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ORIGINAL ARTICLE

Nitrogen availability to maize as affected by fertilizer application and soil type in the Tanzanian highlands

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Abstract Enhancing crop production by maintaining a proper synchrony between soil nitrogen (N) and crop N demand remains a challenge, especially in under-studied tropical soils of Sub-Saharan Africa (SSA). For two consecutive cropping seasons (2013–2015), we monitored the fluctuation of soil inorganic N and its availability to maize in the Tanzanian highlands. Different urea-N rates (0–150 kg N ha^{-1}; split into two dressings) were applied to two soil types (TZi, sandy Alfisols; and TZm, clayey Andisols). In the early growing season, soil mineralized N was exposed to the leaching risk due to small crop N demand. In the second N application (major N supply accounting for two-thirds of the total N), applied urea was more efficient in increasing soil inorganic N availability at TZm than at TZi. Such effect of soil type could be the main contributor to the higher yield at TZm (up to 4.4 Mg ha^{-1}) than that at TZi (up to 2.6 Mg ha^{-1}) under the same N rate. The best-fitted linear-plateau model indicated that the soil inorganic N availability (0–0.3 m) at the tasseling stage largely accounted for the final yield. Further, yields at TZi were still limited by N availability at the tasseling stage due to fast depletion of applied-N, whereas yields plateaued at TZm once N availability was above 67 kg N ha^{-1}. Our results provided a valuable reference for designing the N management to increase yield, while minimizing the potentially adverse losses of N to the environment, in different agro-ecological zones in SSA.

Keywords Seasonal variation · N leaching · N retention · Plant N uptake · Maize yield · Sub-Saharan Africa

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Introduction

Sub-Saharan Africa (SSA) struggles to be food self-sufficient (van Ittersum et al. 2016). By 2050, population growth on the African continent is projected to at least double (United Nations 2017). To maintain even the current level of cereal self-sufficiency (approximately 80%) for the increasing population, a nearly complete closure of the gap between current cropland yields and yield potential is needed (van Ittersum et al. 2016). However, SSA croplands are historically unproductive (Hazell and Wood 2008) due to continuous nutrient mining (especially nitrogen; N) from soil without proper nutrient amendments (Vitousek et al. 2009).

Increased use of fertilizer (especially N) is unequivocally a critical step in offsetting soil nutrient depletion and closing the yield gap in SSA (Dijk et al. 2012; Tamene et al. 2015). Vanlauwe et al. (2014) argued that the appropriate use of fertilizer should be included as a fourth principle to define conservation agriculture in SSA. Indeed, regional and national efforts are underway to increase fertilizer use (AGRA 2009; Mungai et al. 2016). Increasing the use of fertilizer is also encouraged by its benefits on yield increment, doubled or even tripled together with improved seeds, as exemplified in recent studies (Sanchez et al. 2007; Nziguheba et al. 2010).

Despite the importance of increasing fertilizer input, the fate of added nutrients is largely unknown, especially N, the most yield-limiting nutrient in SSA croplands (Mafongoya et al. 2006; Wortmann et al. 2017). Applied-N can be lost from the agroecosystem through several pathways, including ammonia (NH_3) volatilization, nitrate (NO_3^-) leaching, and nitrous oxide (N_2O) emission (Lehmann and Schroth 2003; Ma et al. 2010; Butterbach-Bahl et al. 2013). Each of the pathways has significant environmental consequences such as soil acidification, eutrophication, and global warming (Galloway et al. 2003; Scudlark et al. 2005). The dominant pathways and magnitude of N loss are largely influenced by soil type and land management practices (Mapanda et al. 2012; Russo et al. 2017; Zheng et al. 2018), both of which vary widely across SSA croplands (Dewitte et al. 2013; Tully et al. 2016).

Various soil types—often differ greatly in soil texture, cation exchange capacity (CEC), and pH buffering capacity—can strongly affect N storage and loss in soils. Soil texture is a primary factor controlling water holding capacity (WHC) and permeability, both of which determine the movement and retention of N. Fine-textured soils with higher WHC tend to retain soil N and allow for plant or microbial uptake. Coarse-textured soils may have higher infiltration rates, leading to higher risks of NO_3^- leaching loss (Lehmann and Schroth 2003). When coupled with fertilizer type, soil pH buffering capacity and CEC can affect the magnitude of fertilizer-N loss. Both field and incubation studies (Sigunga et al. 2002; Haden et al. 2011; Zheng et al. 2018) have shown that low pH buffering and low CEC in tropical soils resulted in substantial N losses (up to $> 50\%$ of applied N) through NH_3 emission following the surface application of urea.

Soil type is also an important factor that affects the response of crop yield to increased fertilizer-N rate. Varying soil types are often associated with different agro-ecological zones in SSA. In high potential agro-ecological zones, crop yields generally increase with fertilizer input (mainly N, P, and K) to reduce the yield gap (Vanlauwe et al. 2015). However, yields may also respond poorly to NPK fertilizer input due to micronutrient deficiencies (Njoroge et al. 2017). In nutrient-poor sandy soils, much larger amounts of fertilizer-N input (e.g., organic and/or synthetic) is commonly required to attain the yield level comparable with fertile soil (Mtambanengwe and Mapfumo 2006), yet such increased yields mostly come at the cost of significantly decreased nutrient use efficiency. For example, in depleted sandy soils in Zimbabwe, the significant maize yield response (~ 2 Mg ha^{-1} higher than the control treatment) to chemical N input (100 kg N ha^{-1}) was only observed in the third year after repeated applications of manure at a relatively high rate (equivalent to 180 kg N ha^{-1} years^{-1} and 30 kg P ha^{-1} years^{-1}; Zingore et al. 2007). To achieve the sustainable intensification of African agriculture accompanied by a dramatic increase in fertilizer-N input, proper N strategies targeting different agro-ecological zones and soil resources to improve yield as well as N use efficiency are urgently needed.

Maize is the staple food for the people of SSA (Shiferaw et al. 2011). The highlands in East Africa are generally densely populated and intensively cultivated for production, known as the “bread basket.” For example, in Tanzania, approximately 46% of the maize is produced in southern highlands, which comprises only 28% of the mainland area of this country (Bisanda et al. 1998; Rowhani et al. 2011).

The objective of this study was to investigate the fluctuation of soil inorganic N and its availability to maize in the Tanzanian highlands in two soil types and under different N application rates. Specifically, we investigated (1) the seasonal variations of soil inorganic N and how the inorganic N availability was influenced by N rate and different soil types; (2) the response of maize yield to soil inorganic N availability as affected by N rate and soil type. Finally, we provide appropriate soil-specific N strategies to increase maize yield, while minimizing the potentially adverse losses of N to the environment.

Materials and methods

Study sites

The study was conducted within two maize-based agro-ecological zones (Bisanda et al., 1998) in the Tanzanian highlands. One site (TZi, 1480 m.a.s.l.) is located in Mangalali village (07°46′S, 35°34′E) in the Iringa region. The soil is classified as coarse-loamy, isohyperthermic, Kanhaplic Haplustalfs (Soil Survey Staff 2010). The TZi site was converted from forest to agriculture between 1960 and 1970. Since the late 1990s, maize and tomato were grown in rotation for around 9 years and then followed by a continuous maize cultivation till the establishment of our experiment in November of 2013. During the maize cultivation from 2009 to 2012, N was applied mainly as urea at a rate of ~ 100 kg N ha $^{-1}$ years^{-1}. The other site (TZm, 1780 m.a.s.l.) is located in Uyole town (08°55′S, 33°31′E) in the Mbeya region. The soil is classified as clay-loam, isothermic, Dystric Vitric Haplustands (Soil Survey Staff 2010). The TZm site is owned by the Uyole Agricultural Research Institute and is used as experimental fields since 1968. From 2005 onwards, the land was cropped with maize and N was applied mainly as urea at a rate between 80 and 330 kg N ha^{-1} years^{-1} until the establishment of our experiment in November of 2013. We sampled the topsoil (0–0.15 m) from the field in July of 2013 to evaluate the initial N concentrations, and found that the concentrations of residual N from the preceding experiment were high with large variability [98 ± 67 mg kg^{-1} (mean ± standard deviation), n = 36; range 17–314 mg kg^{-1}].

