Nutr Cycl Agroecosyst (2008) 81:279–290
DOI 10.1007/s10705-007-9163-x

RESEARCH ARTICLE

Quantification of seasonal soil nitrogen mineralization for corn production in eastern Canada

Tian-Yun Wu · B. L. Ma · B. C. Liang

Received: 4 October 2007 / Accepted: 10 December 2007 / Published online: 27 December 2007

Abstract Precise estimation of soil nitrogen (N) supply to corn (*Zea mays* L.) through N mineralization plays a key role in implementing N best management practices for economic consideration and environmental sustainability. To quantify soil N availability to corn during growing seasons, a series of in situ incubation experiments using the method of polyvinyl chloride tube attached with resin bag at the bottom were conducted on two typical agricultural soils in a cool and humid region of eastern Canada. Soil filled tubes were retrieved at 10-d intervals within 2 months after planting, and at 3- to 4-week intervals thereafter until corn harvest. Ammonium and nitrate in the soil and resin part of the incubation tubes were analyzed. In general, there was minimal NH_4^+-N with ranges from 1.5 to 7.3 kg N ha^{-1}, which was declined in the first 30 d and fluctuated thereafter. Nitrate, the main form of mineral N, ranged from 20 to 157 kg N ha^{-1}. In the first 20–50 d, main portion of the NO_3^--N was in the soil and thereafter in the resin, reflecting the movement of NO_3^- in the soil, which was affected by rainfall events and amount. Total mineralized N was affected by soil total N and weather conditions: There was more total mineralized N in the soil with higher total N, and rainy weather stimulated N mineralization. The relationship between the accumulated mineral N and accumulated growing degree-days (GDD) fitted well into first order kinetic models. The accumulated mineralized soil N during corn growing season ranged from 96 to 120 kg N ha^{-1}, which accounted for 2–3% of soil total N. Corn plants took up 110–137 kg N ha^{-1}. While the mineralized N and crop uptake were in the same magnitude, a quantitative relationship between them could not be established in this study.

T.-Y. Wu · B. L. Ma (✉)
Eastern Cereal and Oilseed Research Centre (ECORC), Agriculture and Agri-Food Canada, Central Experimental Farm, 960 Carling Avenue, Ottawa, ON, Canada K1A 0C6
e-mail: mab@agr.gc.ca

B. C. Liang
Environmental Canada, 19th Floor, Place Vincent Massey, 351 St. Joseph Blvd., Hull, QC, Canada K1A 0H3

Keywords Crop management · Maize · In situ N mineralization · N cycling · *Zea mays*

Abbreviations

Growing degree-days	GDD
Total mineralized N	TMN

Introduction

Nitrogen (N) management is crucial in corn (*Zea mays* L.) production for both economic and environmental concerns. The aim of agricultural N management is to enhance soil N mineralization at times when plants need it, i.e., to synchronize soil N mineralization with crop uptake (Campbell et al. 1995; Ma et al. 1999; Murvira and Kirchmann 1993). Therefore, timely and precise estimation of soil N supply during corn growing season plays a key role in establishing N best management practices.

Even though soil N supply comprises the main portion of crop N (54–83% of total crop N; Ma et al. 1999; Stevens et al. 2005), and it may sustain near entire corn growing season (Omay et al. 1998), it is still difficult to estimate the quantity and intensity of soil N supply, for the purpose of adequate and timely application of fertilizer N. The concept of potentially mineralizable N (N_0) and N mineralization rate constant (k) in a first-order dynamic process has been used to estimate the quantity and intensity of soil N supply (Stanford and Smith 1972; Stanford and Epstein 1974; Zak et al. 1999; Campbell et al. 1981; Olness 1983; Griffin and Laine 1983). The parameters have clear mechanistic means and can differentiate N supplies among soils which are of genesis difference and distribute from sub-tropic to cool and humid regions (Stanford and Smith 1972; Campbell et al. 1981, 1984), among soils with different fertilization and rotation systems (Sanchez et al. 2001; Mikha et al. 2006), and cultivation histories (Campbell et al. 1984). However, the parameters are obtained from laboratory incubation studies under optimal temperature (35°C) and soil moisture conditions (usually field capacity) for ammonifiers and nitrifiers (Malhi and McGill 1982; Davidson and Swank 1986), which could not represent soil N mineralization process under field conditions of frequent fluctuations in temperature and dry-wet cycles (Zak et al. 1999; Carpenter-Boggs et al. 2000). Correlations between crop N and the N_0 have been observed in a greenhouse (Stanford et al. 1973b) with inconsistent results (Griffin and Laine 1983). Other attempts also have been made to adjust the N_0 or k with varying soil temperature and moisture in the field (Campbell et al. 1984, 1988; Carpenter-Boggs et al. 2000; Knoepp and Swank 2002).

The strategy of in situ incubation under field conditions was to truly represent soil N mineralization dynamics. Intact soil columns with metal or polyvinyl chloride (PVC) tubes have been used for measuring in situ soil N mineralization, but NO_3^--N leached out of the bottom of the incubation tube was often ignored (Ma et al. 1999). To overcome this problem some researchers use a resin bag attached to the bottom of the tube to absorb NH_4^+-N and NO_3^--N in the leachate (Kolberg et al. 1999; Brye et al. 2002). The advantage and disadvantage of the in situ incubation methods were discussed in detail by Raison et al. (1987), and method comparison was made by Hanselman et al. (2004). The tube method plus resin at the bottom can explicit relatively more N cycling processes associated with N mineralization than the other methods, and this method has produced accurate results in humid regions (Brye et al. 2002; Hanselman et al. 2004).

