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Potential N mineralization and availability to maize in black soils in response to soil fertility improvement in Northeast China

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Abstract

Purpose Understanding the soil nitrogen (N) mineralization potential (N_0) and crop N availability during the growing season is essential for improving nitrogen use efficiency (NUE) and preventing over-fertilization, which lead to negative environmental impacts.

Methods Five black soils with different levels of fertility were selected in Northeast China. The N_0 and kinetics of these soils were estimated through laboratory experiments at different incubation temperatures (15, 25, and 35 °C). N mineralization dynamics were simulated using field soil temperature according to the incubation results. Moreover, the N uptake dynamics of maize were simulated according to the literature.

Results Compared with the very low-fertility soils, the cumulative mineralized nitrogen increased under all incubation temperatures (15, 25, and 35 °C), by 48–136%, 8–61%, and 24–59%, respectively, in the medium- and high-fertility soils. The highest N_0 values (96.90, 115.31, and 121.33 mg/kg at the three different temperatures) were recorded in the very high-fertility soils. The soil N mineralization dynamics and N uptake of maize in the growing season were highly consistent over time, although the soil N supply could not meet the maize growth requirements. The higher the soil fertility, the lower the N fertilizer requirement.

Conclusions Different fertilizer strategies were developed based on the cumulative mineralized N, N uptake by maize, and NUE in soils with different fertility levels. We suggested a reduction of 50–65 kg N/ha in N fertilizer in the two highest fertility soils. This study provided basic data to reduce chemical N fertilizer to improve NUE and reduce negative environmental impacts.

Keywords Black soil zones · Soil fertility · Potentially mineralized nitrogen (N_0) · Nitrogen fertilization · Environmental impacts

1 Introduction

Nitrogen (N) is an abundant element on Earth that accounts for 78.1% of Earth's atmosphere and is an essential nutrient for all forms of life (Geisseler et al. 2009; Stevens 2019). N is also the most common growth-limiting nutrient in agricultural production systems. The N absorbed by crops is primarily derived from soil. Nevertheless, organic N is the main form

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in the soil N pool, which must be transformed into inorganic N through mineralization so that it can be absorbed and utilized by plants. Underestimating soil organic N mineralization causes excess fertilizer application, which results in only a fraction of the N applied to fields being absorbed by crops (Reay et al. 2012; Steffen et al. 2015). This leads to a large quantity of fertilizer N lost to the environment, which negatively affects the soil and ecosystem, resulting in more active N generated in agricultural systems and low N use efficiency (Rockström et al. 2009).

Researchers have reported that the amount of N available for crop absorption through mineralization may range from < 20 to > 200 kg N ha^{-1} (Goh 1983), which depends on soil properties, environmental conditions (soil temperature and moisture), and crop management. Soils with different fertility levels have different physicochemical properties that affect soil N mineralization. Previous studies indicated that soil C and N contents and pH are the main factors related to N transformation (Müller et al. 2011; Aciego-Pietri and Brookes 2008). It was also found that N fertilizer application has negative effects on soil N mineralization, suggesting that N fertilization may decrease mineralized N contents in soils (Carpenterboggs et al. 2000). Additionally, long-term fertilizer management strategies could change soil organic matter (SOM) characteristics and N mineralization potentials (Osterholz et al. 2017).

In the black soil zones of Northeast China, the evolution of black soil fertility with different fertilizer management strategies has always been important. According to the results of long-term experiments, the use of manure, which markedly influences the physical and chemical properties of soil, is an effective measure to improve soil fertility. The long-term application of organic fertilizers has been shown to increase the total soil C content (Cai and Qin 2006). As the soil N content and supply capacity are important soil fertility indicators, many laboratory studies have been carried out on soils with different fertility levels (Lang et al. 2016; Li et al. 2018; Fu et al. 2019). However, very little is known about N mineralization dynamics as well as N availability in soils with different fertility levels during the growing season of maize. As most laboratory N mineralization experiments are incubated at 35 °C, the ideal temperature for mineralization, the incubation results do not represent the field N mineralization status. We selected 3 different incubation temperatures and simulated the dynamics of N mineralization in soils with different fertility levels during the maize growing season using field soil conditions based on laboratory incubation results.