The precipitation at TZi is 560 mm per year on average, lower than that at TZm (860 mm). The mean annual air temperature is higher at TZi (23.5 °C) than that at TZm (17.1 °C). The pattern of annual rainfall is unimodal for both sites. The rainy season generally starts in late November at both sites and ends in mid-April and mid-May at TZi and TZm, respectively. Selected soil properties for the study sites are presented in Table 1. Despite the similar soil pH in the topsoil between two sites, soil organic matter and CEC were substantially lower at TZi compared to those at TZm, because of lower clay content. Soil pH buffering capacity and WHC were both higher at TZm than at TZi.

Experimental design

The experiment was conducted from November of 2013 to June of 2015, with maize cropped consecutively for two seasons. Experimental plots were established in a randomized complete block design receiving four levels of N rate: 0, 50, 100, and 150 kg N ha^{-1}, denoted as 0–150 N, respectively. Each N rate was replicated three times, and plots were 5 m × 5 m. A 1.5 m buffer strip separated each plot and block. Within each experimental plot, three maize (*Zea mays* L.; variety TMV-1 at TZi and UH6303 at TZm) seeds were planted per hole at a spacing of 0.7 m × 0.3 m, and were thinned to one plant per hole 20 days after planting (DAP), giving a population of ~ 48,000 plants ha^{-1}. The maize varieties were recommended by the local extension services, with 6.3 and 7.5 Mg ha^{-1} being the yield potential for variety TMV-1 and UH6303, respectively (Lyimo 2005; Lyimo et al. 2014). Maize was planted in early- to mid-December at both sites and harvested in late March and mid-May at TZi and TZm, respectively (Table 2).

We slightly modified the farming practice recommended by the local extension services. The basal application of diammonium phosphate at the planting date was changed to triple super phosphate to all plots at a rate of 50 kg P ha^{-1}. This is because we hypothesized that the crop N demand is small before our first N application (see below) and indigenous N supply from mineralization of organic matter accumulated during drying season is sufficient. Nitrogen

Table 1 Selected soil physico-chemical properties from the top two layers for TZi and TZm

Site	Depth m	PH (H_2O)	TC[a] g kg^{-1}	TN[a] g kg^{-1}	CEC[b] $cmol_c$ kg^{-1}	PBC[c] mmol OH^- kg^{-1}	WHC[d] %	Soil texture (%)		
								Clay	Silt	Sand
TZi	0–0.15	6.45	3.5	0.3	1.1	9.5	27.2	4.7	6.9	88.4
	0.15–0.3	5.96	1.9	0.2	0.9	NA[e]	NA	6.4	7.9	85.7
TZm	0–0.25	6.85	17.5	1.3	17.5	57.1[f]	66.3[f]	28.4	42.0	29.5
	0.25–0.5	7.09	9.6	0.8	22.7	NA	NA	34.6	32.9	32.5

[a]Total carbon (TC) and N (TN) determined by dry combustion of finely ground soils using Vario Max CHN elemental analyzer

[b]Cation exchange capacity (CEC) determined by the buffered (pH = 7) ammonium acetate saturation method

[c]pH buffering capacity (PBC) determined by titratable acidity (at pH = 8.3) using a potentiometric automatic titrator following Sakurai et al. (1989)

[d]*WHC* maximum water holding capacity

[e]*NA* not analyzed

[f]Samples analyzed for PBC and WHC at TZm were from 0 to 0.15 m depth

was applied by broadcasting urea (46% N, 0% P) twice during the growing season. One-third was applied 21 DAP (maize growth stage V3–4). The remaining two-thirds was added 57 DAP (around the time of maize tasseling, VT). Weeding was carried out when necessary, and all weeded materials were removed from the plots. The schedule of agricultural activities carried out during the experimental period is presented in Table 2. The experiment was not irrigated.

Field environmental monitoring

At each site, soil moisture was monitored with CS616 sensors at 0.05, 0.2, and 0.4 m below the ground surface with two replicates for each of the two blocks (2 blocks × 2 replicates × 3 depths = 12 sensors; Campbell Scientific, Inc., USA). Soil temperature was monitored with T108 sensors (Campbell Scientific, Inc., USA) at 0.05 m depth with two of the block replicates. Air temperature was monitored using one T108 sensor at each site and precipitation was

Table 2 Agricultural activities carried out during the study period

Activity description	TZi		TZm	
	Date	DAP	Date	DAP
The first season				
Planting and P fertilizer application	14-Dec-13	0	8-Dec-13	0
Thinning, first plant sampling (V3–4)[a]	3-Jan-14	20	28-Dec-13	20
First N fertilizer application	4-Jan-14	21	29-Dec-13	21
Second plant sampling (VT)[a]	8-Feb-14	56	3-Feb-14	57
Second N fertilizer application	9-Feb-14	57	4-Feb-14	58
Third plant sampling (PM)[a] and harvest	1-Apr-14	108	19-May-14	162
The second season				
Planting and P fertilizer application	6-Dec-14	0	18-Dec-14	0
Thinning, first plant sampling (V3–4)	26-Dec-14	20	7-Jan-15	19
First N fertilizer application	27-Dec-14	21	8-Jan-15	20
Second plant sampling (VT)	31-Jan-15	56	12-Feb-15	55
Second N fertilizer application	9-Feb-15	65	13-Feb-15	56
Third planting sampling (PM) and harvest	21-Mar-15	105	20-May-15	152

[a]*V3–4* maize growing stage of three-to-four leaves, *VT* tasseling stage, *PM* physiological maturity stage

recorded by a TE525MM rain gauge (Campbell Scientific, Inc., USA). All the monitoring instruments were connected to a data logger (CR1000, Campbell Scientific, Inc., USA), which recorded data every 10 min.

Soil moisture, expressed as volumetric water content, was separately calibrated with soils sampled from each site (R^2 = 0.95 for the calibration function with n = 40 at TZi and R^2 = 0.91 with n = 77 at TZm).

Soil sampling and analysis

Soil sampling was carried out 21 and 29 times at TZi and TZm, respectively, during the experimental period. The soils were sampled every 10–14 days during the cropping season. More sampling times conducted at TZm was due to the longer rainy season at TZm than TZi. Soils were sampled from two depths (0–0.15 and 0.15–0.3 m) using an auger ($\sim$ 0.04 m diameter). Based on our field observation, most of the mature maize roots ($>$ 70%) were distributed in 0–0.2 m, which agreed with the reports by Chikowo et al. (2003) and Sugihara et al. (2012). Therefore, sampling from the top 0.3 m soils should be sufficient to cover the major soil N source for the plant uptake. Four subsamples from the central area (4 m $\times$ 4 m) of each plot were taken and mixed as one replicate. Soil samples were air-dried and sieved through 2-mm mesh before transporting to Japan for the analysis of inorganic N (NH_4^+-N and NO_3^--N). Inorganic N was extracted from 10.0 g soil with 30.0 ml of 1 M KCl for 30 min on a reciprocating shaker, and the suspension was centrifuged (2000 $\times$ g, 10 min) and filtered through filter paper (No. 6, Adventec, Japan). Extracted NH_4^+-N and NO_3^--N were determined colorimetrically using the flow injection auto-analyzer (Flow Analysis Method, JIS K-0170, AQLA-700 Flow Injection Analyzer, Aqualab Inc., Japan).

