Predicting soil nitrogen availability to grain corn in Ontario, Canada

Authors: Stoeckli, Jessica L., Sharifi, Mehdi, Hooker, David C., Thomas, Ben W., Khaefi, Froogh, et al.

Source: Canadian Journal of Soil Science, 101(3) : 389-401

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjss-2020-0104

NRC Research Press

ARTICLE

Predicting soil nitrogen availability to grain corn in Ontario, Canada

Jessica L. Stoeckli, Mehdi Sharifi, David C. Hooker, Ben W. Thomas, Froogh Khaefi, Greg Stewart, Ian McDonald, Bill Deen, Craig F. Drury, Bao-Luo Ma, and Hamid R. Motaghian

Abstract: Predicting the soil-available nitrogen (N) to grain corn over a growing season in humid temperate regions is the key for improving fertilizer N recommendations. The objective of this study was to evaluate a suite of soil-N tests to predict soil N availability to grain corn over two growing seasons at 13 individual sites with long-term history of synthetic N fertilization in Ontario, Canada (13 site-years). At each site, fertilizer N was applied at various rates (0–224 kg N·ha^{-1}) to determine the crop response to N fertilizer, relative yield (RY), and the most economic rate of N (MERN). Across the entire dataset, water-extractable mineral N (WEMN) was the only soil test that strongly correlated to both RY ($r = 0.74^{**}$) and MERN ($r = -0.56^{*}$) indicating that in grain corn fields with long-term history of N fertilization, mineral forms of N in soil solution can be used for fertilizer N recommendations in southern and eastern Ontario. We also provide evidence that grouping soils based on clay content could further refine fertilizer-N recommendations for grain corn in Ontario. A multi-year validation of the WEMN test with more field sites and development of a fertilizer recommendation table for this soil test are recommended.

Key words: maximum economic rate of nitrogen, nitrogen fertilizer recommendation, pre-plant nitrate test, relative yield, water-extractable nitrogen.

Résumé : Si l'on veut améliorer les recommandations concernant l'usage d'engrais azotés dans les régions à climat tempéré humide, il faut absolument pouvoir prévoir la quantité d'azote (N) disponible dans le sol pendant la période végétative pour la culture du maïs-grain. L'étude devait évaluer l'utilité de divers tests de dosage du N pour déterminer la concentration de cet élément dont le maïs-grain dispose dans le sol pendant deux périodes végétatives, à 13 endroits de l'Ontario bonifiés depuis longtemps avec des engrais N synthétiques (13 sites-années). Les auteurs ont appliqué de l'engrais N à différents taux (de 0 à 224 kg de N par hectare) à chaque endroit, afin de vérifier la réaction de la culture à l'engrais et d'en établir le rendement relatif ainsi que le taux d'application le plus économique (TAPE) pour l'engrais. Parmi les données, le dosage du N extractible à l'eau est la seule épreuve qui présente une étroite corrélation avec le rendement relatif ($r = 0{,}74^{**}$) et le TAPE ($r = -0{,}56^{*}$), signe

---

Received 18 August 2020. Accepted 21 January 2021.

J.L. Stoeckli* and B.W. Thomas. Agassiz Research and Development Centre, Agriculture and Agri-Food Canada, 6947 Highway 7, Agassiz, BC V0M 1A0, Canada.

M. Sharifi. Summerland Research and Development Centre, Agriculture and Agri-Food Canada, 4200 Highway 97, Summerland, BC V0H 1Z0, Canada.

D.C. Hooker. Department of Plant Agriculture, University of Guelph Ridgetown Campus, 120 Main Street East, Ridgetown, ON N0P 2C0, Canada.

F. Khaefi and H.R. Motaghian. Department of Soil Science, Shahr-e-Kord University, Shahr-e-Kord, 64165478, Iran.

G. Stewart. Maizex, Guelph, ON N1G 4K6, Canada.

I. McDonald. Ontario Ministry of Agriculture Food and Rural Affairs, University of Guelph, Guelph ON N1G 2W1, Canada.

B. Deen. Department of Plant Agriculture, University of Guelph, 50 Stone Road E, Guelph, ON N1G 2W1, Canada.

C.F. Drury. Harrow Research and Development Centre, Agriculture and Agri-Food Canada, 2585 County Road 20, Harrow, ON N0R 1G0, Canada.

B.-L. Ma. Ottawa Research and Development Centre, 960 Carling Avenue, Ottawa, ON K1A 0C6, Canada.

Corresponding author: Mehdi Sharifi (email: mehdi.sharifi@canada.ca).

*This paper is written based on Jessica Stoeckli M.Sc. thesis at Environmental and Life Sciences, Trent University, 1600 West Bank Drive, Peterborough, Ontario, Canada.

Can. J. Soil Sci. **101**: 389–401 (2021) dx.doi.org/10.1139/cjss-2020-0104

que, dans les champs de maïs-grain fertilisés depuis longtemps avec un engrais azoté, on pourrait se fier à la forme minérale du N présente dans les solutions de sol pour formuler des recommandations sur l'usage des engrais azotés dans le sud et l'est de l'Ontario. Les auteurs fournissent également la preuve que grouper les sols en fonction de leur teneur en argile pourrait affiner les recommandations sur le taux d'application des engrais N pour la culture du maïs-grain en Ontario. Par ailleurs, ils préconisent une validation pluriannuelle du dosage du N extractible à l'eau dans un plus grand nombre de sites et l'élaboration d'un tableau pour les recommandations qui s'appuieront sur cette épreuve. [Traduit par la Rédaction]

Mots-clés : taux d'application d'engrais azoté le plus économique, recommandations sur le taux d'application des engrais azotés, dosage du nitrate avant les semis, rendement relatif, azote extractible à l'eau.

