explicitly examine the effect of fertilizer and depth on soil characteristics (with treatments nested within blocks). We examined the effect of fertilizer source (75 kg N/ha inorganic vs. organic) and depth on concentrations of NO_3^--N and NH_4^+-N and pH in Tumbi, Tanzania. A Welch two-sample *t*-test was used to examine changes in soil N concentrations, pH, and total soil N pools (0–400 cm) after two years of maize cultivation between the two locations between the two different fertilizer treatments. We did not perform any statistics on the soil profile data from September 2014 (after three years of cultivation) in Yala, but report the composite soil data for qualitative comparison with the other profiles.

To examine temporal variation in concentrations of NO_3^--N and NH_4^+-N and pH in topsoil (0–15 cm) among fertilizer treatments (0, 50, 75, 100, 150, 200 kg N/ha/yr) across the study period, we used a repeated measures LME model with N fertilizer rate as the fixed effect and two random effects: (1) effect of plots nested within blocks and (2) collection date. We ran separate LME models for Yala and Tumbi in order to determine the effects of specific treatments at each location.

We used maximum likelihood to understand the relationship between N input fertilizer and soil inorganic N concentrations. Specifically, we identified the maximum likelihood parameters for the linear, exponential, quadratic, and sigmoidal, and step response functions relating fertilizer rates to mean N topsoil concentrations and to pH at the end of the study. Model parameters were determined by simulated annealing using the anneal function in the likelihood package (Murphy 2015). Comparison among the response functions was conducted using corrected Akaike's information criterion (AIC). All statistics were run in the R environment for Mac (R Core Team 2015).

Results

Rainfall and surface soil responses

Yala received 1162 mm of rain in the first and 760 mm of rain in the second maize growing season. In Tumbi, maize received 715 mm of rain in the first and 739 mm of rain in the second growing season (Fig. 1; Table 4). Only 89 mm of rain fell during the dry season in Tumbi, whereas Yala received 330 mm of rain in the short rainy season of 2012.

Soil inorganic N (NO_3^--N and NH_4^+-N) concentrations and pH all varied through time ($P < 0.0001$; Fig. 1) in both Yala and Tumbi. In Yala, we observed an initial flush of NO_3^--N (i.e., Birch effect) with the onset of rains (Fig. 1), but not in Tumbi. In Tumbi, inorganic N pulses generally tracked fertilizer applications and were lower during the dry season (Fig. 1F and G). Ammonium-N concentrations did not show any strong patterns in Yala or Tumbi, but were higher and more variable in Tumbi than Yala. As expected, the range of within-site variability in N concentrations was much larger in Tumbi than Yala (Fig. 1). For example, NO_3^--N concentrations in unfertilized plots ranged between 3 and 32 μg NO_3^--N/g in Tumbi, but only between 2 and 12 μg NO_3^--N/g in Yala. The range of in soil pH was similar in Tumbi and Yala (pH 4.0–7.4 at both sites). Soil pH showed strong intra-annual variation in the acidity levels in topsoils but did not differ between sites (Fig. 1). Inorganic N concentrations in unfertilized soil profiles were significantly higher in Yala, Kenya than in Tumbi, Tanzania ($P < 0.02$ for both NO_3^- and NH_4^+). In general, NO_3^--N was the dominant form of inorganic N (76% in Yala and 64% in Tanzania).

Our likelihood analyses show that that the final mean inorganic N concentrations were a linear function of N fertilizer application rate in Yala, with AIC values more than two units lower than for other models, but we cannot differentiate between the models for N in Tumbi, where the linear, quadratic, and sigmoidal all performed equally well (Appendix S1: Fig. S2, Table S1). Mean soil pH responded non-linearly to fertilization rate in both sites.

Deep soil profiles

In both sites, there was a bulge of inorganic N between 15 and 50 cm with significantly higher concentrations than in deeper subsoils ($P < 0.05$; Fig. 2A and B). In Tumbi, pH decreased in the top 50 cm and then increased with depth ($P < 0.0001$, $r^2 = 0.48$; Fig. 2C). In Yala, pH remained relatively constant throughout the profile. After two years of maize cultivation, inorganic N concentrations were similar in Yala than Tumbi. In Yala, there were no significant differences in soil inorganic N concentrations or pH between the fertilized and unfertilized plots, and inorganic N declined between years 1 and 2 in both fertilizer treatments ($P < 0.01$; Fig. 2A–E). In Tumbi, inorganic N concentrations declined between years 1 and 2 in the unfertilized plots, but increased in plots receiving 200 kg N/ha/yr (Fig. 2A–E). Inorganic N concentrations tended to be higher in the topsoils of the plots receiving inorganic fertilizer compared to organic plots (Fig. 2G, H), but subsoils were similar between the two fertilizer types.