After the first season harvest, soil bulk density at each site was determined by taking additional soil cores (100 cm^3 size; n = 9) for each depth at 0.07 m (representing 0–0.15 m) and 0.2 m (representing 0.15–0.3 m) from soils adjacent to the plots. With soil bulk density and soil thickness, soil inorganic N availability was determined by converting the concentration of total inorganic N (mg kg^{-1}) to an area basis (kg ha^{-1}).

Planting sampling and analysis

In each cropping season, aboveground plant materials were collected at three growing stages: three-to-four leaves, V3–4; tasseling, VT; and physiological maturity, PM (Table 2). For each sampling activity, five plants were collected randomly inside each plot (4 m $\times$ 4 m, avoiding the edge). Plant materials were immediately divided into leaf, stem, cob, and grain after sampling. Field weights of each separated plant materials were recorded before subsamples were taken for moisture correction. All subsamples were oven dried at 60 °C and homogenized using a rotating-disk mill. Total N content was determined by high-temperature combustion and subsequent gas analysis (Vario Max CHN, Elementar, Germany). Plant N uptake in each plot was calculated by $\sum_i^n (N_i \times DM_i)$, where i = categories of separated plant material (e.g., leaf, stem, cob, and grain); n = total number of category; N_i = total N content (%) determined for category i; DM_i = dry matter (kg ha^{-1}) of category i.

To estimate crop yields, maize ears remaining within the sampling area (4 m $\times$ 4 m) were collected from each replicate plot on the harvesting date. Grains were shelled from the ears, and the dry weight was estimated following the same way as other plant material (i.e., field weight $\times$ moisture correction from subsamples).

Calculations

Shortly (10–12 days) after N application, the increase of soil inorganic N availability ($\Delta Navail$) resulting from N application was calculated using Eq. (1):

$$\Delta Navail = [Navail_{-1DAF} - Navail_{10-12DAF}]_{Fertilized plots} - [Navail_{-1DAF} - Navail_{10-12DAF}]_{Control plots} \quad (1)$$

where $Navail_{-1DAF}$ is the soil inorganic N availability 1 day before fertilization; and $Navail_{10-12DAF}$ is the soil inorganic N availability 10–12 days after fertilization. The difference in the soil inorganic N availability in the control plots is subtracted from that in the fertilized plots to account for the inherent change in the soil inorganic N availability (e.g., mineralization, immobilization, etc.). We assume no priming effect of N applications in this calculation.

Statistical analysis

Repeated-measures analysis of variance (ANOVA) was used to determine the effects of N rate (as the between-subjects factor), sampling time (as the within-subjects factor), and their interactions on the concentrations of NH_4^+-N and NO_3^--N. Repeated-measures ANOVA was separately run for each combination of depth, site, and season. Repeated-measures ANOVA was also used to determine the effects of N rate (as the between-subjects factor), season (treated as a within-subject factor), and their interactions on the plant N uptake at three growing stages (V3–4, VT, and PM) as well as yield at each site. Following each *F*-value testing the simple effects of N rate within each level combination of the other effects, multiple comparison of means with a least significant difference (LSD) test was conducted. All statistically significant difference was identified as $P < 0.05$ unless stated otherwise. Statistical analysis was conducted with IBM SPSS Statistics (version 24).

Both the response of plant N uptake at the VT stage and yield to soil inorganic N availability were fitted with three models: quadratic, linear-plateau, and

Fig. 2 Temporal fluctuation of soil NO_3^--N (**a–d**) and NH_4^+-N (**e–h**) concentrations (mg kg^{-1}) at TZi. Downward arrows indicate N applications as well as the plant sampling at V3–4 and VT stages. Error bars represent the standard error of the means ($n = 3$). +, *, and $\overset{*}{*}$ above each sampling time indicate significant difference in means of soil inorganic N concentrations among N treatments at $P < 0.1$, $P < 0.05$, and $P < 0.01$ level ▶