The optimal N fertilizer rate depends not only on the timely availability of non-fertilizer N, which is mainly from N mineralization, but also on the crop N requirements. However, it is difficult to assess the N amount required by crops and the N supply of soils simultaneously (Kpomblekou-A and Genus 2012). In this study, we simulated the dynamic N accumulation process of maize according to the literature results modeled with the Agricultural Production Systems Simulator (APSIM) maize model (Soufizadeh et al. 2018) and the maize yield of a long-term experiment. The above two dynamic processes will be used to make suggestions for the optimum rate and timing of fertilizer application for the development of sustainable land management strategies. Therefore, the primary objective of this study was to increase our understanding of the effect of soil fertility on N mineralization and the different fertility dynamics of black soils during the maize growing season in Northeast China. The secondary objective was to formulate fertilizer application suggestions for maize by estimating the N mineralization dynamics of soils with different fertility levels and crop N uptake dynamics during the growing season.

2 Materials and methods

2.1 Soils and soil sampling

Five soils were selected as representative black soils with different fertility levels. Four of the soil samples were collected from a long-term fertilizer trial that started in 1980 at the research station of the National Soil Fertility and Fertilizer Efficiency Long-term Monitoring Network in Gongzhuling, Jilin Province, China (43° 40′ N, 128° 48′ E). Another soil sample was collected from a nearby field, without fertilizer management for many years, and this planting system and crop were consistent with those of the other four sites. The sites were located in a mid-temperate zone, with a continental monsoon climate and a mean annual temperature of 4.5 °C. The mean annual precipitation is 450–600 mm, and the potential evaporation is 1200–1600 mm/year. The cropping system was spring maize (*Zea mays* L.), which was always sown in early May and harvested at the end of September.

The five soils included unfertilized soil, two soils treated with N, phosphorus, and potassium (NPK) fertilizer at low and conventional application rates (N_1PK and N_2PK, respectively), and two soils treated with manure at conventional and high application rates (M_2 and M_4, respectively). The N_1PK and N_2PK fertilizer treatments consisted of annual applications of 75 and 150 kg N/ha (as urea), respectively, with 75 kg P_2O_5/ha (as superphosphate) and 75 kg K_2O/ha (as potassium sulfate) applied in both treatments. The total N application in the M_2 treatment was the same as that in the N_2PK treatment, but the total N application in the M_4 treatment was twice as high as that in the N_2PK treatment. Approximately 9.4 and 18.8 t/ha of manure (dry weight) were applied annually to the M_2 and M_4 soils, respectively. After nearly 40 years of fertilization, the soil chemical properties differed significantly among the five different fertilized soils.

The soils were sampled prior to planting before any application of fertilizer or irrigation water in spring 2017. Each of the five sites was divided into 4 blocks, and separate soil samples were collected with an auger at depths of 0–20 cm in each block. Based on the analysis of the physical and chemical properties of the above five soil samples, which were obtained by standard analysis methods (Lu 1999), the integrated fertility index (IFI), a soil fertility index, was evaluated by fuzzy and factor analyses (Tang 1997; Ma et al. 2004; Dong et al. 2011). Detailed soil fertility information for the five selected soils is listed in Table 1.

2.2 Incubation experiment

Soil N incubation experiments were carried out according to the intermittent aerobic incubation method. Duplicate 15-g samples of air-dried soil and equal weights of 20-mesh quartz sand were moistened using finely sprayed distilled water and mixed thoroughly; after which, they were added to 50-mL plastic tubes covered with punctured plastic wrap (Stanford and Smith 1972). The tubes were placed in incubators at 15, 25, or 35 °C, with 4 replications. The plastic tubes were destructively sampled after 0, 14, 28, 56, 112, and 252 days, and the soil was analyzed for NH_4^+–N and NO_3^-–N by leaching using $CaCl_2$. The detailed incubation and leaching steps were performed according to Stanford and Smith (1972).

We define mineralizable N as the increase in inorganic N (NH_4^+–N and NO_3^-–N) over 252 days of incubation under constant environmental conditions (constant temperature and moisture content). The potential mineralized N pool was calculated using first-order kinetics (Stanford and Smith 1972; Ju et al. 2000).

$$N_t = N_0\left(1-e^{-kt}\right) \tag{1}$$

where N_t is the cumulative mineralized N (mg/kg) over time t (days); N_0 is defined as the potential mineralized N (mg/kg), which is obtained from fitting the net mineralization data (N_t) throughout the incubation period (t, days) with eq. (1); k is the rate constant of mineralization of N_0 (d^{-1}), which changes with temperature; and t is the incubation time (days).