Introduction

Accurately predicting plant-available nitrogen (N) during the growing season is essential for enhancing the sustainability of grain corn (*Zea mays* L.) production (Ransom et al. 2020). However, predicting corn-available N is complicated due to interactions among drivers of the soil N cycle such as precipitation, soil moisture and temperature, soil properties, crop management history, and current management practices (Morris et al. 2018). Currently, N fertilizer recommendations for corn in Ontario are mostly based on the pre-plant nitrate test (PPNT), or the corn N calculator (GOCorn.net 2010) requiring the yield goal, soil texture, previous crop, and market prices for corn and N fertilizer data. The quantity of labile N fractions and their relative importance (Wu et al. 2008; Zebarth et al. 2009; Luce et al. 2011; Osterholz et al. 2016) in suppling N to grain corn in Ontario soils with long-term history of N fertilization has not been studied. A more reliable soil N test for grain corn can result in more accurate N recommendations and less risk of adverse environmental impacts (Sharifi et al. 2007*b*; Luce et al. 2011; Morris et al. 2018).

The PPNT is the pre-plant soil nitrate-N (NO_3-N) concentration in 0–15 cm soil depth, which can be a useful soil-N test for adjusting fertilizer recommendations based on carryover of NO_3-N from previous growing seasons and early season N mineralization (Sharifi et al. 2007*b*; Ransom et al. 2020). However, the reliability of the PPNT in humid temperate regions has been questioned due to the high mobility of NO_3-N in soil (Sharifi et al. 2007*b*; Luce et al. 2011). Another limitation of the PPNT is its inability to predict the amount of mineralizable soil organic-N, which represents a portion of potential soil N supply (SNS) for corn in humid temperate climates (Wu et al. 2008; Zebarth et al. 2009; Whalen et al. 2013). One alternative to the PPNT is the pre-sidedress NO_3-N test (PSNT). This soil test has gained popularity in northeastern USA and eastern Canada because it accurately determines NO_3-N levels when the corn plant is at the V6 stage just prior to the highest rate of N uptake, enabling timely N fertilizer adjustments (Fox et al. 1989). The PSNT has been shown to predict fertilizer N needs for corn over a wide geographic range (Magdoff et al. 1984; Blackmer et al. 1989; Magdoff 1991; Ransom et al. 2020). Although the PSNT has shown greater accuracy in predicting crop N requirements compared to PPNT, the need for producers to have access to side-dressing equipment, soil sampling during the growing season in a manner to capture soil NO_3-N spatial variability and potential changes in soil NO_3-N concentrations over a short period of time has hindered its widespread use (Beauchamp et al. 2004; Ma et al. 2007). The limitations of the PSNT justifies examination of pre-plant soil-N indicators that account for both pre-plant-available N and organic N that mineralizes to become plant available during the growing season. A more in depth review of N rate recommendation methods for corn was presented by Morris et al. (2018).

In the humid temperate region that characterizes eastern Canada, various laboratory and field-based methods have been tested for assessing the contribution of N mineralization to crop N uptake (Sharifi et al. 2007*b*; Nyiraneza et al. 2009; Sharifi et al. 2009; Nyiraneza et al. 2012; Luce et al. 2014; Thomas et al. 2016*b*). Recent developments for predicting the contribution of mineralizable soil N to crop N uptake have focused on measuring readily mineralizable N, including a biologically active fraction of soil organic-N (pool I) (Sharifi et al. 2007*a*), water-extractable C and N (Luce et al. 2014; Thomas et al. 2016*a*, 2016*b*), and particulate organic matter C (POMC) and N (POMN) (Sharifi et al. 2008; Luce et al. 2014; Thomas et al. 2016*b*). Pool I is the initial flush of N produced in the laboratory by drying and rewetting soil in the first 2 wk of incubation at 25 °C (Sharifi et al. 2007*a*). The water-extractable organic C and N (WEOC and WEON) were considered by Haynes (2000) to be the most dynamic and bioavailable fractions of soil organic matter and have been used as indicators of plant-available N (Zsolnay 2003; Haney et al. 2012; Thomas et al. 2016*b*). The POMC and POMN are composed of partially decomposed plant residues and organic amendments, representing a transient pool of physically uncomplexed organic matter that undergoes decomposition and mineralization processes to supply plant-available N (Gregorich et al. 2006; Thomas et al. 2016*b*).

Although some scientists have found PPNT to be a good predictor of potential corn yield and N uptake (Nyiraneza et al. 2009), others attempted to predict SNS and N fertilizer recommendations for grain corn with soil-N tests that extract biologically active organic-N fractions (Sharifi et al. 2007*a*; Nyiraneza et al. 2012). Nyiraneza et al. (2012) reported that UV absorbance of a 0.01 $mol \cdot L^{-1}$ $NaHCO_3$ extract at 205 nm, and pool I plus

PPNT were the most promising N availability indicators for grain corn ($0.28 \leq r \leq 0.62$) across 25 sites in cold humid temperate regions of Canada. They managed to improve the predictions by grouping the soils based on soil texture. Pool I alone or combined with PPNT were recommended as reliable predictors of available soil N due to their strong correlation with plant N uptake ($R^2 \geq 0.42$) in some studies (Sharifi et al. 2009). Particulate organic matter C and POMN were also reported to be reliable indicators of soil mineralizable N accounting for 30%–70% of the variation in plant N uptake (Luce et al. 2011; Luce et al. 2014; Thomas et al. 2016*b*). These indicators have been also used to predict soil-available N in soils that receive high organic matter inputs (Sharifi et al. 2008). Water-extractable C and N have recently received attention for their ability to predict SNS to various crops (Thomas et al. 2016*a*; Curtin et al. 2017). Yet, the above promising N availability indicators have not been evaluated for grain corn in Ontario.