Soil characteristics, temperature and moisture fluctuation, fertilization histories, and tillage and rotation systems all affect soil N mineralization, dramatically, which are reflected by the N_0 or mineralized N in situ. The variation of the N_0 and k are mainly ascribed to the variation in soil organic matter (Campbell et al. 1981) and is sensitive to agricultural practices (Janzen et al. 1998). Thus ubiquitous spatial variation in N_0 and k can be expected from large geographic scale as Stanford and Smith (1972) and Campbell et al. (1981, 1984) observed, to small scale as in a landscape sequence within 0.2×0.3 km^2 in Southern Ontario (Beauchamp et al. 2004; Dharmakeerthi et al. 2005). Manure (Agehara and Warncke 2005; Ma et al. 1999; Mikha et al. 2006) and chemical N application (Ma et al. 1999; Mikha et al. 2006; Stevens et al. 2005), involving legume in a rotation system (Campbell et al. 1984; Ellert and Bettany 1988; Sanchez et al. 2001), reduced tillage (Lupway et al. 2006; Mikha et al. 2006) or increasing cropping frequency (Kolberg et al. 1999), all can enhance N_0 or k. Consequently, mineralized N in situ responded to these managerial practices and was a reflection of mineralizable N enhancement (Cabrera et al. 2005; Kolberg et al. 1999; Ma et al. 1999; Lupway et al. 2006).

There is an urgent need to understand soil N dynamics under field conditions during the growing season (Beauchamp et al. 2004). Although some research results of mineralized N during specific periods on several soils are available in Ontario (Beauchamp et al. 2004; Dharmakeerthi et al. 2005; Drury et al. 2003), there still have been insufficient data to be generalized or included in the nutrient management protocol such as Ontario Corn N

Calculator. Accordingly, N released from seasonal mineralization is ignored in the N-index calculation (OMAFRA 2004). Therefore, any attempts to include mineralized N in N recommendation systems could be helpful for the development of an improved and more accurate N management strategy.

The objectives of this research were to (1) monitor N mineralization in situ of two typical agricultural soils in eastern Ontario using the improved PVC tube plus resin method, and (2) quantify the effects of soil and weather factors on the amount of mineralized N.

Materials and methods

This study was conducted on two soils, Uplands sandy loam (Orthic Humo-ferric Podzol) and Matilda loam (Gleyed Eluviated Melanic Brunisol) on the Central Experimental Farm of Agriculture and Agri-Food Canada, Ottawa, ON (45°22′ N, 75°43′ W) during corn growing seasons from 2003 to 2006. The selected physical and chemical characteristics of the soils are presented in Table 1.

A series of field incubation experiments was conducted in the corn plots receiving no fertilizer N, using PVC tube methods described by Brye et al. (2002). As shown in Fig. 1, soils of 0–20 cm layer were collected before corn planting from the plots and sieved to passed through 6 mm screen and mixed thoroughly for each plot and stored at 4°C before use. Soil bulk density was analyzed with cylinder method, and soil water content was determined by oven drying at 105°C for 24 h, and these parameters were used to calculate the amount of soil needed to fill each tube. Over the years, about 1,300–1,500 g fresh soil was compacted into a 20 cm soil column in a PVC tube of 25 cm in height (outer diameter = 7.0 cm, inter diameter = 6.7 cm) according to the soil bulk density. Before soil filling, 30 g resin (AG 501-X8 Resin, Bio-Rad Laboratories, CA) was placed in a cap (outer diameter = 7.3 cm, inter diameter = 7.0 cm) of 3 cm in height with 5 holes of 0.5-cm covered from inside by a nylon screen of 100 meshes and then the cap was fitted to the bottom end of the tube and sealed with duct tape around the cap collar. The soil filled PVC tubes with the attached resin cap (Fig. 1) were buried vertically in the unfertilized plots from which the filled soil originally was taken, and the soil surface in the tubes was set at the same level of the outside soil. One (2003, 2004, and 2005) or 9 (2006) tubes filled with Ottawa sand, as control, were buried in each plot. The experiment was arranged in a randomized complete block design with four replications and chronologically repeated sampling which represented different incubation periods. There were nine incubation periods determined by the tube retrieval time since the burying and the tubes filled with Ottawa sand were removed at the end of the incubation, in 2003, 2004, and 2005, and at each sampling in 2006. One tube from each plot was retrieved every 10-d from planting to mid July and at 3- to 4-week intervals thereafter until corn harvest. Totally 80 (two soil types), 40, 40, and 72 (two sample types: soil and sand) tubes were buried in 2003, 2004, 2005, and 2006, respectively.

The soil retrieved from each tube was mixed thoroughly, while the resin was collected in plastic bottles and stored in a refrigerator immediately after taken. A subsample of 5 g soil or 3 g resin was placed in a container of 50 ml 2 M KCl with a metal bar. The sample was extracted on a shaker at 200 rpm for 1 h and then filtered into a 50 ml container. After the first extraction, the residue plus the Whitman filter paper was placed in a new container of 50 ml 2 M KCl and

Table 1 Experimental soils and their characteristics

Exp. No.	Year	Soil series and texture	Particle size (g kg^{-1})			OM (g kg^{-1})	TN (g N kg^{-1})	pH
			Sand	Silt	Clay			
1	2003	Uplands, sandy loam	606	350	43	51.9	1.95	6.2
2	2003	Matilda loam, sandy loam	575	322	103	28.1	1.00	6.1
3	2004	Matilda loam, sandy loam	556	351	93	25.4	1.13	6.3
4	2005	Uplands, sandy loam	691	247	62	51.9	1.72	6.2
5	2006	Uplands, sandy loam	725	204	71	49.9	1.68	6.3

OM, organic matter determined by sample loss on ignition method; TN, soil total N

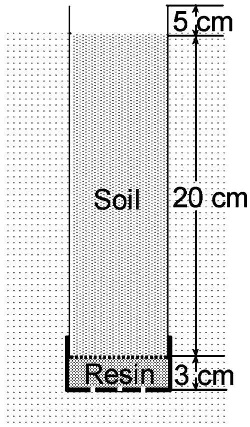

Fig. 1 Diagram of in situ soil tube plus resin mineralization method

extracted again. Such sequential extraction was done for five times on selected resin samples, and all the resin samples were extracted sequentially for two times to recover at least 90% of total mineral N. The NO_3^--N and NH_4^+-N concentrations from each filtered solution of each extraction were determined colorimetrically using a TRAACS 800 Auto-Analyzer (Bran-Luebbe, Analyzing Technologies, Elmsford, NY). The results were expressed on an oven-dry weight basis and converted to kg ha^{-1}. In this study, NO_3^--N and NH_4^+-N in the soil and resin of the incubation system were referred to soil NO_3^--N, resin NO_3^--N, soil NH_4^+-N, and resin NH_4^+-N, respectively. At each sampling, mineralized N in each portion was the product of its concentration by the weight. Total mineralized N (TMN) was calculated as the sum of the four components minus the NO_3^--N and NH_4^+-N in the filled soil before the incubation, and in both the sand and resin part of the control. Nitrogen losses through ammonia volatilization and denitrification during the incubation periods were not taken into account.