Temperature sensitivity (Q_{10}) was selected to reflect the N_{min} changes as the temperature increased by 10 °C and was calculated according to the following equation:

$$Q10 = (k_2/k_1)^{\left[\frac{10}{(T_2-T_1)}\right]} \tag{2}$$

where k_2 and k_1 are the rate constants for the N mineralization process at incubation temperatures T_2 and T_1, respectively (Kirschbaum 1995; Fissore et al. 2013).

The relationship between N_t and the effective cumulative temperature was described by eq. (3) (Yoshino and Dei 1974):

$$N_t = k_t[(T-T_0)t]^n \tag{3}$$

where N_t is the cumulative mineralized N (kg/ha) over time t (days); T is the temperature (°C); T_0 is the effective temperature, 10 °C; and k_t and n are fitting constants, which were calculated based on the cumulative mineralized N in our incubation experiment under different temperatures.

2.3 Nitrogen mineralization dynamics

A soil temperature sensor (EL-USB-1-PRO), which was placed at a depth of 10 cm, was used to record the surface soil temperature every 30 min during the maize growing season in 2017. Based on the observed soil temperature and fitting constants k_t and n in eq. (3), the N mineralization process of soils with different fertility levels was estimated during the growing season of maize (approximately 160–165 days) under field conditions in Gongzhuling. In addition, the N accumulation process of maize was evaluated according to the N concentration dynamics per unit biomass of maize, which was determined by modeling with the Agricultural Production Systems Simulator (APSIM) maize model (Soufizadeh et al. 2018). In the initial period of growth, maize N uptake increased directly and then stabilized in the later period; therefore, a linear + plateau model was chosen to determine the dynamic process

Table 1 Main physicochemical properties of the five studied soils

Soil fertility level	IFI	BD (g/cm^3)	pH (H_2O)	Sand %	Silt %	Clay %	TOC (g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)	C:N
Very low	0.236^c	1.34	5.28^c	47.53^b	18.52	36.02^a	11.4^e	1.10^d	0.44^d	29.71	10.30^c
Low	0.426^b	1.32	7.85^a	40.40^b	25.97	34.23^a	14.6^d	1.26^c	0.50^c	29.34	11.61^a
Medium	0.445^b	1.28	7.61^a	40.83^b	26.16	33.66^b	16.7^c	1.45^b	0.69^b	29.12	11.54^a
High	0.904^a	1.21	7.35^b	53.48^a	17.92	30.62^c	24.1^b	2.26^a	1.46^a	29.42	10.64^b
Very high	0.912^a	1.17	7.48^b	45.06^b	26.34	29.94^c	25.2^a	2.28^a	1.53^a	29.32	11.03^b

IFI Integrated Fertility Index, *BD* bulk density, *TOC* total organic carbon, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium

For each item, mean values followed by the same letter indicate no significant difference ($P < 0.05$). Letters are not displayed if there was no significant difference in the ANOVA of N uptake by maize. Based on the above, we compared the minimum N fertilizer requirement of maize among the five soils with different fertility levels. It should be noted that N use efficiency was not considered when estimating the minimum demand of N fertilizer, which was only the difference in the N uptake of maize and the N mineralization during the maize growing season.

2.4 Statistical analyses

Nonlinear regression was performed to describe the relationship between N_t and the cumulative effective temperature, which was calculated according to eq. (3). The estimated cumulative mineralized N (kg/ha) in the five different fields during the growing season of maize in Gongzhuling was calculated using the average values of the multiple measured daily soil temperatures in 2017. All statistical analyses were carried out with SPSS 17.0, and the figures were generated with SigmaPlot 12.5. Differences with $P < 0.05$ were considered significant.

3 Results

3.1 Physicochemical properties of the studied soils

The main physicochemical properties of the studied soils are reported in Table 1. All values are the averages of the four soil sample replicates. As indicated by the data, the SOC, total N (TN), and total P (TP) contents differed significantly among the five studied soils. In addition, the pH value of the very low-fertility soil was significantly lower than that of the other four soils. However, the clay content in the two low-fertility soils was higher than that in the other three soils. According to the main physicochemical properties (some data are not shown in Table 1) of the five soils, we obtained IFI values, which were recorded as 0.236, 0.426, 0.445, 0.904, and 0.912 for the five soils. The IFI values were used to indicate the soil fertility levels in this study.