In this study, grain corn N response trials were conducted in southern and eastern Ontario over two growing seasons, for a total of 13 site-years. The objectives were to evaluate the relationship between the soil-N tests, and relative yield (RY) and the maximum economic rate of nitrogen (MERN) to select the most appropriate soil-N test for grain corn in the major corn growing regions of Ontario. We hypothesized that soil-N tests that include a measure of readily mineralizable organic-N would more accurately predict N fertilizer recommendations for grain corn compared with PPNT or the corn N calculator.

Materials and Methods

Field sites

The study was conducted in 2013 and 2014 on 13 farmers' fields and (or) university research farms in southern and eastern Ontario, Canada. Site descriptions and cropping history are presented in Table 1. All long-term sites were managed using conventional tillage with synthetic N fertilizers except for the trial at the Trent University Sustainable Agriculture Experimental Farm, which was under organic management for 5 yr prior to establishing the trial. The average growing season air temperature ranged from 15 to 17 °C in 2013 and 14 to 17 °C in 2014, whereas the growing season rainfall ranged from 492 to 748 mm in 2013 and 381 to 585 mm in 2014 (Table 1). The 30 yr mean growing season (May–October) temperature and precipitation for southwestern Ontario are 16 °C and 530 mm, respectively. Soil physical and chemical characteristics are summarized in Table 2.

Experimental design

At each field site, four to five N fertilizer rates were applied to plots arranged in a randomized complete block design with four replicates. Plot size was typically 32 m × 16 m. Rates of N fertilizer ranged from 0 to 222 kg $\mathrm{N{\cdot}ha^{-1}}$, and the N source was urea–ammonium-nitrate or urea (Table 2). The majority of N fertilizers were applied pre-plant, but some sites received "Starter N" through the planter (Table 2). Sites were planted to grain corn (recommended variety and seeding rate for each site according to guidelines provided by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) or a regional crop advisor) in May to early June of each year with 76.2 cm inter-row spacing. Phosphorous and potassium fertilizers were applied at planting according to soil test and OMAFRA recommendations.

Soil sampling and analyses

Eight soil cores (2.5 cm diameter, 30 cm depth) were collected from each replicated zero-N plot with a soil probe 5 to 10 d prior to planting and fertilizer application. Soil samples were thoroughly mixed and then divided into two subsamples. One subsample was kept moist and stored at 4 °C, whereas the other was air-dried and sieved (<2 mm) until analysis. Soil moisture content was determined by drying a field moist subsample at 105 °C for 24 h. Soil pH was determined in a 1:2 soil to deionized water suspension. Particle size distribution was determined following organic matter removal by the pipette method (Gee and Bauder 1986).

Eight laboratory biological and chemical soil test indicators of the SNS were evaluated (Table 3). Soil mineral N was extracted from field moist soil with 2 $\mathrm{mol{\cdot}L^{-1}}$ KCl (1:5 soil to extractant ratio), and the NO_3-N and ammonium-N (NH_4-N) concentrations were determined by colorimetry using the modified indophenol blue technique (Sims et al. 1995) with an Epoch microplate spectrophotometer (BioTek Instruments Inc., Winooski, VT, USA). The soil mineral N at planting is referred to as $\mathrm{SMN_p}$. The KCl-extractable NO_3-N in spring soil samples is referred to as PPNT. Water extractions were conducted by shaking 4 g air-dried soil in 20 mL of room temperature deionized water for 60 min (Curtin et al. 2006; Chantigny et al. 2009). Water extracts were then centrifuged at 4500*g* for 20 min, and the supernatant was decanted and analyzed for WEOC using a Schimadzu TOC-$\mathrm{V_{CPH}}$ (Schimadzu, Kyoto, Japan) and analyzed for water-extractable mineral N (WEMN) using the modified indophenol blue method as described above. Total water-extractable N (WEN) was determined using the persulfate oxidation method (Cabrera and Beare 1993). The WEON was calculated by subtracting the WEMN from the WEN. For POMC and POMN, 25 g of air-dried soil was dispersed in 100 mL of a 5 $\mathrm{g{\cdot}L^{-1}}$ sodium hexametaphosphate solution in a 250 mL nalgene bottle by shaking for 16 h, and then dispersed soil was passed through a 53 μm sieve (Gregorich et al. 2003). The retained sand and macro-organic matter were air-dried overnight and then oven-dried at 50 °C for 24 h. The concentration of POMC, POMN, organic C, and total N of

Table 1. Summary of the selected experimental sites' description and management history in Ontario.