At physiological maturity, straw and grain samples of five plants from each plot were taken and dried at 70°C to a constant weight. After dry weight was recorded, all the samples were ground to pass through a 1-mm screen. All samples were re-dried in an oven at 60°C for 24 h before weighing for N analysis. Total N concentration of each sample was determined by the micro-Kjeldahl method. Combine harvesting was done from the two central rows (13.7 m^2 area) to determine grain yield. Total N accumulation in grain and stover was calculated as the product of grain or stover dry matter (based on the HI and grain yield) and N concentration in specific component.

At each sampling date, mean mineralized N in each portion was calculated as the product of the mineral N concentration and the total mass across the four replications. Regression analysis for the accumulated mineralized N during specific periods and across the entire growing season was conducted using the REG and NLIN procedures of SAS. The Gauss-Newton method was used in the NLIN procedure (SAS Inst. 1996) to derive a first order kinetic model for mineralized N as a function of accumulated thermal time (GDD).

Results

Weather pattern and crop phenology during the incubation

Daily mean air temperature and rainfall dramatically varied within a growing season and among the years (Fig. 2a–d). As expected, air temperatures increased from 1 May to 20 June, reached to maximum near the end of July, and then decreased gradually to the end of October. Evident and frequent fluctuations in mean air temperatures occurred in each growing season. Corn was usually planted in mid to end of May, reached to V6 (over 50% plants with 6 fully expanded leaves) growth stage in late June and early July when air temperatures raised substantially. The crop progressed to flowering (pollination and silking) near the end of July and early August while air temperatures were at maximum. The grain filling started from mid August, and ceased by late September. During this period of time, the air temperatures were gradually declined. Accordingly, the plant ceased to grow once physiological maturity is reached in late September. Variations in mean air temperatures within a growth stage were not as dramatic as those among the years; whereas evident differences occurred across the growth stages (Table 2).

Rainfall event distribution and amount were erratic in a growing season or among the years. The only likely common trend for the experimental years was the frequent rainfall events after the corn reached physiological maturity in all years except in 2004 (Fig. 2b–d). Rainfall events were generally evenly distributed in the corn-growing season in 2004 (Fig. 2b) and 2005 (Fig. 2c) whereas several short periods of drought occurred in 2003 (Fig. 2a) and

Fig. 2 Precipitation and daily average air temperature from May 1 to end of October

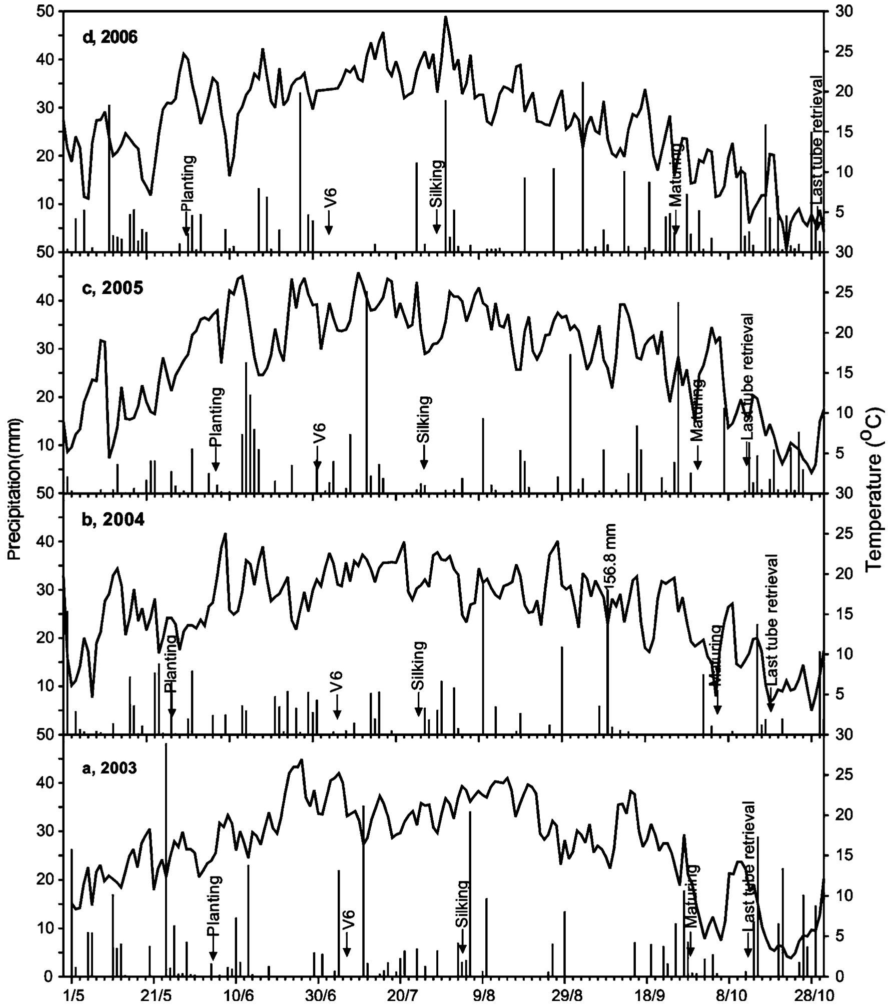

Table 2 Average air temperature and accumulative precipitation during different experiment stages