3.2 Nitrogen mineralization in soils with different fertility levels

In the five soils with different fertility levels, N mineralization was examined at three incubation temperatures (15, 25, and 35 °C). The cumulative mineralized N increased with increasing incubation time and temperature in all five soils. Generally, at specific incubation temperatures, the mineralization rate and amount of mineralized N in soils with high fertility levels were higher than those in soils with low fertility levels (Fig. 1). Overall, an increasing trend of cumulative mineralized N was observed, with values of 48–136%, 8–61%, and 24–59% among the soils with low to very high fertility levels, compared with those of the very low-fertility soil, after 252 days of incubation at the three incubation temperatures of 15, 25, and 35 °C, respectively (Fig. 1).

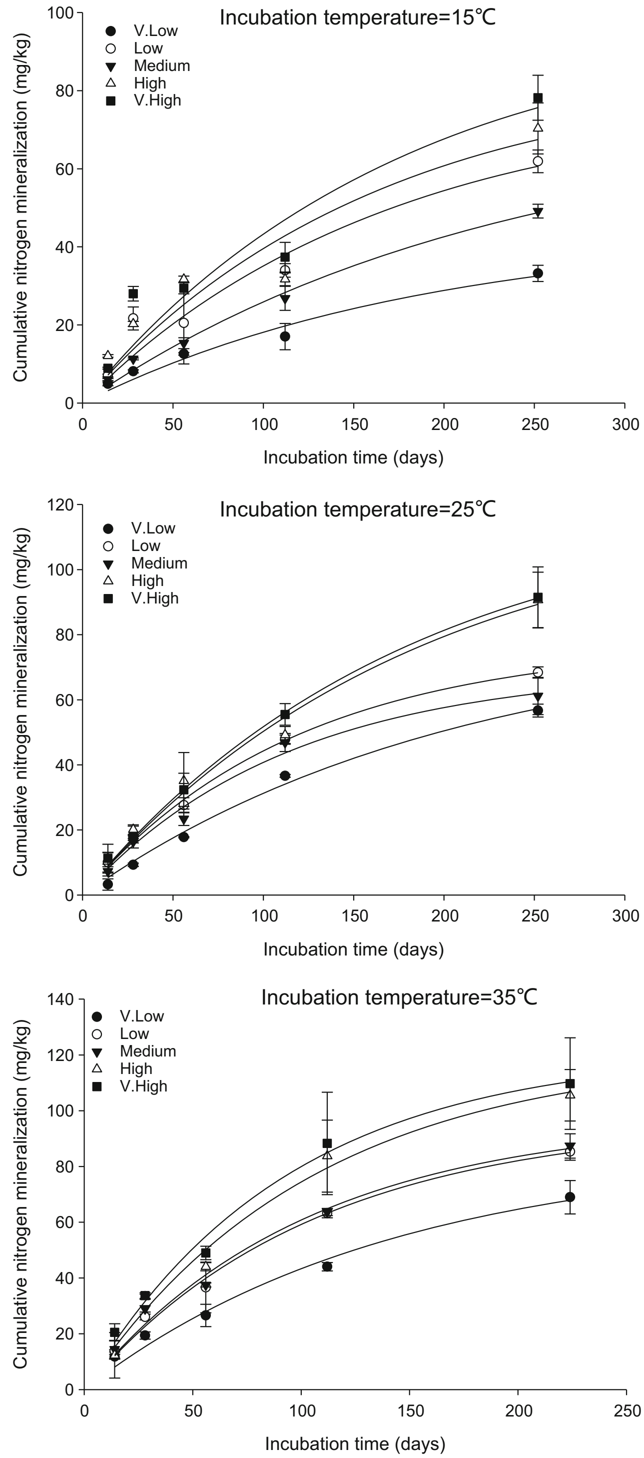

Fig. 1 Variation in cumulative mineralized N (NH_4^+-N and NO_3^--N) content throughout the incubation period at the different temperatures in the soils with different fertility levels: V. Low (very low fertility), Low (low fertility), Medium (medium fertility), High (high fertility), V. High (very high fertility). The bars indicate the standard deviation for $n = 4$ replicate samples

The values of the N mineralization potential, N_0, revealed an increasing trend among the soils with different fertility levels from low to high at the specific incubation temperatures. As listed in Table 2, the N_0 values for the soils with different fertility levels were 44–97, 67–115, and 85–121 mg/kg at the different incubation temperatures (15, 25, and 35 °C, respectively). Furthermore, regression analysis (Fig. 2a) demonstrated that N_0 had a positive relationship with the SOC content, which clearly indicated that SOC is an important soil component that affects soil N mineralization. In addition, N_0 increased with the incubation temperature. The highest N_0 values were observed when the incubation temperature was 35 °C for all soils (Table 2).