In Yala, soil inorganic N pools (0–400 cm) contained 240 kg N/ha after one year of unfertilized maize cultivation (Fig. 3A; Table 5), but after two years, topsoil N pools were significantly smaller, reducing the overall
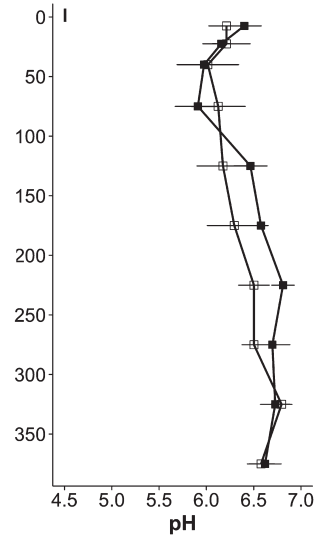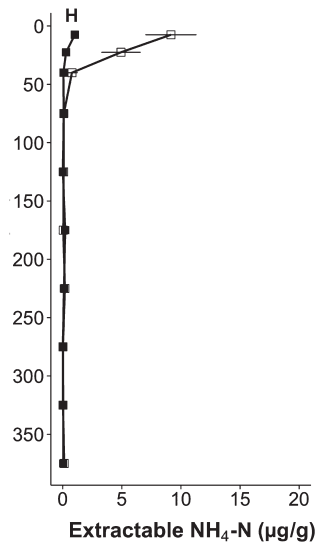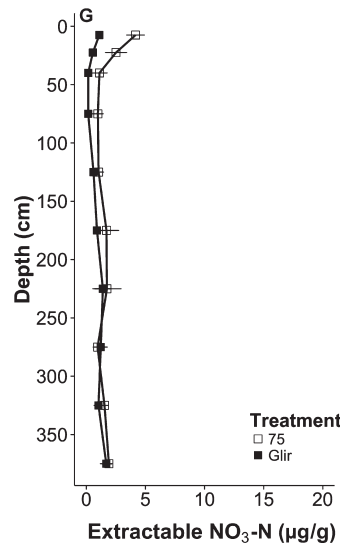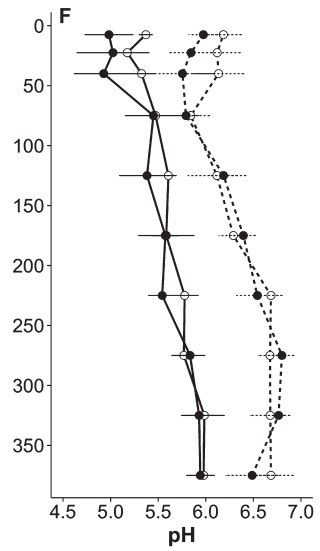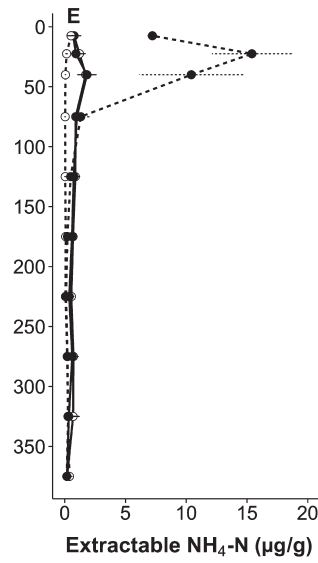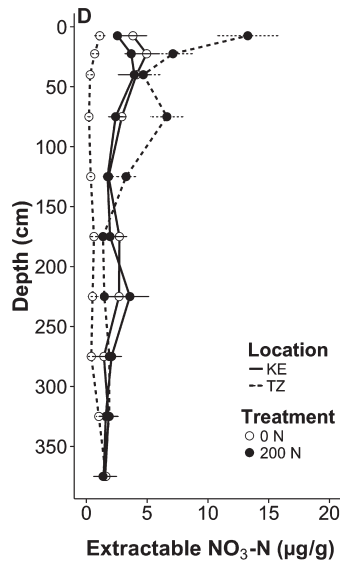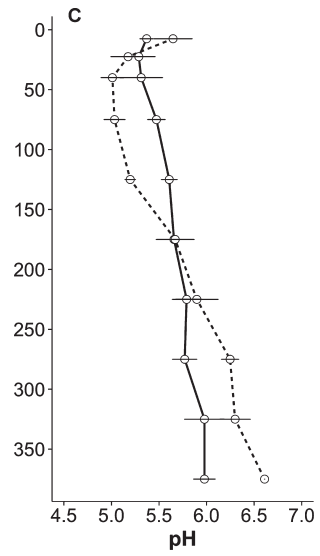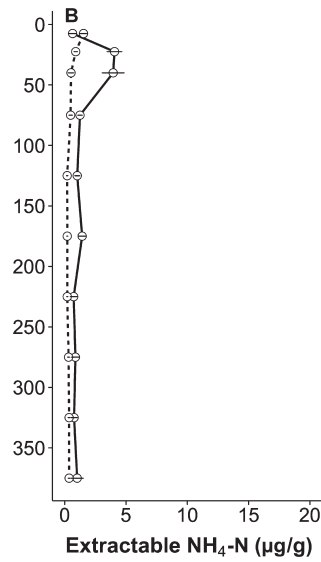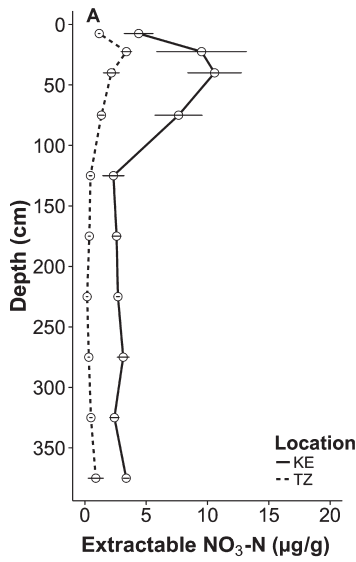
Fɪɢ. 2.   Vertical distribution of soil (A) NO_3^--N concentrations, (B) NH_4^+-N concentrations, and (C) pH after one year of unfertilized maize in Yala, Kenya, (solid lines) and Tumbi, Tanzania (dashed lines). Vertical distributions of soil (D) NO_3^--N concentrations, (E) NH_4^+-N concentrations, and (F) pH in Yala, Kenya, (solid lines) and Tumbi, Tanzania, (dashed lines) in unfertilized plots (open circles) and plots receiving 200 kg N/ha/yr (filled circles) after two years of maize cultivation. Vertical distributions of soil (G) NO_3^--N concentrations, (H) NH_4^+-N concentrations, and (I) pH in Tumbi, Tanzania, in plots receiving 75 kg N/ha/yr of inorganic fertilizer (filled squares) and 75 kg N/ha/yr as *Gliricidia* green manure (open squares) after two years of maize cultivation. Points are placed at the midpoint of each sampling depth, and error bars are standard error of the mean.