Exp. stage	2003			2004			2005			2006		
	Time[a]	T (°C)[b]	R (mm)[c]	Time	T (°C)	R (mm)	Time	T (°C)	R (mm)	Time	T (°C)	R (mm)
Planting	Jun 5	13.6	155.6	May 27	13.8	83.9	Jun 6	13.0	52.2	May 30	14.1	87.6
V6	Jul 7	20.5	77.8	Jul 6	17.5	86.5	Jun 29	21.4	93.7	Jul 4	19.4	104.7
Silking	Aug 5	20.0	79.9	Jul 26	21.0	24.8	Jul 25	23.0	85.7	Aug 1	23.0	53.5
Maturity	Oct 5	17.6	142.0	Oct 5	17.0	278.1	Sep 30	19.2	178.8	Sep 25	17.3	148.7
Last retrieval	Oct 16	10.5	41.4	Oct 18	10.6	28.8	Oct 14	13.6	31.2	Oct 30	7.8	146.2

[a] The start time for the parameter calculation was set on May 1 arbitrarily

[b] Average air temperature from previous stage to present

[c] Accumulative precipitation from previous stage to present

2006 (Fig. 2d). There were about eight rainfall events with more than 20 mm from 1 May to the end of October in 2003, 2005, and 2006, but only four such events in 2004 with occurrence of one heavy rainstorm (157 mm) on 10 September (Fig. 2b). There was no heavy rainfall from 1 May to 30 July 2003, even though more frequent rainfalls occurred during this period (Fig. 2b). Considerable differences in accumulated precipitation occurred from 1 May to planting, from silking to maturity, and from maturity to harvest (the last retrieval of the tube) among the experimental years. The accumulated precipitation from planting to V6 was not evidently different, but apparent differences in the succeeding periods were recorded among the years (Table 2). The long-term (1960–2005) average of annual total precipitation from 1 May to 15 October was 467 mm. Above long-term average of annual total rainfall during the incubation period occurred in 2003, 2004, and 2006.

Pattern of mineralized nitrogen

Ammonium N

There was minimal NH_4^+-N in the soil layer throughout the incubation periods each year except for one occasion. Usually, NH_4^+-N in the resin (resin NH_4^+-N) was less than 1 kg N ha^{-1} in each period of the incubation (Fig. 3a–e), and this N inherited from the resin product. It was clear that NH_4^+-N did not move easily from the soil into the intimately attached resins, displaying the strong adsorption of soil colloids to NH_4^+-N with these sandy loam soils.

Ammonium N in the soil (soil NH_4^+-N) usually ranged from 0.5 to 7.3 kg N ha^{-1}, and fluctuated considerably throughout the incubation period. There was a dramatic increase of soil NH_4^+-N (24.2 kg N ha^{-1}, Fig. 3c) on 21 September 2004, which corresponded to the heavy rainstorm event (total 157 mm) at 10 d before sampling (Fig. 2b).

Nitrate N

Nitrate N was the main form of mineral N in the soils, and it changed dramatically during the growing seasons.

Nitrate N in the resin (resin NO_3^--N), representing the accumulation of NO_3^--N leached out of the 0–20 cm soil layer, increased slightly at the beginning, accelerated increment from late June and largest increase occurred in the later period of the incubation. During the incubation period, the average resin NO_3^--N changed from 2 to 140 kg N ha^{-1}, but the accumulated resin NO_3^--N at each sampling period differed greatly between soils and years (Fig. 3). The total resin NO_3^--N was higher in the Matilda soil (140 kg N ha^{-1}; Fig. 3a) than the Uplands soil (120 kg N ha^{-1}; Fig. 3b) in 2003. However, within a soil type, the total resin NO_3^--N varied substantially among years (Fig. 3a–e). The time of the resin NO_3^--N beginning to increase also varied in the Uplands, from approximately 50 d (22 July) after planting in 2003 (Fig. 3b) to 20 d (22 June) in 2005 (Fig. 3d), and 40 d in 2006 (Fig. 3e), which was paralleled with the rainfall events: 40 mm on 14 July 2003 (Fig. 2a), 30 mm from 10 to 13 June 2005 (Fig. 2c), and 40 mm from 27 to 30 June 2006 (Fig. 2d), respectively. In 2003, resin NO_3^--N increased 10 d earlier in the Matilda soil than the Uplands soil (Fig. 3a, b), whereas it remained constant until the end of August in 2004 (Fig. 3c), probably due to the fact that there was an even distribution of rainfall without considerable rainstorm event during this period of time (Fig. 2b).

The peaks of soil NO_3^--N varied between the soils in 2003 and among the years within a soil type. The Matilda soil had lower maximum soil NO_3^--N (28 kg N ha^{-1}) than the Uplands soil (72 kg N ha^{-1}) in 2003 (Fig. 3a, b). Considerable reductions in soil NO_3^--N occurred during the last month of the incubations in all years except in 2005 (Fig. 3), assuming that these losses of NO_3^--N resulting from denitrification during this period.

Total mineral N and total mineralized N

Total mineral N, the sum of NO_3^--N and NH_4^+-N in the soil and resin, increased evidently within the first month of the incubations, followed by a sharp increase in the second month; it then increased slightly in the third month and increased substantially in the final one or one and half months in both 2003 and 2005 or increased slightly in the final month of 2006 (Fig. 4). An exception was the Matilda soil in 2004 in which a linear increase in total mineral N through the incubation period was recorded (Fig. 4c). There was a missing collection of samples around 29 July 2004 due to weather limitations, which may have caused the deviation of such a trend.