3.3 Influence of soil fertility and temperature on nitrogen mineralization

The mineralization constant (k, d^{-1}) ranged from 0.0044 to 0.0108 (Table 2). Similar to N_0, k also increased sharply with increasing SOC content (data not shown) and incubation temperature for all soils, especially between 25 and 35 °C. However, as shown in Fig. 2b, the soil clay content had a negative effect on k, which may explain why soil fertility had no notable effect on k (Table 2). Based on the potentially mineralizable N (N_0) expressed in kg N ha^{-1}, which was converted from mg kg^{-1} using the bulk density listed in Table 1, and the mineralization constant (k) expressed in d^{-1}, we calculated $N_0 \times k$ expressed as g N m^{-2} day^{-1} for all five soils with different fertility levels, which allowed us to predict the N mineralization kinetics. The N mineralization kinetics were 0.153, 0.231, 0.240, 0.292, and 0.330 g N m^{-2} day^{-1} at the 35 °C incubation temperature for the five respective studied soils with different fertility levels.

Thereafter, we analyzed the temperature sensitivity of N mineralization (Q_{10}) according to eq. (2), which varied from 1.15 to 1.47 for all soils (Table 2), with an average of 1.30. The Q_{10} values were positively correlated with the soil C:N ratio (Fig. 2c) and negatively correlated with the soil sand content (Fig. 2d).

3.4 Dynamic process of soil nitrogen mineralization during the maize growing season

Based on the values of the fitting constants k_t and n for all five studied soils (Table 3) and the daily soil temperature measured during the maize growing season, which ranged from 10.3 to 27.6 °C, the dynamic process of N mineralization was estimated for all soils. The results showed that the total N mineralized from the soil organic N was approximately 73.6, 107.7, 117.8, 142.0, and 150.2 kg N ha^{-1} during the maize growing season for the five soils with different fertility levels (Fig. 3a), corresponding to a small proportion of the soil total N (approximately 2.5–3.4%).

As shown in Fig. 3a, the cumulative mineralized N increased sharply during the first 60–90 days after sowing (DAS), and the higher the soil fertility, the later the date, and then slowly increased and stabilized from 120 DAS. We determined a similar tendency in the N uptake dynamic process of maize, which increased sharply from 20 to approximately 90 DAS and then stabilized (Fig. 3b). This implies that these two processes were consistent over time. However, the soil cumulative mineralized N could not meet the growth requirements of maize from approximately 25 to 60 DAS for the five soils with different fertility levels. The total cumulative mineralized N was significantly lower than the N requirement of maize during its growing season, especially for the low-fertility soils. This means that fertilizer application is necessary for maize cultivation, and the higher the soil fertility, the lower the N fertilizer requirement.

4 Discussion

4.1 Nitrogen mineralization in soils with different fertility levels

N mineralization varied and increased significantly among the soils with different fertility levels in our incubation experiments. The N_0 values also increased with increasing soil

Table 2 Values of potentially mineralizable nitrogen (N_0) and the mineralization constant k (d^{-1}) obtained from fitting the net mineralization data (N_t) throughout the incubation period (t, days) with eq. (1), $N_t = N_0(1 - e^{-kt})$

Soil fertility level	15 °C			25 °C			35 °C			Q_{10}
	N_0 (mg/kg)	k (day^{-1})	R^2	N_0 (mg/kg)	k (day^{-1})	R^2	N_0 (mg/kg)	k (day^{-1})	R^2	
Very low	44.13 ± 10.38	0.0053	0.9661	66.90 ± 6.44	0.0049	0.9896	85.38 ± 12.12	0.0071	0.9806	1.16
Low	72.91 ± 13.20	0.0060	0.9333	74.69 ± 10.46	0.0085	0.9959	96.43 ± 6.15	0.0095	0.9923	1.47
Medium	82.82 ± 26.79	0.0044	0.9884	74.76 ± 2.80	0.0088	0.9865	97.27 ± 8.23	0.0098	0.9851	1.37
High	80.46 ± 20.87	0.0063	0.9781	113.50 ± 15.16	0.0055	0.9844	120.85 ± 11.27	0.0096	0.9847	1.15
Very high	96.90 ± 32.14	0.0058	0.8925	115.31 ± 4.18	0.0056	0.9987	121.33 ± 8.19	0.0108	0.9887	1.33