Site location	Latitude and longitude (°N°W)	Growing season rainfall[a] (mm)	Mean growing season air temperature (°C)	Crop heat unit (CHU)[b]	Previous crop	Rates applied (kg N·ha^{-1})	Starter N applied (kg N·ha^{-1})	N source	Tillage
2013									
Ilderton	43°11′, 81°30′	748	NA	2900	Winter wheat	0,56,112,168,224	33.6	UAN	NA
Hart	43°13′, 80°82′	492	16.9	2890	Soybean	0,56,112,168,224	28	UAN	No till
Rutherford	43°13′, 80°82′	492	16.9	2890	Grain corn	0,56,112,168,224	4.5	UAN	Fall moldboard plow, spring cultivate
Moorefield	43°75′, 80°77′	670	15.3	2700	Winter wheat	0,56,112,168,224	0	UAN	Fall chisel plow, spring cultivate 2×
Bornholm	43°52′, 81°13′	720	NA	2820	Winter wheat	0,56,112,168,224	0	UAN	Fall coulter harrow, spring coulter harrow
OMAFRA–Elora	43°65′, 80°39′	701	15.3	2680	Soybean	0,56,112,168,224	12.3	UAN	Fall chisel plow, spring cultipacked
2014									
Pinkerton	44°13′, 81°17′	395	17.0	2700	Soybean	0,94,134,202	0	UAN	NA
Teeswater	44°10′, 81°22′	395	17.0	2700	Soybean	0,94,134,202	0	UAN	Strip-tillage
U of G–Elora	43°38′, 80°23′	410	14.0	2680	Grain corn	0,28,57,115,188	30	UAN	Fall moldboard plow
AAFC–Woodslee	42°12′, 82°44′	525	16.5	3560	Grain corn	0,50,100,150,200	28.4	UAN	Disk, triple K cultivation, harogated and packed
U of G–Ridgetown	42°27′, 81°53′	525	16.5	3340	Soybean	0,50,100,150	11	UAN	NA
Trent Experimental Farm	44°21′, 78°16′	463	15.0	2500	Buckwheat	0,30,60,120,180	0	Urea	Disc and harrow
AAFC–Ottawa	45°22′, 75°43′	381	16.0	2900	Grain corn	0,50,100,150	0	Urea	Fall moldboard plow, spring cultivate

Note: UAN, urea ammonium nitrate fertilizer (28% N); NA, not applicable.

[a] From May to October: http://climate.weather.gc.ca/prodsservs/cdnclimatesummarye.html.

[b] OMAFRA factsheet: crop heat units for corn and other warm season crops in Ontario.

Table 2. Soil physical and chemical characteristics for 13 selected experimental sites in Ontario, Canada ($n = 4$).

		Soil texture[a]						
Site location	Soil series	Clay ($g \cdot kg^{-1}$)	Silt ($g \cdot kg^{-1}$)	Sand ($g \cdot kg^{-1}$)	pH[b]	Organic C[c] ($g \cdot kg^{-1}$)	Total N ($g \cdot kg^{-1}$)	C/N ratio
2013								
Ilderton	London loam	194	438	367	7.7	20.7	1.60	13.0
Hart	London loam	192	320	431	7.7	23.0	2.10	11.0
Rutherford	Perth silt loam	112	373	487	7.6	16.1	1.60	10.0
Moorefield	Perth loam	225	546	228	7.8	21.1	1.80	11.7
Bornholm	Perth clay loam[d]	274	584	141	6.8	23.6	1.80	13.0
OMAFRA–Elora	Woolwich silt loam[d]	87	470	442	8.0	19.2	1.70	11.3
2014								
Pinkerton	Teeswater silt loam	155	257	588	7.4	29.0	2.60	11.1
Teeswater	Teeswater silt loam	168	353	479	7.9	35.0	2.80	12.5
U of G–Elora	Woolwich silt loam	200	480	320	7.8	24.0	2.10	11.5
AAFC–Woodslee	Brookston clay loam	406	336	258	6.6	19.0	2.20	8.60
U of G–Ridgetown	Brookston clay loam	440	250	310	7.8	22.0	1.90	11.5
Trent Experimental Farm	Otonabee loam	155	136	709	8.1	29.0	2.30	12.6
AAFC–Ottawa	Brandon clay loam	350	270	380	6.8	14.0	1.30	10.8

[a] Pipette method (Gee and Bauder 1986).
[b] pH in water (1:2 soil/water ratio, Hendershot et al. 2008).
[c] Dry Combustion (VarioMAX Cube, Elementar Analysensysteme GmbH, Hanau, Germany).
[d] Site was tile drained.

each soil was determined following carbonate removal using a CNS analyzer (VarioMAX cube, Elementar Analysensysteme GmbH, Hanau, Germany). Pool I, the flush of readily mineralizable N at the second leaching event 2 wk after the initial time 0 leaching, was measured as described by Thomas et al. (2015).

Corn yield and N uptake

Grain yield was measured in each plot either by hand harvesting an area of at least 6 m^2 (two corn rows, 8 m in length) or machine harvesting using a plot or commercial scale combine. Grain yields were reported at an adjusted moisture content of 155 $g \cdot kg^{-1}$. Corn N uptake was measured by harvesting 10 random plants per plot at the same time as harvest. Harvested corn plants were partitioned into kernels, cobs, and stover, and then oven-dried at 60 °C until constant dry mass was achieved. Tissue samples were finely ground to pass a 1 mm sieve, and the N concentrations were determined by dry combustion with a CNS analyzer (VarioMAX Cube, Elementar Analysensysteme GmbH, Hanau, Germany).

Calculations

The corn N uptake in the zero-N treatment (PNU_{0N}) was calculated as the product of tissue N concentration and dry matter yield for each replicated plot minus any fertilizer N applied at planting as starter N.