N pool by about 100 kg N/ha ($P = 0.03$ in unfertilized and $P = 0.009$ in fertilized plots; Fig. 3B, C). About 12% of the total inorganic N was stored in topsoils (0–30 cm), 80% of which was in the form of NO_3^-. Inorganic N pools collected after three years (September 2014) appeared to be closer to baseline levels (280 kg N/ha; Fig. 3D,E). It should be noted that in Yala, year 1 and 3 soils were collected after cultivation of one season of long rain maize and in year 2 following two seasons of continuous maize cultivation (i.e., long and short rain maize).

In Tumbi, inorganic soil N pools were initially small (79 kg N/ha), and pools in unfertilized plots and plots receiving organic fertilizer did not change after two

years of cultivation (Fig. 3F–H; Table 5). However, plots receiving inorganic fertilizer (either 75 or 200 kg N/ha/yr) were significantly larger following two years of cultivation and fertilization ($P = 0.008$ and $P = 0.029$, respectively; Fig. 3I, J). The majority (36%) of the accumulated N was found in the top 30 cm of soil and 47% in the form of NH_4^+. This contrasted with the unfertilized and organic fertilizer plots, where only about 12% of the total soil N pool (400 cm) was stored in the topsoil. In Yala and Tumbi, the top 30–50 cm tended to store the greatest amount on N per unit soil area, except for plots in Yala receiving 200 kg N/ha/yr, where N was evenly distributed throughout the profile (Appendix S1: Fig. S1).
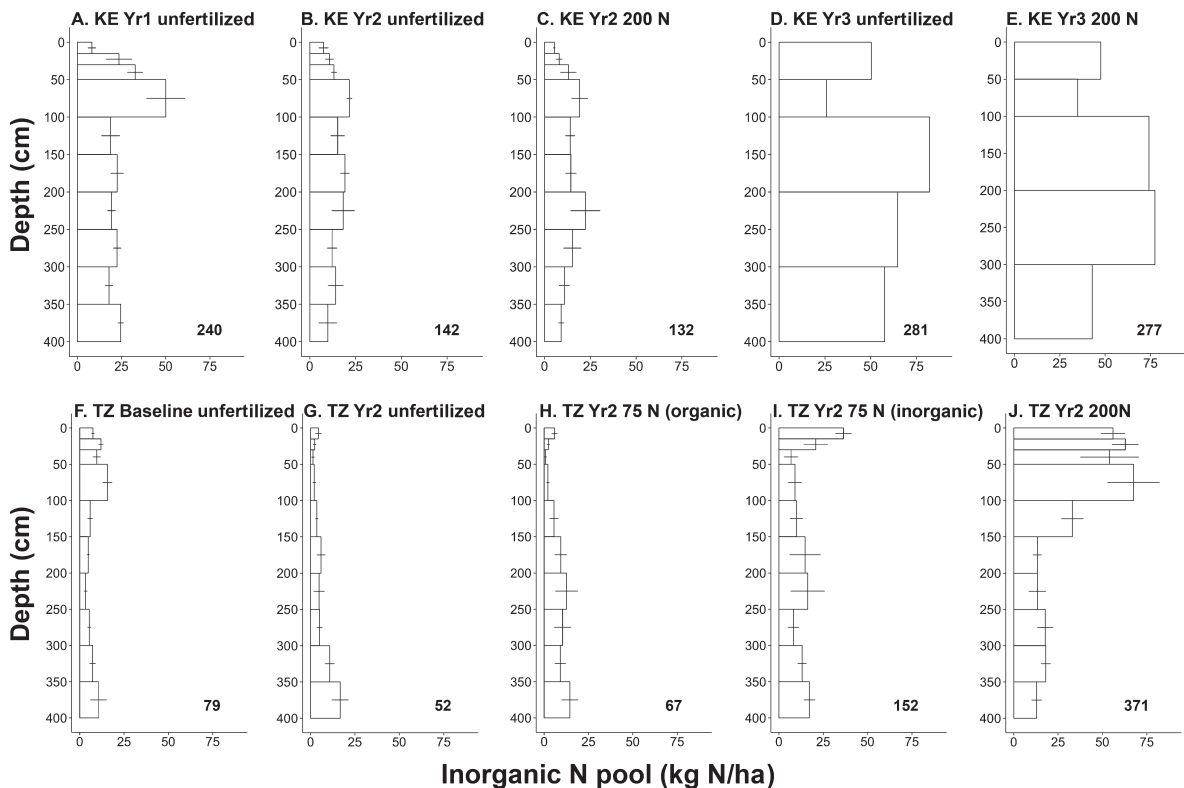

Fɪɢ. 3.   Inorganic N pools in Yala, Kenya in (A) unfertilized plots after one year of maize cultivation, (B) unfertilized plots after two years of maize cultivation, (C) plots fertilized with 200 kg N/ha/yr after two years of maize cultivation, (D) unfertilized plots after three years of maize cultivation, and (E) plots fertilized with 200 kg N/ha/yr after three years of maize cultivation. Note that pools appear larger in D and E at each depth, but this because samples were bulked every 100 cm rather than 50 cm. Inorganic N pools in Tumbi, Tanzania in (F) unfertilized plots before maize cultivation, (G) unfertilized plots after two years of maize cultivation, (H) plots fertilized with 75 kg N/ha/yr as *Gliricidia* leaves after two years of maize cultivation (organic), (I) plots fertilized with 75 kg N/ha/yr (inorganic) after two years of maize cultivation, (J) plots fertilized with 200 kg N/ha/yr after two years of maize cultivation. Error bars are the standard error of the mean. There are no error bars on D and E because these samples were bulked across plots. Values in bold are the mean total inorganic N pools from 0 to 400 cm.