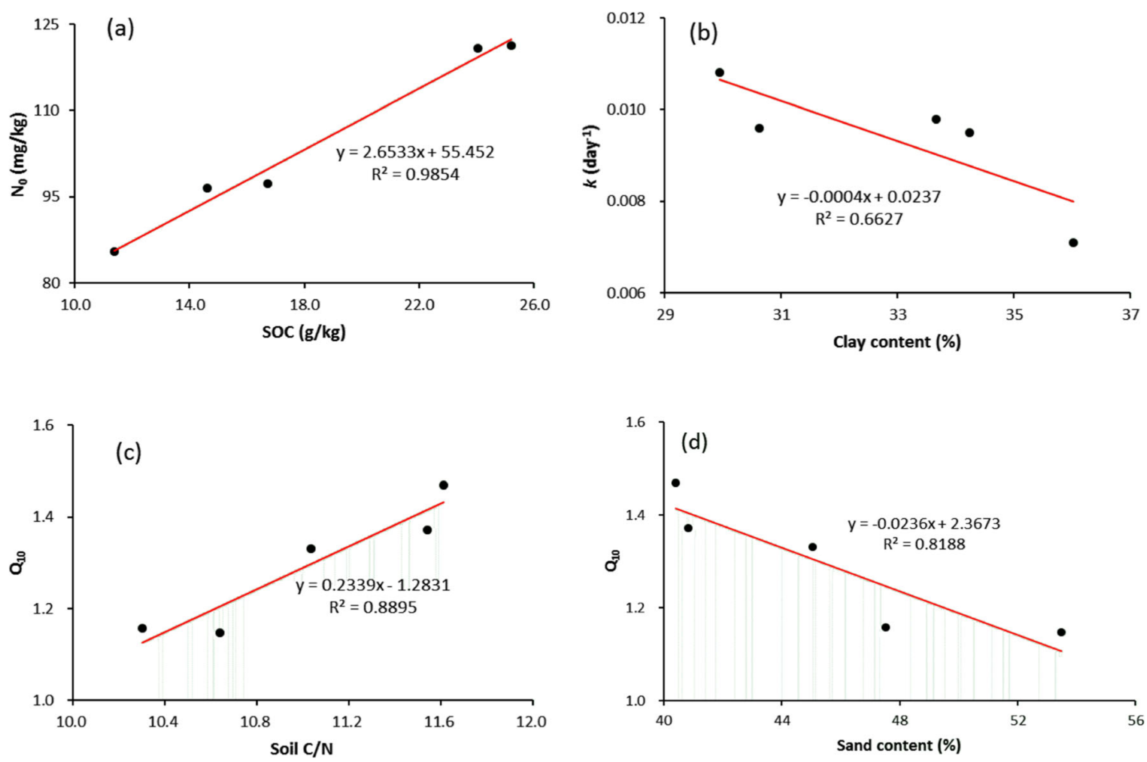

Fig. 2 Relationships of the potentially mineralizable N (N_0) and SOC content (**a**), mineralization constant k (d^{-1}) and clay content (**b**), temperature sensitivity (Q_{10}) of N_{min} and soil C:N ratio (**c**), and Q_{10} and soil sand content (**d**). The values of k and Q_{10} used here were obtained from incubation at 35 °C

fertility, and the highest value was obtained in the very high-fertility soil, showing the same trend as reported in previous studies (Ju et al. 2000; Canali et al. 2004). This may be due to the high soil organic matter and TN contents in the high-fertility soils, to which organic fertilizer had continuously been applied for longer than 30 years, and the previous fertilizer management strategy (Carpenterboggs et al. 2000). Our results are consistent with previous studies, which reported an increase in N mineralization with increasing TOC and organic nitrogen (ON) soil enrichment (Duguet et al. 2006). N_0 also exhibited different degrees of improvement after 15 years of fertilization in other types of soils, or long-term application of chemical and organic N fertilizers may have increased N_0 (Ju et al. 2000). Researchers also reported similar results in temperate grassland soil, and gross N mineralization increased significantly after many years of repeated application of organic manure (Müller et al. 2011; Osterholz et al. 2017).