Relative yield for each replicate was calculated as follows (Sharifi et al. 2007*b*):

$$\text{(1)} \qquad RY = \left(\frac{GY_{0N}}{GY_{\text{optimal-N}}}\right) \times 100$$

where GY_{0N} is the grain yield from the plot receiving no N fertilizer, and $GY_{\text{optimal-N}}$ is the grain yield from the highest yielding N fertilizer rate. To estimate the SNS, at corn harvest, soil samples were collected from the zero-N rate treatments (0–30 cm depth) as described above and stored at 4 °C until analysis. The composite soil samples collected at harvest were analyzed for mineral N (SMN_h) as described above. The SNS was calculated as sum of the PNU_{0N} and SMN_h with an assumed bulk density of 1.1 $Mg \cdot m^{-3}$.

The corn N response (Dahnke and Olson 1990) for each site was calculated using a quadratic regression equation (McGonigle et al. 1996; Rashid et al. 2004):

$$\text{(2)} \qquad Y = a + bN - cN^2$$

where Y is the corn grain yield ($kg \cdot ha^{-1}$); N is the fertilizer N applied ($kg\ N \cdot ha^{-1}$).

The derivative of the quadratic equation was used to determine MERN:

$$\text{(3)} \qquad dY/dN = b\text{–}(2cN)$$

where dY/dN is the price ratio of 1 kg fertilizer to 1 kg of grain corn defined as R below to solve for the MERN:

$$\text{(4)} \qquad R = b\text{–}(2cN) \text{ and therefore } MERN = (b\text{–}R)/2c$$

R was determined using the 2014 grain corn and N fertilizer prices: corn price = \$0.18·kg^{-1}, N fertilizer price = \$1.38·kg^{-1}. The maximum economic yield (MEY) was then calculated using the MERN for each site:

$$(5)\quad \mathrm{MEY} = a + b(\mathrm{MERN}) – c(\mathrm{MERN})^2$$

Statistical analyses

All statistical analyses were performed using SAS version 9.2 (SAS Institute Inc. 2011). Data were first tested for normality using the Kolmogorov–Smirnov test and then for outliers. Sites were grouped based on clay content into two groups of ≤240 and >240 g clay·kg^{-1}. The field-based indices of N supply, soil characteristics, and the soil-N test mean values were correlated with RY and MERN using PROC CORR. Correlations were assessed by Pearson's correlation for the parameters with normal distribution or Spearman's rank correlation where parameters did not have a normal distribution. Regression analysis was used to determine the associations between the laboratory-based measures of N availability and RY to select the best predictive soil-N test. Stepwise regression (probability of F to enter the model ≤0.05, probability of F to remove from the model ≤0.10) were used in an attempt to improve the relationship between the selected laboratory-based measures of N availability and RY by including soil characteristics.

Results

Soil-N tests

Soil organic C and total N ranged from 14.0 to 35.0 g C·kg^{-1} and 1.30 to 2.80 g N·kg^{-1}, respectively (Table 2). The SMN$_\mathrm{P}$ and PPNT values represented 2.8%–18.8% and 5.5%–19% of the total SNS across both years, respectively (Table 3). The WEON concentrations varied among sites, ranging from 26 to 48 mg N·kg^{-1}, representing an average of 1.6% the total soil N. The WEN ranged from 29 to 65 mg N·kg^{-1} with an average of 76% in the organic-N form. The WEOC values averaged about 1% of the soil organic C, ranging from 156 to 403 mg C·kg^{-1}. The WEOC/WEON ratio was between 5.6:1 and 12.0:1, which is on average 70% of the soil C/N ratio (8.6:1–13.0:1). The POMC ranged from 684 to 6758 mg C·kg^{-1}, and the POMN ranged from 49.5 to 266 mg N·kg^{-1}. On average, POMC and POMN concentrations were 12% of the soil organic C and 6.0% of the soil total N, respectively. The POMC/POMN ratios varied (7.3–33.2), averaging 1.8 times the soil C/N ratio. Pool I ranged from 24 to 60 mg N·kg^{-1} and represented 1.3%–3% of the total soil N (Table 3). The pool I values represented 56%–197%, and 42%–497% of the SNS in 2013 and 2014, respectively. Soil mineral N at harvest (SMN$_\mathrm{h}$) values varied and ranged from 7.2 to 75 kg N·ha^{-1} (average 24 kg N·ha^{-1}) over the 13 site-years (Table 4).

Corn yield and total N uptake

Corn grain yields ranged from 3.5 to 9.0 Mg·ha^{-1} in the zero-N plots and 5.6 to 12.8 Mg·ha^{-1} in the non-limiting N rate plots, with each site exhibiting a strong quadratic response to fertilizer N application ($R^2 = 0.93–0.99$, Table 5). Over both growing seasons, RY ranged from 42% ± 4.9% to 101% ± 7.9%. The MERN values ranged from 103 to 257 kg N·ha^{-1}. The PNU$_\mathrm{0N}$ ranged from 67 to 126 kg N·ha^{-1} in 2013 and from 50 to 194 kg N·ha^{-1} in 2014 (Table 4).