TABLE 5. Fertilizer application rates, maize yields, N exported in maize (grains only), inorganic N pools, and residual N (difference between soil pools and harvest N) in Yala, Kenya, and Tumbi, Tanzania.

Fertilizer N (kg/ha)	Inorganic N pool (kg/ha)	Maize yield (tons/ha)	Harvest N (kg/ha)	Residual N (kg/ha)
Kenya 2012: early growing season; one maize crop in prior year				
0 N	240	6.2	75	165
Kenya 2013: early growing season; two maize crops in prior year				
0 N	142	3.8	47	95
200 N	132	4.9	73	59
Kenya 2014: following harvest; one maize crop in prior year				
0 N	281	3.8	47	234
200 N	277	7.2	105	172
Tanzania 2013: early growing season; no crop in prior year				
0 N	79	1.2	15	64
Tanzania 2014: following harvest; one maize crop in prior year				
0 N	52	0.2	3	50
75 N (organic)	70	1.3	21	48
75 N (inorganic)	152	1.2	18	134
200 N	371	0.8	13	357

Notes: Soil N was measured at the beginning of the growing season in 2012 and 2013 in Yala and in 2012 in Tumbi. Soil N was measured at the end of the growing season in 2014 in Yala and Tumbi.

DISCUSSION

Soil N varies with soil type and fertilizer rate

By comparing soil N pools in plots that received a range of fertilizer application rates, we captured the varied effects increased fertilizer applications may have on N dynamics in soils with highly contrasting textures. Soils in both Yala and Tumbi stored large quantities of N (Fig. 3). In Tumbi, these pools increased with fertilizer application and were depleted when cultivated without fertilizers, while pools were of similar size in Yala regardless of fertilizer treatment. In Tumbi, the positive relationship between N inputs and soil inorganic N concentrations suggests that fertilizer rates have an important direct control over soil inorganic N storage in these soils (Appendix S1: Fig. S2B, Table S1). The larger initial soil N pool in Yala was consistent with higher retention capacity in clays compared with sands. Low N accumulation in Yala may also be the result of higher maize yields in the clayey than sandy site.

In Yala, soil N pools were nearly twice as large after one season of maize cultivation (~266 kg N/ha) as pools after two consecutive seasons of maize cultivation (~137 kg N/ha; Table 5). Maize is an N-demanding crop, and the climate in Yala allows two growing seasons. Therefore, the second (unfertilized) maize crop likely consumed most of the residual topsoil N, leading to similar sized N pools in unfertilized and fertilized plots. Soil N pools measured at the same point in the growing season did not show evidence of N accumulation even in plots receiving 200 kg N/ha/yr (more than double the rate promoted by the AGR). This suggests that recommended fertilizer rates may not replenish soil N pools in the short-term if two seasons of maize are cultivated each year. Not all farmers in the region plant two seasons of maize;

many cultivate beans, peas, groundnuts, or potatoes (sometimes as intercrops) in the short rains, though they are typically unfertilized. Crop type and N-demand will also alter soil N pools. Fallowing or planting leguminous cover crops over the short rainy season may capture N from the soil profile and release to the next long rain maize crop providing a mechanism to recycle N (the N safety-net hypothesis; Babbar and Zak 1995, Mekonnen et al. 1997, Udawatta et al. 2002). While previous studies found large pools of N in cultivated Kenyan soils (199 kg NO_3^--N/ha to 4 m; Mekonnen et al. 1997), large N storage in sandy Tumbi soils were surprising, particularly because this N may be susceptible to leaching as fertilizer application rates increase.

In Tumbi, where the dry climate only permits one season of maize per year, soil inorganic N pools were twice as large as initial pools in plots that received 75 kg N/ha/yr of inorganic fertilizer and four times larger than initial pools in plots that received 200 kg N/ha/yr of inorganic fertilizer after two years of cultivation (Fig. 3). Although the amount of N accumulation (292 kg N/ha) in Tumbi seems high, it is still substantially lower than accumulation (363 kg N/ha to 300 cm) in maize fields near Beijing, China, receiving 240 kg N/ha/yr (Ju et al. 2004). Unlike China, where maize yields range between 6 and 11 ton/ha, annual maize yields in Tumbi were low and close to the regional average for East Africa of 1 ton/ha (Sanchez 2015) even when fertilized. Annual precipitation in Tumbi is half that in Yala (Table 4), and short dry periods at the beginning of the growing season (see December 2012; Fig. 1E) can severely impact maize yields. Further, Tumbi soils have a low water holding capacity (<10%), compared with Yala (40%), and very low residual soil moisture (3% by vol.; T. A. Russo, et al, *unpublished data*) following the dry season. As a result, the quantity of N exported in the harvest was about six times lower in