Table 3 Values of fitting parameters k_t and n obtained from fitting the net mineralization data (N_t) throughout the incubation period (t, days) with eq. (3), $N_t = k_t [(T - T_0)t]^n$

Soil fertility level	k_t	P^*	n	P^{**}	R^2
Very low	0.2691	0.0024	0.6337	< 0.0001	0.9755
Low	0.6588	0.0111	0.5641	< 0.0001	0.949
Medium	1.0818	0.0263	0.5092	< 0.0001	0.9095
High	1.0397	0.0306	0.5398	< 0.0001	0.9149
Very high	1.2302	0.0400	0.5246	< 0.0001	0.8994

P^* and P^{**} indicate significant correlations for k_t and n, respectively

Additionally, loam and clay soils always have higher bacterial biomasses than sandy soils (Hassinld et al. 1993), which means that the decreased clay content may reduce the microbial biomass, indirectly affecting N mineralization (Sollins et al. 1996; Santruckova et al. 2003). Moreover, soil acidity is also a main factor that negatively affects mineralization, and N mineralization is limited at low pH levels (Amlinger et al. 2003). These findings also explain the lower N_0 values in the low-fertility soils with a high sand content and low pH value in our study. It seems evident that the capacity of soils to supply N increases with an increase in the SOC concentration (Ros 2012). This means that it is possible to reduce the dependence of crops on chemical fertilizers through soil fertility improvement.

The values of the mineralization constant (k) obtained in our study are within the range of values reported in earlier studies (Stanford and Smith 1972; Ju et al. 2000; Heumann and Böttcher 2004). The k values and rate of mineralization increased with the incubation temperature, especially between 25 and 35 °C, which was also reported in earlier studies (Kemmitt et al. 2008). This result may be caused by the more intense activity of the exocellular enzymes at high

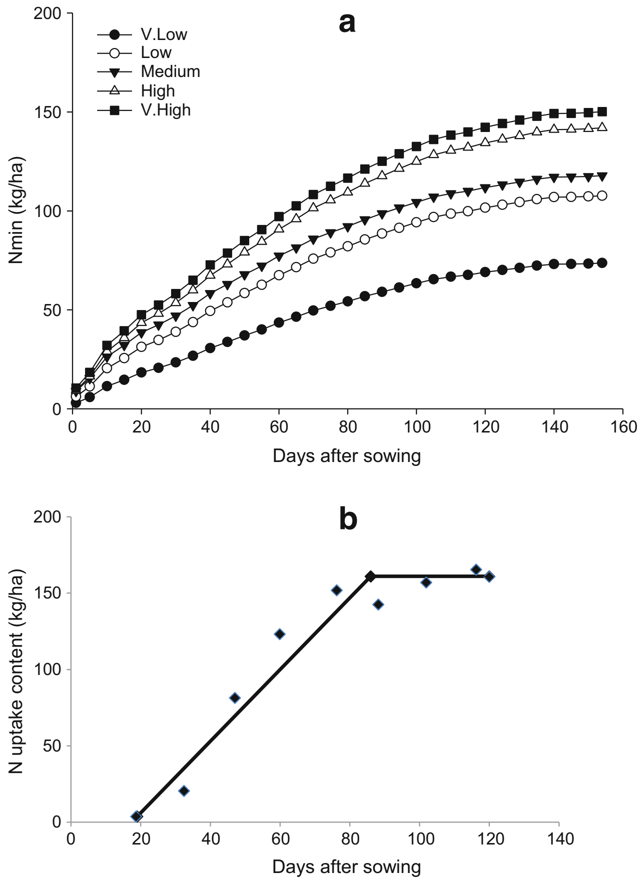

Fig. 3 Cumulative nitrogen mineralization of the five studied soils (**a**) and nitrogen uptake by maize (**b**) versus days after sowing at our study site

temperatures (Schimel and Bennett 2004). It has been reported that the activity of the main enzymes that promote the first stage of organic matter decomposition increases markedly between 30 and 50 °C (Trasar-Cepeda et al. 2007). However, the *k* values showed no significant differences among the soils with different fertility levels in our study. The main reason may be that the soil clay content and *k* had a negative relationship (Fig. 2b; Sistani et al. 2008). And a negative relationship was also found between the clay content and TN and SOC content, which had a positive effect on *k*. That may make these two effects of clay and SOC on *k* cancel each other out. Moreover, soils with higher fertility levels had lower clay and silt contents in our study, which may explain why soil fertility had no significant effect on *k*.

The mean Q_{10} value for all soils (1.30) in our study is lower than that estimated for global cropland systems (2.02) but within the range of previously presented values, i.e., from 1.03 to 11.89 (Liu et al. 2017). This mainly occurred because the soil C:N ratios, which were positively correlated with the Q_{10} values (Fig. 2c; Bengtsson et al. 2003), were lower in our study than in most of the previous studies. In addition, the soil sand content and pH significantly affected Q_{10} in a negative way (Fig. 2d; Priha et al. 2001), and the low fertility soils in this study had a high sand content and a low pH level.