Soil test correlation

A strong relationship between field-based indices of N availability (i.e., MERN, grain corn yield in zero-N fertilized plots, PNU, and SNS) and RY was observed (Table 6; $r = 0.60–0.78$). Although the relationships were improved when sites with clay >240 g·kg^{-1} were excluded (Table 6), the correlation result after grouping based on clay content was not reliable for sites with clay >240 g·kg^{-1} due to the low number of sites ($n = 5$). The soil N availability indicators were correlated to RY and MERN (Table 6). Only the indicators that had a significant correlation with RY were considered as reliable soil N tests, and their relationship with MERN was then assessed for fertilizer recommendations. The significant correlation between an indicator and RY confirms that variation in corn RY as a result of N availability in soil can be predicted by the indicator. Relative yield was positively correlated to only WEMN ($r = 0.74$) among tested indicators (Table 6 and Fig. 1). Among the evaluated laboratory-based indices of N availability only WEMN was significantly correlated with both RY and MERN ($r = –0.56$). A wider range of WEMN, RY, and MERN were observed in sites with clay ≤240 g·kg^{-1} than sites with greater clay content. Inclusion of soil properties in the relationship between WEMN and RY or MERN using stepwise regression did not result in any improvement (data not shown).

Discussion

Soil mineral N at planting and harvest is highly variable across Ontario soils

The wide range of potentially mineralizable N observed in the soils from the selected field sites was probably due to interactions among the broad range of soil properties, cropping history and differences in rainfall and temperature across southern and eastern Ontario. Using an assumed bulk density for all sites (1.1 Mg·m^{-3}), the SMN$_\mathrm{P}$ in this study is estimated to have contributed similar amounts to the SNS as observed in different studies for grain corn in eastern Ontario and Quebec that showed the mineral N at planting represented 16% to 27% of the SNS (Ma et al. 2007; Wu et al. 2008; Nyiraneza et al. 2009). This suggests that more than 70% of corn N uptake may derive from soil organic-N mineralization during the growing season in non-fertilized soils.

Table 3. Mean values ($n = 4$) for soil nitrogen (N) availability indicators for 13 selected experimental sites in Ontario, Canada.

Site location	SMN_p (mg·kg^{-1})	PPNT (mg·kg^{-1})	Pool I (mg·kg^{-1})	WEMN (mg·kg^{-1})	WEON (mg·kg^{-1})	WEN (mg·kg^{-1})	WEOC (mg·kg^{-1})	WEOC/ WEON	POMC (mg·kg^{-1})	POMN (mg·kg^{-1})	POMC/POMN (mg·kg^{-1})
2013											
Ilderton	9.80 (1.5)[a]	6.10 (1.2)	36 (10)	11.8 (5.5)	26.8 (9.5)	38.1 (6.2)	204 (8.5)	8.9 (1.7)	3325 (261)	12.7 (8.2)	24.2 (5.5)
Hart	8.16 (2.3)	4.98 (0.61)	31 (16)	9.34 (2.0)	25.9 (6.2)	35.2 (5.2)	246 (4.1)	9.0 (0.91)	2351 (600)	142 (45)	17.1 (4.4)
Rutherford	9.12 (2.2)	4.30 (0.79)	24 (3.8)	8.33 (1.0)	26.7 (2.1)	35.0 (1.5)	185 (4.9)	7.0 (0.14)	1975 (400)	111 (35)	18.4 (4.1)
Moorefield	12.2 (4.3)	8.60 (2.1)	34 (3.0)	10.5 (2.5)	31.6 (3.4)	42.2 (3.8)	188 (5.2)	6.0 (0.41)	3190 (1440)	11.6 (4.6)	27.6 (4.4)
Bornholm	11.0 (1.5)	8.10 (0.49)	53 (4.2)	8.82 (2.1)	32.5 (2.5)	41.3 (3.2)	312 (7.1)	9.8 (0.51)	1910 (737)	8.42 (3.0)	22.7 (2.8)
OMAFRA–Elora	10.1 (1.2)	8.20 (1.3)	35 (4.0)	8.85 (1.4)	28.0 (1.5)	36.9 (14)	192 (3.6)	7.3 (0.24)	2488 (237)	60.2 (46)	33.2 (14)
2014											
Pinkerton	21 (3.9)	19.7 (3.9)	43 (13)	16.1 (0.37)	48.7 (2.8)	64.7 (4.4)	306 (11)	6.4 (0.5)	3305 (183)	216 (13)	15.4 (1.6)
Teeswater	11.2 (1.7)	9.8 (1.5)	37.8 (12)	14.6 (0.24)	41.4 (2.1)	56.1 (2.7)	230 (5.5)	5.6 (0.6)	6758 (268)	266 (13)	25.6 (4.6)
U of G–Elora	10.2 (1.2)	8.9 (1.1)	30.6 (10.6)	3.58 (0.14)	26.9 (3.3)	30.3 (4.2)	209 (8.3)	7.8 (0.6)	3817 (292)	146 (17)	29.3 (14)
AFFC–Woodslee	8.7 (2.6)	7.0 (3.0)	59.7 (3.1)	3.8 (0.17)	34.7 (8.6)	38.6 (9.2)	403 (11)	12 (3.6)	1247 (146)	125 (8.3)	9.67 (2.1)
U of G–Ridgetown	15.7 (5.5)	15.4 (6.4)	41.9 (3.9)	11.4 (0.78)	29.7 (11.1)	37.5 (8.1)	156 (25.6)	6.8 (3.3)	3100 (759)	159 (43)	20.8 (4.9)
Trent Experimental Farm	13.9 (8.6)	12.3 (10)	30.3 (8.9)	9.2 (0.35)	33.5 (9.4)	42.7 (10.8)	171 (2.5)	6.5 (2.6)	5632 (143)	175 (2.8)	32.1 (1.4)
AFFC–Ottawa	10.9 (1.5)	10.9 (1.6)	39.2 (13.3)	8.3 (0.39)	27.7 (2.8)	36.1 (4.4)	186 (9.7)	6.8 (1.4)	1363 (87)	133 (3.3)	10.4 (3.4)
Mean ($n = 52$)	9.7	8.8	38	10.6	32.16	42.3	238.8	7.7	2644	119	23
SD ($n = 52$)	4.3	3.7	11.6	4.3	8.38	11.3	68.5	2.4	2306	91	9.8