Tumbi than in Yala, which may explain why soil N pools in Tumbi were larger after two years of cultivation and fertilization. For example, the initial soil pool in Tumbi was 79 kg N/ha and 400 kg N was applied over two years in the highest treatment plots, but only 49 kg N/ha were removed in the maize harvests (in 2013 and 2014 combined), a difference of 430 kg N/ha in the soil profile. We observed 371 kg N/ha in the profile (Table 5). The difference between the expected and observed size of the soil N pools could be explained by leaching losses, which may occur during a rainfall event during the dry season or the onset of rains in mid-December (>50 kg N/ha/yr; K. L. Tully, et al., *unpublished data*). The accumulation of N in the soil profile at Tumbi may lead to large economic and environmental losses if N is rapidly released from topsoils into lower soil layers or shallow groundwater. Cultivation of drought-tolerant cover crops or relay cropping into the dry season could improve N capture in sandy soils. The return of organic material (in the form of cover crops or residues) would improve nutrient and water retention in these low-yielding soils and improve yields (Tully et al. 2015*b*). In Tumbi, maize yields appear to respond nonlinearly to fertilizer inputs with the highest yields in moderately fertilized plots regardless of fertilizer type (Table 5), which suggests that fertilizer applications in excess of 75 kg N/ha may accumulate in the soil profile and be subject to leaching losses. Thus, we show that both environmental and food production objectives may be met through moderate applications of inorganic and organic fertilizers especially when coupled with strategies to improve field-level water use efficiency.

Water limitations and farm management alter intra-annual variability

There was evidence of differences in pH between Tumbi and Yala, but Tumbi topsoils showed high intra-annual variability in pH throughout the growing season likely because Tumbi parent material was less buffered to changes in pH than Yala parent material. In both sites, most of the variability in soil N pools occurred in the topsoil (0–30 cm). Soil inorganic N concentrations were more variable in Tumbi than Yala, which may be caused, in part, by water limitations early in the growing season and the site's low soil moisture content. Young maize plants likely experienced fertilizer burn in plots receiving high doses of fertilizer, because low rainfall left fertilizer undiluted long enough to damage plant roots. This may explain why we observed low yields in high fertilizer plots in Tumbi and the consistently high N concentrations throughout the course of the study in the heavily fertilized plots (Table 5).

In both sites, the majority of N was applied in the form of urea ($CO(NH_2)_2$), which is usually rapidly mineralized to NH_4^+ and nitrified to NO_3^-. However, the dry conditions in Tumbi soils may have slowed or prevented nitrification. Further, as NH_4^+ was not readily leached, we found higher concentrations and build-up of NH_4^+ in the

sandy Tumbi topsoils compared with moister, clayey Yala topsoils.

An increase in fertilizer applications as promoted by the African Green Revolution has clear implications for biogeochemical cycling across SSA. Soil type and climate will combine to create very different outcomes for both farm productivity and N cycling across the region.

Summary

Soil texture and farm management combine to create variation in soil N pools across the two East African agricultural sites. In the clayey soil, large initial soil N pools were consistent with a higher density of binding sites and anion exchange capacity, which can provide greater overall storage of N in the soil profile and a lower potential for N loss to leaching. However, cultivation of two maize crops per year, compared to one crop in Tumbi, reduced N storage in the soil profile in Yala. Yields on the sandy soil were low (even by regional standards), and reduced N uptake by maize may have led to the accumulation of N in the topsoils of fertilized plots. Large variation in topsoil N concentrations in the sandy Tumbi soils provided some evidence that they were prone to leaching losses during rainfall events that follow fertilizer applications. Planting legume cover crops or permitting vegetative fallow could improve N cycling by storing and/or replenishing soil N and C pools in both regions. Further, consistently low maize yields in Tumbi, regardless of fertilizer rate suggest, that N may not be limiting productivity as much as other factors, such as soil moisture. A better understanding of the vertical distribution of soil N pools and how they vary through time improves the ability to predict the potential environmental effects of a dramatic increase in N fertilizer application rates that will accompany the intensification of African croplands.