Because the soil NH_4^+-N and resin NH_4^+-N contributed little to the total mineral N, the main portion of total mineral N can be easily identified by the relative value of the soil and resin NO_3^--N (Fig. 3). In 2003, the main portion was soil NO_3^--N within the first 30 d in

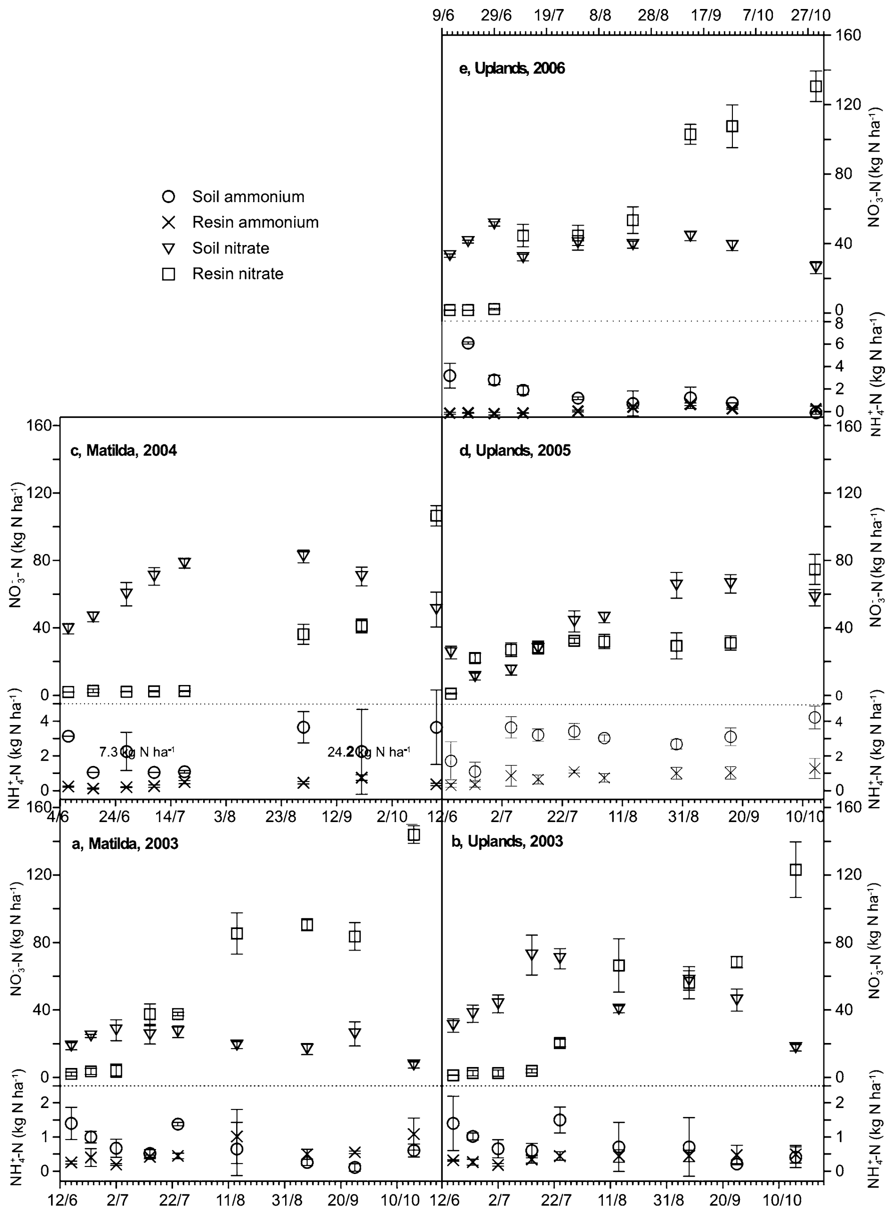

Fig. 3 Ammonium and nitrate in soil and resin part for the two soils in the experimental year. Two points with high soil ammonium out the scale in 2004 are depicted with the values. The error bars represent standard deviations

the Matilda soil (Fig. 3a) or 50 d of incubation (Fig. 3b) since planting in the Uplands soil; this was likely extended to 90 d (later September) in 2004 in the Matilda soil (Fig. 3c). A more complicated pattern was observed in the Uplands soil in 2005: soil NO_3^--N was the main portion in the first 20 d, followed by the resin NO_3^--N in the next 20 d, then the soil NO_3^--N became the main portion until September (Fig. 3d).

There was difference in total mineralized N between the two soils (Table 3). Higher total mineralized N in the Uplands soil than the Matilda was recorded in 2003, reflecting the influence of higher total N in the Uplands soil on the mineralized N (Table 3). Although there was minimal inter-annual change in the total mineralized N of the Matilda soil was recorded, some variations (from 96 to 120 kg ha^{-1} of mineralized N) were observed in the Uplands soil from 2003 to 2006. Minor differences in mineral N inherited from the previous year were also noted, which was represented by the total mineral N in the soils before the start of incubation (Table 3). About 13–20 kg N ha^{-1} was in the control tubes filled with Ottawa sand, which represented accumulated N during the growing season originated from rainfall.