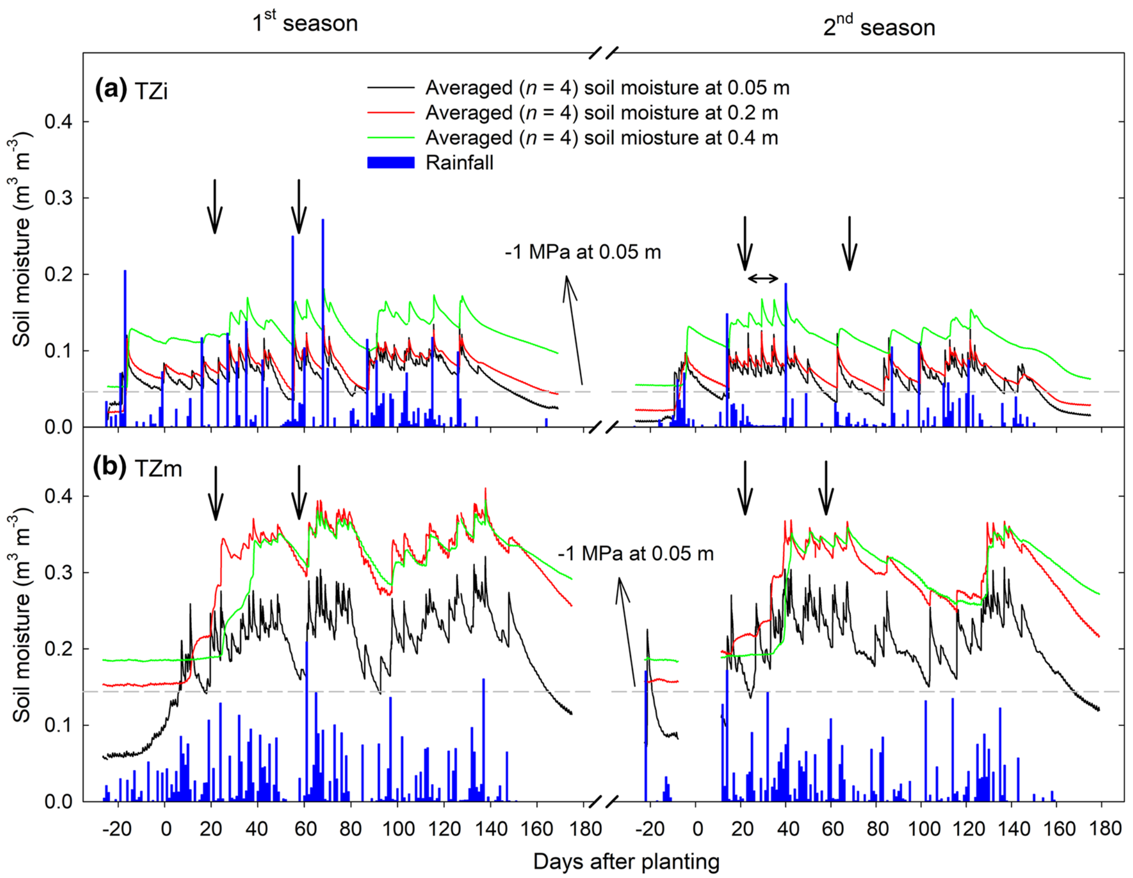
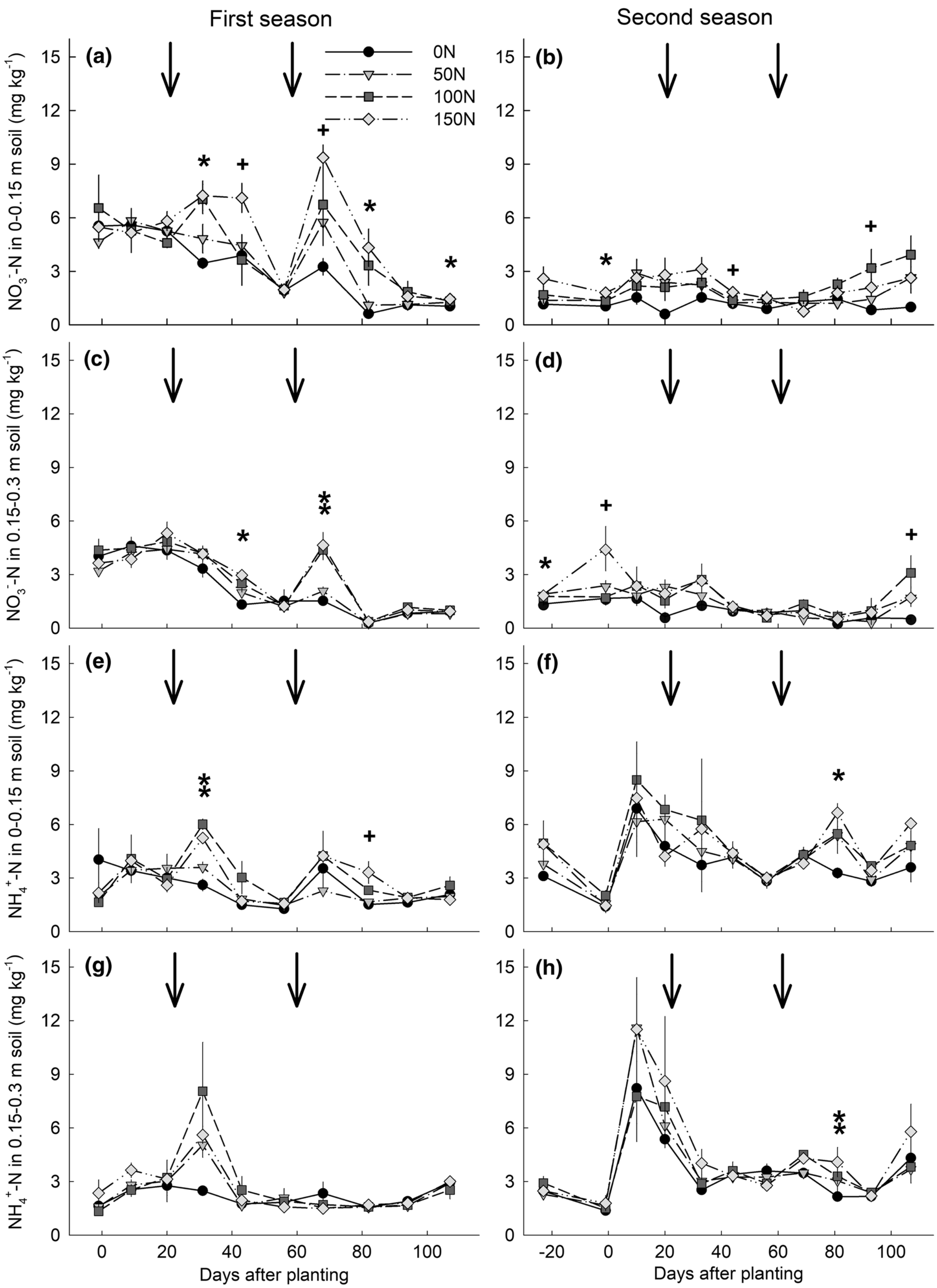
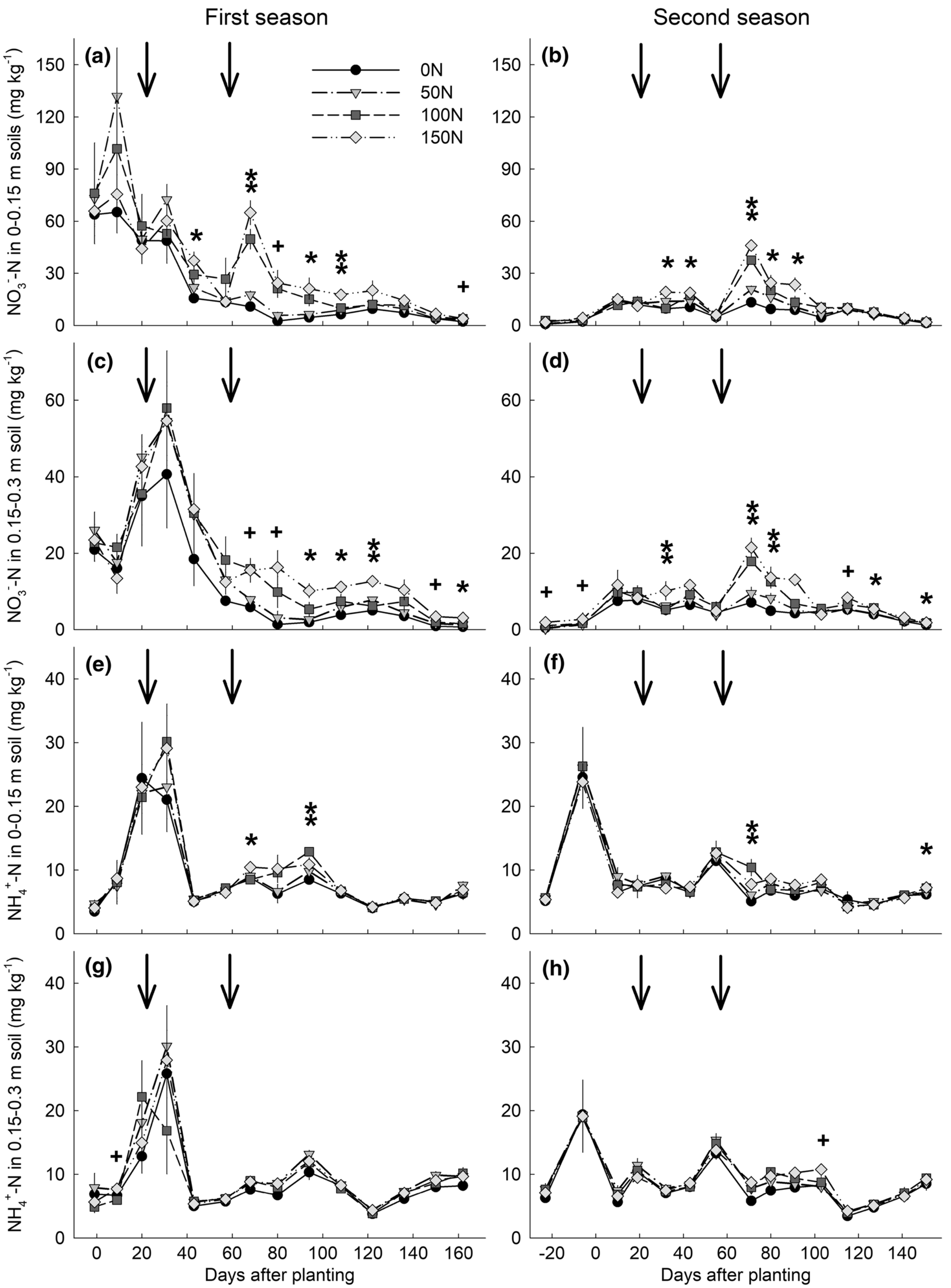