Note: SMNp, soil mineral-N at 0–30 cm soil depth prior to planting (2 mol L^{-1} KCl-extractable NH_4-N plus NO_3-N); PPNT, extractable NO_3-N with 2 mol·L^{-1} KCl at 0–30 cm soil depth prior to planting; WEMN, water-extractable mineral-N; WEON, water-extractable organic-N; WEN, water-extractable N; WEOC, water-extractable organic-C; WEOC/WEON, water-extractable organic C to N ratio; POMC, particulate organic matter C; POMN, particulate organic matter N; POMC/POMN, particulate organic matter C to N ratio.

[a] Numbers in parentheses are standard deviations (SD).

Table 4. Mean values ($n = 4$) for field-based indicators of soil nitrogen (N) supply for 13 selected experimental sites in Ontario in 2013 and 2014.

Site	Zero-N yield ($Mg{\cdot}ha^{-1}$)	Full N yield ($Mg{\cdot}ha^{-1}$)	Relative yield (%)	PNU_{0N} ($kg{\cdot}ha^{-1}$)	Soil N supply ($kg{\cdot}ha^{-1}$)	SMN_h ($kg{\cdot}ha^{-1}$)
2013						
Ilderton	6.4 (1.6)[a]	12 (1.2)	64 (15)	67 (12)	82 (12)	15 (1.2)
Hart	4.3 (0.5)	11 (1.0)	56 (5.0)	98 (24)	111 (22)	13 (2.7)
Rutherford	6.7 (1.1)	13 (0.9)	55 (6.9)	116 (29)	127 (29)	11 (0.5)
Moorefield	6.4 (0.9)	11 (0.8)	69 (7.0)	126 (13)	138 (14)	12 (1.1)
Bornholm	6.8 (0.8)	12 (0.2)	60 (7.2)	94 (14)	111 (17)	17 (2.3)
OMAFRA–Elora	7.0 (0.5)	11 (0.8)	64 (2.2)	88 (20)	102 (21)	15 (2.7)
2014						
Pinkerton	9.0 (0.5)	11 (0.5)	101 (7.9)	194 (7.3)	269 (23)	75 (18)
Teeswater	7.2 (0.5)	11 (0.3)	70 (3.4)	177 (9.0)	203 (11)	26 (3.8)
U of G–Elora	4.7 (0.5)	12 (0.6)	42 (4.9)	61 (3.5)	98 (9.2)	38 (5.3)
AAFC–Woodslee	4.5 (0.4)	10 (0.8)	51 (15)	50 (6.2)	81 (13)	31 (5.7)
U of G–Ridgetown	8.2 (1.0)	12 (1.8)	55 (13)	99 (30)	114 (26)	16 (6.3)
Trent Experimental Farm	3.7 (1.1)	5.6 (0.4)	65 (17)	69 (18)	87 (15)	18 (8.3)
AFFC–Ottawa	3.5 (1.4)	7.1 (0.9)	52 (24)	51 (15)	58 (14)	7.2 (1.4)
Mean ($n = 52$)	6.5	11	58	97	122	24
SD ($n = 52$)	1.5	1.0	13	7.3	15	19

Note: Relative yield = $[(GY_{0N}/GY_{optimal\text{-}N}) \times 100]$; GY, grain yield; PNU_{0N}, corn N uptake in zero-N plots; soil N supply = $PNU_{0N} + SMN_h$; SMN_h, soil mineral-N at harvest.

[a] Numbers in parentheses are standard deviations (SD).

Table 5. Recommended rate of nitrogen (N) fertilizer for selected experimental sites in 2013 and 2014 using quadratic equations based on corn yield response to fertilizer N rates, and the recommended rate based on the corn N calculator.

Site	Quadratic equation[a]	R^2	MEY ($Mg{\cdot}ha^{-1}$)	MERN ($kg\ N{\cdot}ha^{-1}$)	Corn N calculator ($kg\ N{\cdot}ha^{-1}$)
2013					
Ilderton	$y = -0.15x^2 + 63.7x + 4472$	0.99	11.3	191	168
Hart	$y = -0.12x^2 + 63.4x + 2643$	0.98	11.1	238	145
Rutherford	$y = -0.07x^2 + 42.9x + 6475$	0.98	13.1	257	186
Moorefield	$y = -0.11x^2 + 42.7x + 6390$	0.99	10.5	162	149
Bornholm	$y = -0.13x^2 + 49.7x + 6775$	0.99	11.6	166	177
OMAFRA–Elora	$y = -0.14x^2 + 51.8x + 6374$	0.98	11.2	160	125
2014					
Pinkerton	$y = 0.07x^2 + 23.2x + 9027$	0.99	10.7	103	121
Teeswater	$y = -0.14x^2 + 48.9x + 7191$	0.98	11.3	145	128
U of G–Elora	$y = -0.18x^2 + 80.1x + 2874$	0.99	11.8	203	153
AAFC–Woodslee	$y = -0.14x^2 + 62.8x + 2824$	0.98	9.77	196	196
U of G–Ridgetown	$y = 0.03x^2 + 21.2x + 7995$	0.93	11.2	221	212
Trent Experimental Farm	$y = -0.03x^2 + 15x + 3760$	0.98	5.30	145	109
AFFC–Ottawa	$y = -0.07x^2 + 34.7x + 3527$	0.98	7.40	182	134

Note: MEY, maximum economic yield ($Mg{\cdot}ha^{-1}$); MERN, maximum economic rate of N ($kg{\cdot}ha^{-1}$).