Literature Cited

Annan, K. 2004. Africa's green revolution: a call to action. Proceedings of the July 5th, 2004 high-level seminar, Addis Ababa, Ethiopia, convened by the Government of Ethiopia and the UN Millennium Project. MDG Centre Speech, Nairobi, Kenya. http://www.africangreenrevolution.com/en/green_revolution/addis_call_to_action/index.html

Babbar, L. I., and D. R. Zak. 1995. Nitrogen loss from coffee agroecosystems in Costa Rica: leaching and denitrification in the presence and absence of shade trees. Journal of Environmental Quality 24:227.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2013. lme4: linear mixed-effects models using Eigen and S4. https://cran.r-project.org/web/packages/lme4/lme4.pdf.

Bationo, A., A. Hartemink, O. Lungu, M. Naimi, P. Okoth, E. Smaling, L. Thiombiano, and B. Waswa. 2012. Knowing the African soils to improve fertilizer recommendations. Pages 19–42 in J. Kihara, D. Fatondji, J. W. Jones, G. Hoogenboom, R. Tabo, and A. Bationo, editor. Improving soil fertility recommendations in Africa using the decision support system for agrotechnology transfer (DSSAT). Springer Dordrecht, The Netherlands.

Bellini, G., M. E. Sumner, D. E. Radcliffe, and N. P. Qafoku. 1996. Anion transport through columns of highly weathered acid soil: adsorption and retardation. Soil Science Society of America Journal 60:132–137.

Berg, W. A., and G. W. Thomas. 1959. Anion elution patterns from soils and soil clays. Soil Science Society of America Journal 23:348–350.

Birch, H. F. 1964. Mineralisation of plant nitrogen following alternate wet and dry conditions. Plant and Soil 20:43–49.

Box, G., and D. R. Cox. 1964. An analysis of transformations. Journal of the Royal Statistical Society B 26:211–252.

Brady, N. C., and R. R. Weil. 2007. The nature and properties of soils, Fourteenth edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559–568.

Chikowo, R., P. Mapfumo, P. Nyamugafata, and K. E. Giller. 2004. Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agriculture, Ecosystems and Environment 102:119–131.

Denning, G., et al. 2009. Input subsidies to improve smallholder maize productivity in Malawi: toward an African green revolution. PLoS Biology 7:e23.

Dewitte, O., et al. 2013. Harmonisation of the soil map of Africa at the continental scale. Geoderma 211–212:138–153.

Dixon, J., D. P. Gibbon, and A. Gulliver, editors. 2001. Farming systems and poverty. FAO, Food and Agriculture Organization, United Nations, Rome, Italy.

FAO, IFAD, WFP. 2014. The state of food insecurity in the world 2014. Food and Agriculture Organization, United Nations, International Fund for Agricultural Development, and World Food Programme, Rome, Italy.

Forester, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, and J. Haywood. 2007. Changes in atmospheric constituents and in radiative forcing. Pages 129–234 in S. Solomon, et al. editors. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, and B. J. Cosby. 2003. The nitrogen cascade. BioScience 53:341–356.

Gee, G. W., and J. W. Bauder. 1986. Particle-size analysis. Pages 383–411 in A. Klute, editor. Methods of soil analysis. Part 1. Physical and mineralogical methods. Soil Science Society of America, Madison, Wisconsin, USA.

Gradwell, M. W. 1972. Methods for physical analysis of soils. Page 32. New Zealand Soil Bureau, Wellington, New Zealand.

Hardy, F. 1946. Seasonal fluctuations of soil moisture and nitrate in a humid tropical climate. Tropical Agriculture Trinidad 23:40–49.

Hickman, J. E., R. J. Scholes, T. S. Rosenstock, C. Pérez García-Pando, and J. Nyamangara. 2014. Assessing non-CO_2 climate-forcing emissions and mitigation in sub-Saharan Africa. Current Opinion in Environmental Sustainability 9–10:65–72.

Hickman, J. E., K. L. Tully, P. M. Groffman, W. Diru, and C. A. Palm. 2015. A potential tipping point in tropical agriculture: Avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya. Journal of Geophysical Research: Biogeosciences 120:938–951.

Hothorn, T., F. Bretz, and P. Westfall. 2008. Simultaneous inference in general parametric models. Biometrical Journal 50:346–363.