Fig. 1 Temporal variation in soil moisture and daily rainfall at TZi (**a**) and TZm (**b**) during the study period. The breaks of horizontal axis separate the data into two seasons: the first season (2013–2014) on the left and the second season (2014–2015) on the right. Horizontal dash lines indicate − 1 MPa. Downward arrows indicate the timing of fertilizer-N applications. Double line arrow represents the period when rain gauge failed to function (25–36 DAP) in the second season at TZi. (Color figure online)


First season
Second season
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
0N
50N
100N
150N
NO3−-N in 0-0.15 m soil (mg kg−1)
NO3−-N in 0.15-0.3 m soil (mg kg−1)
NH4+-N in 0-0.15 m soil (mg kg−1)
NH4+-N in 0.15-0.3 m soil (mg kg−1)
Days after planting
Days after planting


First season
Second season
(a)
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(h)
0N
50N
100N
150N
NO3−-N in 0-0.15 m soils (mg kg−1)
NO3−-N in 0.15-0.3 m soil (mg kg−1)
NH4+-N in 0-0.15 m soil (mg kg−1)
NH4+-N in 0.15-0.3 m soil (mg kg−1)
Days after planting
Days after planting

◀**Fig. 3** Temporal fluctuation of soil NO_3^--N (**a**–**d**) and NH_4^+-N (**e**–**h**) concentrations (mg kg^{-1}) at TZm. Downward arrows indicate N applications as well as the plant sampling at V3–4 and VT stages. Error bars represent the standard error of the means (*n* = 3). +, *, and $\overset{*}{*}$ above each sampling time indicate significant difference in means of soil inorganic N concentrations among N treatments at $P < 0.1$, $P < 0.05$, and $P < 0.01$ level

quadratic-plateau. Model comparison was conducted using the Akaike Information Criterion (AIC) together with 'pseudo R^2', which was calculated as 1 − (residual sum of squares/total sum of squares). Model fitting and comparison were performed using the R software (version 3.3.3; http://www.r-project.org).

Results

Environmental factors

Rainfall amount and distribution varied inter-seasonally and across the two sites (Fig. 1). Higher rainfall amounts were recorded at TZm (883 mm in the first season and 707 mm in the second season) than at TZi (638 mm in the first season and 385 mm in the second season). During the rainy seasons, soil moisture contents were generally sufficient for maize growth (> − 1 MPa at 0.05 m; Fig. 1), except for the second season at TZi, where lower precipitation (by 40% compared with the first season) and the erratic distribution resulted in several distinct dry periods (e.g., 7–15 DAP, 57–63 DAP, and 71–84 DAP in the second season; Fig. 1a).

Fluctuation of soil inorganic N concentrations

Soil NH_4^+-N and NO_3^--N concentrations varied both intra-seasonally (Fig. 2, 3) and inter-seasonally (Table S1) in the 0 N treatment, and the response to N application varied with site and depth (Fig. 2, 3). Soil inorganic N concentrations were generally higher at TZm (up to 30 and 132 mg kg^{-1} for NH_4^+-N and NO_3^--N, respectively) than those at TZi (up to 12 and 9 mg kg^{-1} for NH_4^+-N and NO_3^--N, respectively).

At TZi, the variability of soil NH_4^+-N and NO_3^--N concentrations differed between the two seasons (Fig. 2). In the first season, both soil NH_4^+-N and NO_3^--N concentrations responded to N application (Fig. 2a, c, e, g). The effect of N rate on soil NO_3^--N concentrations in two depths depended on sampling time ($P < 0.05$ for the interaction N rate × sampling time; Table S1), while soil NH_4^+-N concentrations were significantly affected by seasonal variation ($P < 0.001$ for the sampling time, Table S1). The increased soil inorganic N concentration resulting from applied N, indicated by the significant difference among N treatments after N application, was retained up to 25 days (Fig. 2a). In the second season, no immediate response of either soil NH_4^+-N or NO_3^--N concentration to N application was observed in either depth (Fig. 2b, d, f, h). Soil NO_3^--N concentrations in

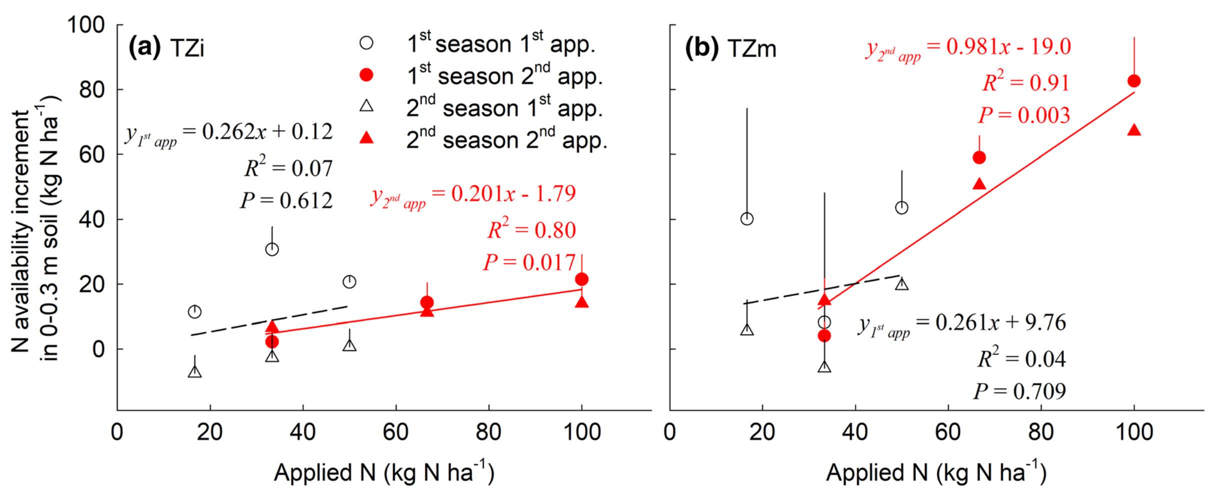

Fig. 4 Relationship between N application rate and Δ*Navail* (Eq. 1; N availability increment) after N application in 0–0.3 m at TZi (**a**) and TZm (**b**). Error bars represent positive standard error of the means (*n* = 3)

Table 3 Plant N uptake (kg N ha^{-1}) at three growing stages (three-to-four leaves, V3–4; tasseling, VT; and physiological maturity, PM) and yield (Mg ha^{-1}), and the *F*-values from the results of repeated-measures ANOVA showing the effects of N application rate (N rate), seasonal variation, and their interactions on these variables