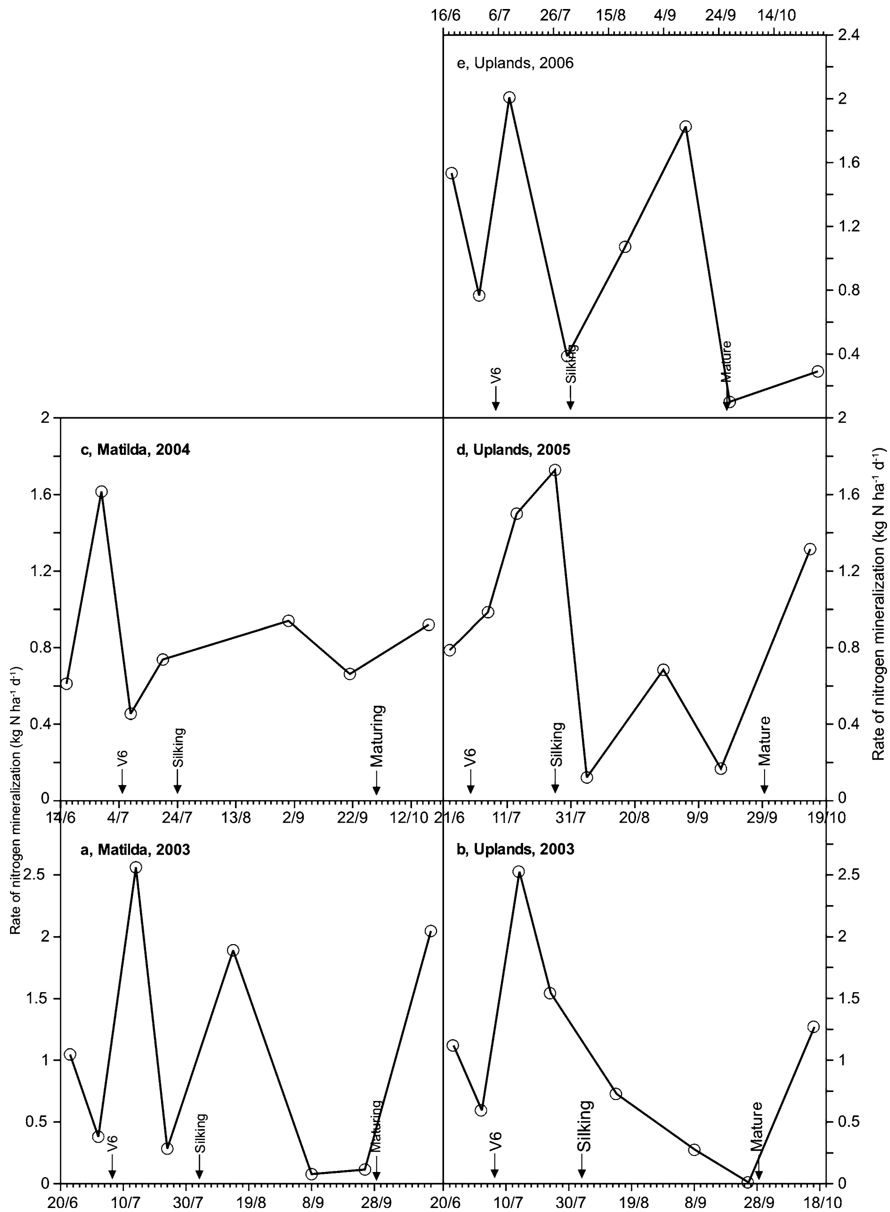

Fig. 4 Rate of nitrogen mineralization of the two soils in the experimental years

Total mineralized nitrogen in relation to accumulated growing degree-days

During the four years of the in situ incubation study, the quantitative relationships between the total mineral N and accumulated growing degree-days (GDD) followed first order kinetic models with $R^2 > 0.9$ (Table 4). However, between the two soil types and across years, both the potentially mineralizable N, N_0, and the rate of change, k, varied considerable, highlighting the dynamic nature of soil N mineralization process and the impact of other factors on seasonal mineralization than air temperatures.

Discussion

The N release curve from mineralization in this research generally paralleled with the reported N uptake by the corn plant. As reported, the first peak

Table 3 Total mineralized nitrogen of the two soils in the four years

Soil	Year	Total mineral N (kg N ha^{-1})			Total mineralized N^a (kg N ha^{-1})
		In control (Ottawa sand tube)	Before incubation	After incubation	
Matilda	2003	12.7	30.2	141.7	98.8
Uplands	2003	12.7	20.1	153.0	120.2
Matilda	2004	16.5	39.3	161.5	105.6
Uplands	2005	13.6	28.4	138.2	96.2
Uplands	2006	20.3	26.7	157.7	110.7

[a] Total mineralized N = total mineral N after incubation − total mineral N before incubation − total mineral N in control

Table 4 Relationships between total mineral N and GDD of the two soils in the four years

Soil	Year	$N_m = N_0 \times (1 - e^{-k \times GDD})$			
		N_0 (kg N ha^{-1})	k	R^2	MSE
Matilda	2003	149.9	0.00065	0.95	67
Uplands	2003	127.3	0.00116	0.97	46
Matilda	2004	145.4	0.00103	0.90	119
Uplands	2005	116.1	0.00098	0.97	24
Uplands	2006	200.6	0.00057	0.92	140

N_m (kg N ha^{-1}), total mineral N; N_0, potentially mineralizable N; GDD, growing degree-days; MSE, mean square error. The data pairs of the last tube retrieves were excluded

of N uptake by corn plant occurred around 40–60 d after planting, corresponding to V6 growth stage (Ma and Dwyer 1998; Magdoff 1991), and the second peak was about 100 d after the emergence (Olness 1983). For the two soils observed in this study over the four years, the first peak of N mineralization commenced in early July 2003 or mid June 2004, which corresponded to the V6 growth stage (Fig. 4a, b). In 2005, increased rate of N mineralization occurred in later June and reached to its peak in later July, which corresponded to the growth stages from V6 to silking (Figs. 3d, 4d). The last peak of the N mineralization occurred in mid to later September, which corresponded to the grain filling stage (Figs. 3, 4). The first peak rate of N mineralization reached at 1.6–2.5 kg N ha^{-1} d^{-1} in the Matilda soil and 1.7–2.5 kg N ha^{-1} d^{-1} in the Uplands soil in the experimental years (Fig. 4a, e), which was higher than the peak rate of N accumulation in corn plants (0.78–1.18 kg N ha^{-1} d^{-1}; 70,000 plants ha^{-1}) calculated from the summarized results by Olness (1983). Magdoff (1991) calculated that the peak rate of N accumulation at V6 stage was 2.2–4.0 kg N ha^{-1} d^{-1} for normally fertilized corn and 11.7 kg N ha^{-1} d^{-1} for heavily fertilized corn. Our results are comparable to the rate of normally fertilized corn, reflecting great N supply in the two investigated soils. The average grain yield of 8.50 Mg ha^{-1} also displayed that soil N supplying power was high with considerable spatial variations, which was not demonstrated by the results of this research.