4.2 N dynamics and fertilizer applications

Researchers have reported that N uptake by maize starts at approximately 20 DAS, and the total crop N uptake sharply increases and then reaches a plateau at approximately 90 DAS (Soufizadeh et al. 2018). Our results showed that the soil N mineralization process was consistent with the dynamic N uptake of maize over time (Fig. 3), although the total N mineralized from the soil organic N corresponded to a small proportion of the soil total N, which implies a lower N supply for maize production in the studied soils. The amount of N mineralized during the maize growing season was in the range of 70–150 kg/ha for the five soils with different fertility levels (Fig. 3). This range is slightly higher than that reported in a previous study, with a range from 6 to 166 kg/ha during a 20-week season (Geisseler et al. 2019). The cumulative mineralized N was approximately 2.2–3.4% of the organic N pool, which is also higher than that found in a previous study (1–3%) (Meisinger et al. 2008). This was mainly due to the high content of SOC in our study. The results also showed higher soil fertility with a greater amount of mineralized N (Fig. 3), as the addition of organic N fertilizers could enhance the supply of available inorganic N (Osterholz et al. 2017). It is worth noting that the cumulative N mineralized in the lowest fertility soil, which was unfertilized for a long time, was higher than the N uptake of maize without fertilizer in the growing season (data not shown).

Based on our laboratory incubation, field simulation results, and the N use efficiency (NUE) of maize in soils with different fertility levels, we suggest a reduction of 50–65 kg N/ha in the N fertilizer application for the two highest fertility soils, especially during the beginning period of the maize growing season, when N mineralization may meet the growth requirements of maize. It is worth noting that the NUE value used to calculate the N reduction dose was 50% in the two soils with the highest fertility; this value was obtained in our field pot experiment and has not been published. This could reduce the N fertilizer cost, restrict undesirable N losses to the environment, and improve the use efficiency of N applied during this stage. However, in the rapid growth period, N fertilizer application should be increased to obtain a suitable maize yield. We suggest manure with chemical fertilizer compost application during the maize growing season, which would increase the soil labile organic C content (Liu et al. 2003; Hou et al. 2010) and fertilizer use efficiency. Previous studies reported that inorganic fertilizer application, especially the addition of organic manure, reduced the negative environmental effects by promoting N conservation and decreasing NO_3^- production and the risk of NO_3^- leaching (Lang et al. 2016). However, we should pay more attention to N_2O and CO_2 emissions caused by the application of organic manure

(Hynšt et al. 2007; Aguerre et al. 2012). Therefore, further investigation of the soil N supply during the crop growing season, as well as evaluation of the comprehensive effect of fertilization regimes on the environment, should be conducted in agricultural management systems.

The maximum daily N uptake rate of maize from the soil is 0.029 g N m^{-2} °C day^{-1} (Hammer et al. 2010; Soufizadeh et al. 2018), which is lower than the N mineralization kinetics in our study. However, under field conditions, N_0 cannot be obtained, which means that perfect N mineralization kinetics could not be obtained in the field. The main reason is that not only soil properties but also environmental conditions and fertilizer management affect the soil N mineralization process. Therefore, to quantify the N fertilizer dose more accurately, further studies should be conducted to assess the dynamic N mineralization process under field conditions and the available N content in soils with different fertility and fertilizer application levels and to synchronize N release with crop demands.

5 Conclusion

The mineralized N content in five black soils with different fertility levels estimated through laboratory experiments indicated that soil properties, especially SOC and TN, directly affected soil N mineralization. Simulation of N mineralization dynamics for soils with different fertility levels using the field soil temperature and N uptake dynamics of maize demonstrated that the N fertilizer application rate should be reduced by 50–65 kg N/ha in high-fertility soils during the maize growing season. We suggest a possible way to reduce the dependence of crops on chemical fertilizers by improving soil fertility via organic manure application in cropping management systems. Both the N requirements of crops and the N supply in soils with different fertility levels, which are also affected by environmental conditions and fertilizer management, should be considered to suitably estimate the fertilizer application rate and timing. Furthermore, chemical fertilizers with or without organic manure application must be carefully managed when developing fertilization regimes for soils with different fertility levels to improve the N use efficiency and reduce the negative impact on the environment by leaching or volatilization.

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