	TZi				TZm			
	V3–4 (kg N ha^{-1})	VT (kg N ha^{-1})	PM (kg N ha^{-1})	Yield (Mg ha^{-1})	V3–4 (kg N ha^{-1})	VT (kg N ha^{-1})	PM (kg N ha^{-1})	Yield (Mg ha^{-1})
The first season								
0 N	2.1a	8.1a	10.7a	0.18a	2.3a	21.5a	48.3a	2.9a
50 N	2.0a	9.5ab	26.9b	1.2b	2.3a	25.1a	80.5a	3.9b
100 N	2.0a	14.7bc	43.9c	2.0bc	2.1a	30.1a	122.1b	4.3b
150 N	2.3a	17.2c	59.3c	2.6c	2.5a	25.6a	153.2b	4.3b
SED[a]	0.3	2.8	6.8	0.41	0.37	3.18	17.1	0.4
The second season								
0 N	1.9a	2.7a	9.2a	0.18a	1.3a	5.3a	32.7a	1.5a
50 N	3.0a	3.9a	15.6ab	0.34a	1.7a	8.5ab	52.3ab	2.9b
100 N	3.4a	5.1a	18.5bc	0.33a	2.0a	10.5b	69.6bc	3.6bc
150 N	2.7a	5.1a	24.9c	0.33a	2.0a	12.3b	93.0c	4.4c
SED	1.1	1.1	3.7	0.12	0.25	2.0	11.5	0.4
Source	*F*-values							
N rate	0.615^{ns}	8.14**	15.6**	10.5**	2.85^{ns}	3.72^{ns}	25.5***	19.2***
Season (S)	2.60^{ns}	50.8***	115***	78.9***	10.5*	249***	27.4***	20.4**
N rate × S	0.756^{ns}	2.03^{ns}	18.6***	13.4**	0.919^{ns}	1.56^{ns}	1.93^{ns}	3.43^{ns}

Values followed by different letters within a column in each cropping season indicate significant difference at $P < 0.05$ (LSD test)

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$, *ns* non-significant

[a]*SED* standard error of the difference

both depths were low (< 4 mg kg^{-1}) throughout the season (Fig. 2b, d), and they significantly ($P < 0.05$) differed among N treatments and sampling times (Table S1). Soil NH_4^+-N concentrations were significantly controlled by seasonal variation ($P < 0.001$, Table S1) as observed in the first season. During − 1 to 10 DAP in the second season (Fig. 2f, h), we observed the increase of soil NH_4^+-N concentrations across the whole field, likely due to the rapid mineralization of organic matter during the onset of rain.

At TZm, the soil NO_3^--N concentrations at the beginning of the first season (e.g., before N application) were substantially greater (44–132 mg kg^{-1} in 0–0.15 m and 13–45 mg kg^{-1} in 0.15–0.3 m) than those in the second season (1–15 mg kg^{-1} in 0–0.15 m and 0–12 mg kg^{-1} in 0.15–0.3 m). In the first season, the soil NO_3^--N concentrations showed relatively large variation among treatments at the second sampling (9 DAP in Fig. 3a), but not significantly different ($P > 0.1$). In both seasons, soil NO_3^--N concentrations responded to N application (Fig. 3). Soil NH_4^+-N concentrations generally maintained a similar level among treatments in each depth across each season (Fig. 3), as suggested by the simple main effect of sampling time ($P < 0.001$, Table S1). The increased soil NO_3^--N concentration resulting from N application was retained up to 63 days (Fig. 3c). At the beginning of the second season, we observed the increase of soil NH_4^+-N concentrations (− 23 to − 6 DAP in Fig. 3f, h) followed by NO_3^--N flushes (− 6 to 10 DAP in Fig. 3b, d) across the field.

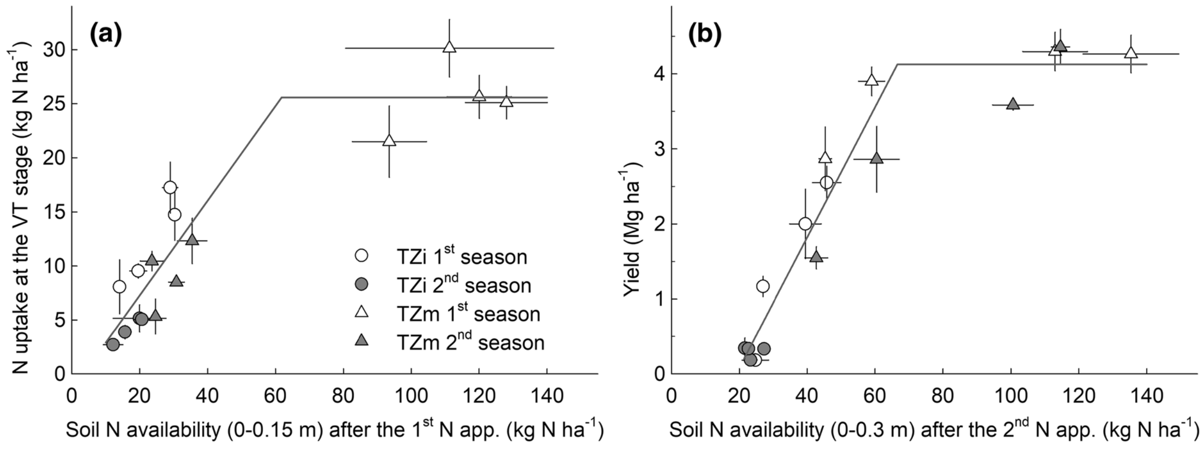

Fig. 5 Response of plant N uptake at the VT stage (**a**) and yield (**b**) to soil inorganic N availability after the first and second N applications (i.e., 31–33 DAP and 68–71 DAP), respectively. Error bars represent standard error of the means (n = 3)

Relationship between N rate and Δ*Navail* at each site

Shortly (10–12 days) after N application, Δ*Navail* (calculated using Eq. 1) in 0–0.3 m increased significantly with N rate for the second N application ($P = 0.017$ at TZi and $P = 0.003$ at TZm) but not for the first N application ($P = 0.612$ at TZi and $P = 0.709$ at TZm) across sites (Fig. 4). For the second N application, the higher slope of the regression line at TZm (0.98) shows that applied urea increased plant-available N in soils more efficiently compared to TZi (0.20), especially at higher urea-N rates (Fig. 4). For example, a single application of urea with 100 kg N ha^{-1} increased ~ 79 kg N ha^{-1} of inorganic N in the 0–0.3 m soils at TZm, but only increased ~ 18 kg N ha^{-1} at TZi (Fig. 4). In the first season at TZm, vast ranges were observed for the Δ*Navail* (Eq. 1) with the same N rate after the first N application (showed by the large standard error in Fig. 4b).

Plant N uptake and yield

Plant N uptake of mature maize (i.e., PM stage) varied with site and season (Table 3). In the plots treated with the same N rate, uptakes at TZm were 24–94 kg N ha^{-1} higher than those at TZi during the two seasons. Similarly, uptakes in the first season were 2–60 kg N ha^{-1} higher than those in the second season across two sites (Table 3).

The effect of N rate and season on plant N uptake was different across plant growing stages at each site. At the V3–4 stage (i.e., before N application), plant N uptake was small (< 3.5 kg N ha^{-1}) and similar across sites and seasons, though a difference ($P < 0.05$) was detected at TZm between the two seasons (Table 3). At the VT stage, significant ($P < 0.001$) seasonal variation of plant N uptake at each site was observed, while the effects of N rate varied with season (i.e., only significant in the first season at TZi and the second season at TZm; Table 3). At the PM stage, the effects of N rate were significant ($P < 0.01$) in all cases (Table 3).