The rate of soil N mineralization is affected by fertilization history and rotation systems. Ma et al. (1999) reported that the rate of soil N mineralization from planting to V6 growth stage was 0.48 kg N ha^{-1} d^{-1} in the unfertilized plot, 1.81–1.92 kg N ha^{-1} d^{-1} in the fertilized plot (200 kg N ha^{-1} through chemical fertilizers) or 1.43–1.53 kg N ha^{-1} d^{-1} in the fall-applied manured field (50 Mg ha^{-1} of rotted manure (i.e., incompletely composted; Ma et al. 1999); annually for 6 years), on a Brandon loam soil. The results of Ma et al. (1999) were lower than the current study it was probably due to the different incubation methods. A sequential tube sampling method was used in Ma et al. (1999), which excludes NO_3^--N leached out the soil at the tube bottom, while in the current study, such portion of mineralized N was captured and presented in the resin. Our results were obtained on the soils with typical cereal (oat)-corn rotation; in all cases sufficient chemical N was applied to the preceding crop in the previous years.

The N mineralization rates presented in Fig. 4 could be contributed to the combination effect of inhomogeneous substrate, temperature variation, and probably uneven disposition from the canopy associated with N release from senescent plants. Increasing rate of N mineralization with increase of air temperature after planting was speculated (Magdoff 1991) and observed (Ma et al. 1999), and this was contributed to the stimulated soil microbial activity by increasing soil temperatures (Malhi and McGill 1982;

Davidson and Swank 1986; Zak et al. 1999). The reduced mineralization rate following the first peak was most likely due to the depletion of readily decomposable pool of organic N, as indicated by Stanford and Smith (1972). This part of organic N pool originates from soil microbial biomass and plant residual of the preceding crops in these soils without manure input in previous years.

More N was mineralized in the Uplands soil than the Matilda soil, highlighting the important role of soil characteristics in controlling N mineralization (Stanford and Smith 1972; Campbell et al. 1984). These two soils are similar in particle size distribution and pH, but soil total N and organic matter in the Uplands soil were nearly doubled those in the Matilda soil (Table 1). Therefore, it is reasonable to speculate that soil organic N played an important role in N mineralization during in situ incubation in this cool and humid region. The response of potentially mineralizable N to total organic matter or total N has been well documented in laboratory incubation studies (Stanford and Smith 1972; Campbell et al. 1984, 1988; Drury et al. 2003), but scarce evidence has been collected in situ field experiments (Ma et al. 1999) for its labor intensity and cost. The total mineralized N in the 0–20 cm layer in this study ranged from 1.9 to 3.1% of soil total N, which was in support of the statement by Beauchamp et al. (2003) that one to three percent of total soil N is mineralized annually in Ontario.

Weather conditions played a major role in affecting the rate of soil N mineralization, and their impact on soil N mineralization was evident in this in situ field incubation study. Compared to the average daily temperature of 17.3°C and total precipitation of 497 mm from 1 May to corn harvest in 2003, year 2005 was warmer (18.5°C) and drier (443 mm), while year 2006 cooler (16.1°C) and rainier (541 mm). More N was mineralized in years with more evenly distributed rainfall than the other year for both the Matilda and Uplands soils (Table 3). Even though the preliminary results of this investigation showed plenty rain likely intensified N mineralization in this region, further studies are needed.

The relationships between accumulated mineralized N and GDDs followed first order kinetic models (Table 4). Dharmakeerthi et al. (2005) also reported nonlinear relationships between accumulated mineral N (in corn plants plus in the 0–30 cm soil layer) and GDD in southern Ontario. It was clear that mineralizable N varied between soils in 2003 and among years for a given soil, which was also observed in southern Ontario (Dharmakeerthi et al. 2005).

The average crop N uptake from the unfertilized plots was 110 kg N ha^{-1} on the Matilda soils in 2003 and 123 kg N ha^{-1} on the Uplands soil in 2005, respectively, which were at the same magnitude of total mineralized N for the corresponding soils and years (Table 3). We failed to establish a quantitative relationship between crop N uptake and total mineralized N, which was most likely due to a relatively narrow range of the data sets resulting from the similar physical and chemical soil characteristics, fertilization histories, and cropping systems on the two investigated soils. The dynamic patterns of soil total mineral N in our study are very similar to those of N accumulation in corn plants recorded by Beauchamp et al. (2004) on a silt loam in southern Ontario. Further investigation is warranted to identify the relationship between the crop N and total mineralized N during crop growing season using this in situ incubation method, due to the promise of the same magnitude of the crop N uptake and total mineralized N, and for accurate estimation of soil N supply.

Conclusion

In this in situ incubation study with two typical agricultural soils over four corn growing seasons, total mineralized N in the 0–20 cm soil layer followed a sigmoid shape against thermal time. The rate of N mineralization roughly paralleled with corn N uptake pattern reported in this area. The two soils, with similar texture and pH, but different contents of organic matter and total N, released different amounts of mineralized N in the same year, and the values also varied in different years: There was more total mineral N released from mineralization in soils with higher total N, and sufficient and evenly distributed rainfall promoted the mineralization process. The relationship between total mineral N in the 0–20 cm soil layer and GDD followed first order kinetic models, which might be used to predict N availability in practice on these soils. About 99–120 kg N ha^{-1} was released through mineralization during corn growing seasons and accounted for 2–3% of total N in the 0–20 cm soil layer. The total mineralized N was in the same magnitude of corn N uptake, however, a quantitative relationship between them could not be established, likely due to the limited variation in soil characteristics and management practices on the selected soils.

Acknowledgement The excellent technical assistance of L. Evenson, D. Balchin, K. Subedi, and V. Deslauriers is gratefully acknowledged.