Ishiguro, M., K. C. Song, and K. Yuita. 1992. Ion transport in an allophanic andisol under the influence of variable charge. Soil Science Society of America Journal 56:1789.

Jobbágy, E. G., and R. B. Jackson. 2001. The distribution of soil nutrients with depth: global patterns and the imprint of plants. Biogeochemistry 53:51–77.

Ju, X., X. Liu, F. Zhang, and M. Roelcke. 2004. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. AMBIO: A Journal of the Human Environment 33:300–305.

Katou, H., B. E. Clothier, and S. R. Green. 1996. Anion transport involving competitive adsorption during transient water flow in an andisol. Soil Science Society of America Journal 60:1368.

Mehlich, A. 1984. Determination of cation- and anion-exchange properties of soils. Communications in Soil Science and Plant Analysis 15:1409–1416.

Mekonnen, K., R. J. Buresh, and B. Jama. 1997. Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize fields. Plant and Soil 188:319–327.

Murphy, L. 2015. Methods for maximum likelihood estimation. https://cran.r-project.org/web/packages/likelihood/likelihood.pdf

Nziguheba, G., et al. 2010. The African green revolution. Advances in Agronomy 109:75–115.

Palm, C. A., C. N. Gachengo, R. J. Delve, G. Cadisch, and K. E. Giller. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agriculture, Ecosystems and Environment 83:27–42.

Palm, C. A., S. M. Smukler, C. C. Sullivan, P. K. Mutuo, G. I. Nyadzi, and M. G. Walsh. 2010. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. Proceedings of the National Academy of Science USA 107:19661–19666.

R Core Team. 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Sanchez, P. A. 2002. Soil fertility and hunger in Africa. Science 295:2019–2020.

Sanchez, P. A. 2015. En route to plentiful food production in Africa. Nature Plants 1:1–2.

Sanchez, P., et al. 2007. The African millennium villages. Proceedings of the National Academy of Sciences USA 104:16775–16780.

Sanchez, P. A., G. L. Denning, and G. Nziguheba. 2009. The African Green Revolution moves forward. Food Security 1:37–44.

Schmidt, C. M., A. T. Fisher, A. J. Racz, B. S. Lockwood, and M. L. Huertos. 2011. Linking denitrification and infiltration rates during managed groundwater recharge. Environmental Science & Technology 45:9634–9640.

Snapp, S. S., M. J. Blackie, R. A. Gilbert, R. Bezner-Kerr, and G. Y. Kanyama-Phiri. 2010. Biodiversity can support a greener revolution in Africa. Proceedings of the National Academy of Sciences USA 107:20840–20845.

Solorzano, L. 1969. Determination of ammonia in natural waters by the phenolhypochlorite method. American Society of Limnology and Oceanography 14:799–801.

Tilman, D. 2002. Agricultural sustainability and intensive production practices. Nature 418:671–677.

Tully, K., C. Sullivan, R. Weil, and P. Sanchez. 2015a. The state of soil degradation in sub-Saharan Africa: baselines, trajectories, and solutions. Sustainability 7:6523–6552.

Tully, K. L., S. A. Wood, M. Almaraz, C. Neill, and C. Palm. 2015b. The effect of mineral and organic nutrient input on yields and nitrogen balances in western Kenya. Agriculture, Ecosystems and Environment 214:10–20.

Udawatta, R. P., J. J. Krstansky, G. S. Henderson, and H. E. Garrett. 2002. Agroforestry practices, runoff, and nutrient loss. Journal of Environment Quality 31:1214.

Vitousek, P. M., et al. 2009. Nutrient imbalances in agricultural development. Science 324:1519–1520.

Wetselaar, R. 1961. Nitrate distribution in tropical soils. I. Possible causes of nitrate accumulation near the surface after a long dry period. Plant and Soil 15:121–133.

Wild, A. 1976. Nitrate leaching under bare fallow at a site in northern Nigeria. Journal of Soil Science 23:315–324.

Wood, S., K. L. Sebastian, and S. J. Scherr, World Resources Institute. 2000. Pilot analysis of global ecosystems, Agroecosystems, A joint study by International Food Policy Research Institute and World Resources Institute. International Food Policy Research Institute and World Resources Institute, Washington, DC.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1890/15-1518R1.1/suppinfo

DATA AVAILABILITY

Data associated with this paper have been deposited in Dryad: http://dx.doi.org/10.5061/dryad.5qr62