A significant effect between season × N rate ($P <$ 0.05) on the yield was observed at TZi but not TZm (Table 3). At TZi, yields in the first season (0.2–2.6 Mg ha^{-1}) were generally higher than those in the second season (0.2–0.3 Mg ha^{-1}), with a significant effect of the N rate on the yield only observed in the first season (Table 3). At TZm, higher yields in the first than the second season were observed at lower (0–50 N) but not higher N rates (100–150 N) (Table 3). With similar rainfall amount received in the first season at TZi (638 mm) and the second season at TZm (707 mm), yield at TZm (1.5–4.4 Mg ha^{-1}) was higher than that at TZi (0.2–2.6 Mg ha^{-1}) with the same N rate applied (Table 3).

Plant N uptake at the VT stage and yield in response to soil inorganic N availability

The response of plant N uptake at the VT stage to soil inorganic N availability (0–0.15 m) at 31–33 DAP (i.e., after the first N application; Fig. 5a) and the response of yield to soil inorganic N availability (0–0.3 m) at 68–71 DAP (i.e., after the second N application; Fig. 5b) were all best-fitted by linear-plateau model (Table S2). The models suggest that 62 and 67 kg N ha^{-1} was the minimum soil inorganic N availability after N application to achieve maximum plant N uptake at the VT stage and yield, respectively (parameter *c* for linear-plateau models in Table S2). The maximum yield calculated from the linear-plateau model was 4.1 Mg ha^{-1}.

Discussion

Potential leaching loss of inorganic N in the early growing seasons

At the beginning of the rainy season, rainfall often triggers rapid mineralization of organic matter accumulated during the drying season and therefore causes the flush of inorganic N in the topsoil, known as "Birch Effect" (Birch 1964). However, the mineralized N is usually excessive and susceptible to leaching at this timing as crop N demand is small (Chikowo et al. 2004). For example, during the nitrification of soil mineralized NH_4^+ at TZi (i.e., decreasing soil NH_4^+-N concentrations during 10–20 DAP in Fig. 2f, h), reduction in soil inorganic N availability in 0–0.3 m (12.7 kg N ha^{-1}) was larger than the plant N uptake at V3–4 stage (2.7 kg N ha^{-1}). Similarly, during the period of NO_3^--N pulse at TZm (− 6 to 10 DAP in Fig. 3b, d), N loss was estimated as 14 kg N ha^{-1} by comparing the decrease in N amount from the top 0.3 m (15.5 kg N ha^{-1}) with the plant N uptake at V3–4 stage (1.7 kg N ha^{-1}). These estimated leaching losses of N were within the ranges reported by previous studies (4.3–39 kg N ha^{-1}) across sandy and clayey soils in SSA (Kamukondiwa and Bergström 1994; Mapanda et al. 2012). As the major driver of these potential leaching losses, the flush of inorganic N has been reported in both sandy and clayey soils in SSA (Chikowo et al. 2004; Tully et al. 2016; Russo et al. 2017) as well as other tropical regions (Wetselaar 1961). Our results support the findings of previous studies that managing indigenous N resource in the early growing season was challenging regardless of soil type, because crop roots were under-developed and N demands were too small to utilize the excessively mineralized N. Consequently, the mobile N was largely exposed to the risk of leaching.

At TZm, the substantially higher soil NO_3^--N concentrations with large variation at the beginning of the first season (Fig. 3a, c) compared to the second season (Fig. 3b, d) was attributed to the residual N from the preceding study. Such high residual soil N from the previous season could be prone to leaching loss upon sufficient rainfall in the current season (Rasouli et al. 2014; Masvaya et al. 2017). For example, during 31–43 DAP in the first season, both soil NH_4^+-N and NO_3^--N concentrations substantially dropped across all the plots and depths (Fig. 3a, c, e, g; equivalent to 133 kg N ha^{-1}), while the plant N uptake between V3–4 and VT was small (23 kg N ha^{-1}). Given the high precipitation (116 mm) during this period and the high initial soil moisture (> 0.21 and > 0.32 m^3 m^{-3} at 0.05 and 0.2 m, respectively, in Fig. 1b), leaching could be main pathway of this N loss. Such a substantial N loss (~ 110 kg N ha^{-1}) largely eliminated the effect of residual N before the second N application (Fig. 3a, c, e, g).

Effects of N application and soil type on soil inorganic N

The increased soil inorganic N concentration resulting from N application, indicated by the significant difference among treatments after N application, was retained longer at TZm (up to 63 days in Fig. 3c) than at TZi (up to 25 days in Fig. 2a). The longer N retention at TZm was likely a result of a higher WHC (Table 1). Better N retention may also be explained by the anion exchange capacity developed by variable charge clay minerals (Ishiguro et al. 1992; Katou et al. 1996) at TZm, which can lead to NO_3^- adsorption.

For the first N application, N rate had no significant effect ($P > 0.05$) on $\Delta Navail$ (Eq. 1) across sites (Fig. 4). This could be attributed to the relatively high and variable concentrations of initial soil N (Fig. 2, 3) and the low rates of N application (17–50 kg N ha^{-1}). In the first season at TZm, the variation of initial N concentrations was largely contributed by the high residual N from the preceding experiment, which masked the effect of the first N applications (soil inorganic N availability among treatments were not significantly different following the first N application; Fig. S1).

For the second N application, the effect of N rate on Δ*Navail* (Eq. 1) clearly differed between the two soils, with applied urea more efficiently increased plant-available N in soil at TZm than at TZi (Fig. 4). This could be mainly attributed to the higher susceptibility of the soil to NH_3 volatilization from surface-applied urea at TZi than that at TZm. Soils with coarse texture and low organic matter (i.e., TZi) are generally low in CEC and pH buffering capacity (Table 1), and therefore inherently weak to buffer the NH_3 loss (Ferguson et al. 1984; Corstanje et al. 2008). This is supported by the result of another research from our team, where we quantified NH_3 loss from surface-applied urea on the current two sites: under the same urea-N rate (30–100 kg N ha^{-1}, as single application), sandy Alfisols had a larger fraction of N loss as NH_3-N (36–50% of applied N) compared to clayey Andisols (5–20%) (Zheng et al. 2018). Furthermore, accumulated rainfall during the 12 days after N applications did not exceed 40 mm in either season at TZi, which excluded the possibility of dominant contribution from leaching to N loss. Therefore, NH_3 volatilization should be the major pathway of N loss from urea during the short period (10–12 days) after application at TZi, which led to the low efficiency of applied urea in increasing plant-available N at TZi.

Plant N uptake at the VT stage and yield in response to soil inorganic N availability

Plant N uptake at the VT stage did not consistently show significant difference among N treatments (Table 3) due to the effects of inter-seasonal variations of soil or climatic condition. In the first season at TZm, the residual N from the preceding study contributed to sufficient N supply for plant until the VT stage, as well as the relatively high yield even at 0 N plots (2.9 Mg ha^{-1}). A relatively high yield (3.2 Mg ha^{-1}) and final N uptake (115 kg N ha^{-1}) resulting from sufficient indigenous soil N supply was also observed in a clayey soil in Morogoro, Tanzania (Sugihara et al., 2012). At TZi, drought in the early crop growth period of the second season may have severely affected the yield (Table 3). Such climatic effects were common in sandy soils in SSA croplands. For example, both Tully et al. (2016) and Masvaya et al. (2017) reported low maize yields (in sandy soils of Tanzania and Zimbabwe) in dry season or due to drought experienced in the early growing period. Apart from these inter-seasonal variations, split N application could still be necessary as in the normal seasons we observed a significant difference in N uptake at the VT stage among N treatments (Table 3).