References

Agehara S, Warncke DD (2005) Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. Soil Sci Soc Am J 69:1844–1855

Beauchamp EG, Pararajasingham R, Kay BD (2003) Relationships of total soil nitrogen to several soil nitrogen indices. Commun Soil Sci Plant Anal 34:505–518

Beauchamp EG, Kay BD, Pararajasingham R (2004) Soil tests for predicting the N requirement of corn. Can J Soil Sci 84:103–113

Brye KR, Norman JM, Nordheim EV, Gower ST, Bundy LG (2002) Refinements to an in-situ soil core technique for measuring net nitrogen mineralization in moist, fertilized agricultural soil. Agron J 94:864–869

Cabrera ML, Kissel DE, Vigil MF (2005) Nitrogen mineralization from organic residues: Research opportunities. J Environ Qual 34:75–79

Campbell CA, Myers RJK, Weier KL (1981) Potentially mineralizable nitrogen, decomposition rates and their relationship to temperature for five Queensland soils. Aust J Soil Res 19:323–332

Campbell CA, Jame YW, Winkleman GE (1984) Mineralization rate constants and their use for estimating nitrogen mineralization in some Canadian prairie soils. Can J Soil Sci 64:333–343

Campbell CA, Jame YW, de Jong R (1988) Predicting net mineralization over a growing season: model verification. Can J Soil Sci 68:537–552

Campbell CA, Jame YW, Akinremi OO, Cabrera ML (1995) Adapting the potentially mineralizable concept for the prediction of fertilizer N requirements. Fertil Res 42: 61–75

Carpenter-Boggs L, Pikul JL Jr, Vigil MF, Riedell WE (2000) Soil nitrogen mineralization influenced by crop rotation and nitrogen fertilization. Soil Sci Soc Am J 64:2038–2045

Davidson EA, Swank WT (1986) Environmental parameters regulating gaseous nitrogen losses from two forested ecosystems via nitrification and denitrification. Appl Environ Microbiol 52:1287–1292

Dharmakeerthi RS, Kay BD, Beauchamp EG (2005) Factors contributing to changes in plant available nitrogen across a variable landscape. Soil Sci Soc Am J 69: 453–462

Drury CF, Zhang TQ, Kay BD (2003) The non-limiting and least limiting water ranges for soil nitrogen mineralization. Soil Sci Soc Am J 67:1388–1404

Ellert BH, Bettany JR (1988) Comparison of kinetic models for describing net sulfur and nitrogen mineralization. Soil Sci Soc Am J 52:1692–1702

Griffin GF, Laine AF (1983) Nitrogen mineralization in soils previously amended with organic wastes. Agron J 76: 171–172

Hanselman TA, Graetz DA, Obreza TA (2004) A comparison of in situ methods for measuring net nitrogen mineralization rates of organic soil amendments. J Environ Qual 33:1098–1105

Janzen HH, Campbell CA, Izaurralde RC, Ellert BH, Juma N, McGill WB, Zentner RP (1998) Management effects on soil C storage on the Canadian prairies. Soil Till Res 47:181–195

Knoepp JD, Swank WT (2002) Using soil temperature and moisture to predict forest soil nitrogen mineralization. Biol Fertil Soils 36:177–182

Kolberg RL, Westfall DG, Peterson GA (1999) Influence of cropping intensity and nitrogen fertilizer rates on in situ nitrogen mineralization. Soil Sci Soc Am J 63: 129–134

Lupway NZ, Clayton GW, O'Donovan JT, Harker KN, Turkington TK, Soon YK (2006) Nitrogen release during decomposition of crop residues under conventional and zero tillage. Can J Soil Sci 86:11–19

Ma BL, Dwyer LM (1998) Nitrogen uptake and use of two contrasting maize hybrids differing in leaf senescence. Plant Soil 199:283–291

Ma BL, Dwyer LM, Gregorich EG (1999) Soil nitrogen amendment effects on seasonal nitrogen mineralization and nitrogen cycling in maize production. Agron J 91: 1003–1009

Magdoff FR (1991) Understanding the Magdoff pre-side dress nitrate test for corn. J Prod Agric 4:297–305

Malhi SS, McGill WB (1982) Nitrification in three Alberta soils: effect of temperature, moisture and substrate concentration. Soil Biol Biochem 14:393–399

Mikha MM, Rice CW, Benjamin JG (2006) Estimating soil mineralizable nitrogen under different management practices. Soil Sci Soc Am J 70:1522–1531

Murvira HK, Kirchmann H (1993) Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under manure fertilization. Commun Soil Sci Plant Anal 24: 2343–2359

Olness A (1983) Nitrogen mineralization potentials, N_0, and correlations with maize response. Agron J 76:171–172

OMAFRA (2004) Nutrient management workbook. http://www.omafra.gov.on.ca/english/nm/ar/workbook

Omay AB, Rice CW, Maddux LD, Gordon WB (1998) Corn yield and nitrogen uptake in monoculture and in rotation with soybean. Soil Sci Soc Am J 62:1596–1603

Raison RJ, Connell MJ, Khanna PK (1987) Methodology for studying fluxes of soil mineral-N in situ. Soil Biol Biochem 19:521–530

Sanchez JE, Willson TC, Kizilkaya K, Parker E, Harwood RR (2001) Enhancing the mineralizable nitrogen pool through substrate diversity in long term cropping systems. Soil Sci Soc Am J 65:1442–1447

SAS Inst. (1996) SAS/Stat user's guide. Version 6. SAS inst., Cary, NC

Stanford G, Epstein E (1974) Nitrogen mineralization-water relations in soils. Soil Sci Soc Am Proc 38:103–107

Stanford G, Smith S (1972) Nitrogen mineralization potentials of soils. Soil Sci Soc Am Proc 36:465–473

Stanford G, Legg JO, Smith SJ (1973b) Soil nitrogen availability evaluations based on nitrogen mineralization potentials and uptake of labeled and unlabeled nitrogen by plant. Plant Soil 39:113–124

Stevens WB, Hoeft RG, Mulvaney RL (2005) Fate of nitrogen-15 in a long-term nitrogen rate study: I. interactions with soil nitrogen. Agron J 97:1037–1045

Zak DR, Holmes WE, MacDonald NW, Pregitzer KS (1999) Soil temperature, matric potential, and the kinetics of microbial respiration and nitrogen mineralization. Soil Sci Soc Am J 63:575–584