As indicated by the linear-plateau model (Fig. 5a), the optimal soil inorganic N availability (0–0.15 m) after the first N application (parameter c = 61.8 kg N ha^{-1} in Table S2) was much higher than plant N uptake at the VT stage, which may promote N leaching (e.g., 31–43 DAP at TZm in the first season; Fig. 3a, c, e, g). Further, high N fertilizer rates for the first application are not practical in SSA croplands. Fortunately, soil inorganic N availability after the second N application seemed more important for the final N uptake and yield (Fig. 5, S2). For example, the major N uptake (on average $\sim$72% across sites and seasons) occurred between VT and PM. Furthermore, the second N application frequently resulted in different ($P < 0.05$) levels of yields while plant N uptakes at the VT stage showed insignificant differences ($P > 0.05$; Table 3).

Soil inorganic N availability in 0–0.3 m at the tasseling stage (after the second N application or 68–71 DAP) largely accounted for the final yield (Table S2; Fig. 5). This result is in line with the study conducted on sandy soils in Zimbabwe by Mtambanengwe and Mapfumo (2006). More often, relationships were set up between yield and N rate (Wang et al. 2017) or N rate plus soil available N before N application (Hartmann et al. 2015), for facilitating the determination of optimal N rate. Yet in the current study, we observed notable effects of inter-seasonal variations on the yields (i.e., residual N from the preceding study at TZm and decreased rainfall with erratic distribution at TZi). Also, the efficiency of applied urea in increasing plant-available N in soil could differ greatly between TZm and TZi (Fig. 4). It is therefore soil inorganic N availability after N application could integrate all these effects (direct and/or indirect) into one simple factor that significantly accounted for the final yield. The success of including all yield data in one linear-plateau model indicated the dominant control of soil inorganic N availability

(0–0.3 m) at the tasseling stage over the final yield across sites and seasons.

A closer inspection on the yield–soil N response pattern (Fig. 5b) revealed that maize yield at TZi could still be limited by soil inorganic N availability at the tasseling stage, whereas yield at TZm may be co-limited by other nutrients (Njoroge et al. 2017) once the soil inorganic N availability was above 67 kg N ha^{-1}, considering the yield potential of the variety (Lyimo 2005). The yield plateau in the model for TZi should be interpreted with caution, as the maximum yield observed at TZi in this study was only 2.6 Mg ha^{-1}. Nevertheless, such plateau of yields from the model fitting was supported by another experiment at TZi with higher N supply ($\sim$ 4 Mg ha^{-1}; Zheng et al. *unpublished*). Nutrient input through chemical fertilizer and/or organic resources could be indispensable in the infertile, sandy soil to ensure maize yield (Mtambanengwe and Mapfumo 2006; Masvaya et al. 2017). For example, yields at TZi from the 0 N plots were below 0.2 Mg ha^{-1} due to limited soil inorganic N availability. However, maintaining high soil inorganic N availability simply by increasing urea-N rate at sandy soils like TZi could be challenging (Mtambanengwe and Mapfumo 2006) as a single N application of 100 kg ha^{-1} only increased $\sim$ 18 kg ha^{-1} available N in soil (Fig. 4a). Such fast N depletion lowered the availability of applied N to maize, leading to the low N use efficiency (e.g., 17–23 kg grain kg^{-1} N applied at TZi vs. 29–57 kg grain kg^{-1} N applied at TZm; Table S3) and insignificant ($P > 0.05$) difference in yields between the 100 N and 150 N treatments (the first season at TZi; Table 3).

Implications for N management in SSA croplands

Conserving the soil mineralized N in the early growing season has long been a challenge to improve N synchrony. Many approaches focus on reduced tillage (Masvaya et al. 2017) to delay net mineralization or application of low-quality organic resources (Sugihara et al. 2012) to immobilize leachable N by microbes. The effect of reduced tillage may be too short-lived to improve the N synchrony (Chikowo et al. 2004) or even negative on maize yield (Masvaya et al. 2017). Although Gentile et al. (2008) showed in a laboratory incubation that adding a low-quality organic resource (i.e., high C:N ratio) had immobilized soil-derived N for more than 90 days, actual benefit on increasing crop yield in the field was seldom observed (Gentile et al. 2009; Chivenge et al. 2010; Sugihara et al. 2012). Mechanistic studies and field verifications are needed to provide practical recommendation to immobilize the leachable N until mid-season for crop uptake. Nevertheless, fertilizer-N input can be reduced if mobile N can be utilized efficiently. In the second season of our study, captured net nitrogen mineralization at the onset of rains provided $\sim$ 33 and 47 kg N ha^{-1} in 0–0.3 m at TZi and TZm, respectively.

Maintaining high levels of available N in sandy soils (i.e., at TZi) and simultaneously achieving high recovery by crops is challenging (Mtambanengwe and Mapfumo 2006), as the sandy soil is more susceptible to NH_3 volatilization (e.g., from surface-applied urea in our study) and N leaching loss. In the period of high crop N demand in sandy soils (e.g., at the tasseling stage in our study), dissolving the urea in a water container and applied through an affordable, easy-to-construct dripping irrigation system (Postel et al. 2001; Kahimba et al. 2015) could be promising (schematic layout and examples of in situ implementation of this system are provided as Fig. S3, S4 in the supplementary material). The main function of such dripping irrigation system is to increase N use efficiency (by reducing potential NH_3 loss without raising labor cost) rather than to supply water, yet in abnormally drought years/periods (e.g., 7–15 DAP in the second season at TZi) it can also serve for water supply to prevent yield failure.

At TZm, future research is required to identify the co-limiting nutrients to further improve the yield. Co-limitation of secondary nutrients or micronutrients on the yield in SSA croplands (Kihara et al. 2016) such as at TZm may be solved by applying animal manure (Zingore et al. 2007; Sileshi et al. 2016), which is unlikely to significantly increase the cost on smallholder farmers. Manure application before or at the time of planting for slower release of nutrients and side-dressing with proper urea-N rate (e.g., 75 N based on Fig. 5) at the tasseling stage may achieve desirable yields in croplands with similar soil type to TZm.

Conclusions

In the current study, seasonal variations of soil inorganic N availability revealed the challenge of N management in the early growing season in SSA croplands: excessive soil mineralized N was susceptible to leaching loss due to limited crop N demand. Future researches should focus on how this excessive soil mineralized N can be immobilized until mid-season when crop N demand is high, and especially verification in the field that such immobilization benefits the crop yield. At higher urea-N rates (i.e., during the second application), soil type (i.e., sandy Alfisols at TZi vs. clayey Andisols at TZm) strongly affected the efficiency of applied urea in increasing plant-available N in soils. Fast depletion of applied urea-N at TZi was likely due to substantial N loss through NH_3 volatilization, as supported by the poorly pH-buffered soil with low CEC. This largely contributed to the different yield levels at two sites—lower at TZi (up to 2.6 Mg ha^{-1}) than TZm (up to 4.4 Mg ha^{-1}) under the same N rate. We also found that yield was strongly controlled by the soil inorganic N availability in 0–0.3 m at the tasseling stage (i.e., after the second N application or 68–71 DAP). Furthermore, maintaining high levels of N availability at the tasseling stage and supplying secondary nutrients or micronutrients would be the keys to further improve yields at TZi and TZm, respectively. Our results contribute to a better understanding of temporal patterns of soil N pools across soil types and how they affect the yield response in SSA croplands, which is important for designing the best fertilizer-N management practices to achieve higher yield and lower environmental impact as N application rates increase.

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Compliance with ethical standards

Conflict of interest The author declares that they have no conflict of interest.

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