[a] Quadratic equation based on the response of corn grain yield to fertilizer N rate, where y is the grain yield in $kg{\cdot}ha^{-1}$, and x is the N fertilizer rate in $kg{\cdot}ha^{-1}$.

A wide range in SMN_h was also observed, but there was no consistent pattern across sites. The variation in SMN_h has been related to differences in precipitation or irrigation during the growing season (Jokela and Randall 1989), soil properties, and management practices (Rasouli et al. 2014). Similar to SMN_p, the majority of SMN_h was NO_3-N. In Ontario, between 1981 and 2006, an average of 57 kg NO_3-$N{\cdot}ha^{-1}$ remained in agricultural soils at harvest (De Jong et al. 2009). High residual NO_3-N at harvest indicates asynchrony between SNS and

Table 6. Correlation coefficients (*r*) of soil nitrogen (N) availability indicators with relative yield (RY) and maximum economic rate of N (MERN) at 13 selected experimental sites in Ontario in 2013 and 2014.

Parameter	Correlation method	Full data set ($n = 13^a$) RY	Full data set ($n = 13^a$) MERN	Clay $\leq$ 240 g·kg^{-1} ($n = 8^b$) RY	Clay $\leq$ 240 g·kg^{-1} ($n = 8^b$) MERN	Clay > 240 g·kg^{-1} ($n = 5$) RY	Clay > 240 g·kg^{-1} ($n = 5$) MERN
MERN	Pearson	−0.698**	1.00	−0.751*	1.00	−0.585	1.00
MEY	Spearman	−0.363	0.540	−0.714*	0.898**	−0.100	−0.600
Zero N Yield	Pearson	0.600*	−0.397	0.764*	−0.415	0.006	−0.804
PNU_{0N}	Pearson	0.777**	−0.458	0.832*	−0.478	0.518	−0.880*
SNS	Spearman	0.692**	−0.526	0.833*	−0.491	0.700	−0.700
Clay	Pearson	−0.324	−0.013	−0.255	0.083	−0.722	0.353
Sand	Pearson	0.397	−0.201	0.525	−0.478	0.040	0.281
Silt	Pearson	−0.217	0.187	−0.487	0.383	0.387	−0.359
pH	Spearman	0.080	−0.103	0.048	−0.241	0.527	−0.949*
Organic C	Pearson	0.404	−0.578*	0.483	−0.695	−0.106	−0.615
Total N	Pearson	0.352	−0.468	0.592	−0.646	−0.765	0.172
C/N ratio	Pearson	0.203	−0.414	−0.059	−0.484	0.661	−0.862
SMN_p	Spearman	0.533	−0.799**	0.866**	−0.787*	−0.068	−0.623
PPNT	Spearman	0.357	−0.727**	0.825*	−0.888**	−0.123	−0.423
Corn N Calculator	Pearson	0.476	0.656*	−0.500	−0.314	0.816	0.725
Pool I	Pearson	0.114	−0.408	0.726*	−0.812*	−0.607	0.481
Pool I +SMN_p	Pearson	0.301	−0.616*	0.879**	−0.878**	−0.680	−0.065
WEMN	Pearson	0.743**	−0.559*	0.753*	−0.589	0.678	−0.945*
WEON	Spearman	0.407	−0.515	0.667	−0.611	−0.500	0.400
WEN	Pearson	0.562*	−0.375	0.847**	−0.514	−0.746	0.674
WEOC	Spearman	−0.170	0.041	0.333	−0.228	−0.800	0.300
WEOC/N	Pearson	−0.551	0.399	−0.574	0.604	−0.765	0.715
POMC	Pearson	0.172	−0.359	0.255	−0.515	−0.315	−0.244
POMN	Pearson	0.273	−0.294	0.540	−0.473	−0.453	0.133
POMC/N	Pearson	−0.043	−0.242	−0.327	−0.235	0.515	−0.911*
SMN_h	Spearman	−0.133	−0.256	0.286	−0.595	−0.800	0.300

Note: MEY, maximum economic yield; PNU_{0N}, corn total N uptake in zero-N plots; SNS, soil N supply ($PNU_{0N} + SMN_h$); SMN_p, soil mineral-N at 0–30 cm soil depth prior to planting; PPNT, extractable NO_3-N with 2 mol·L^{-1} KCl at 0–30 cm soil depth prior to planting; WEMN, water-extractable mineral-N; WEON, water-extractable mineral-N; WEN, water-extractable N; WEOC, water-extractable organic-C; WEOC/N, water-extractable organic C to N ratio; SMN_h, soil mineral-N at harvest; POMC, particulate organic matter C; POMN, particulate organic matter N; POMC/N, particulate organic matter C to N ratio; SMN_h, soil mineral-N at harvest. Correlation coefficients are presented for full data set, clay $\leq$ 240 g·kg^{-1} and clay > 240 g·kg^{-1} soil groups. *, $P < 0.05$; **, $P < 0.01$.

[a] Numbers of sites for SMN_h was 12 due to removal of one outlier.

[b] Numbers of sites for SMN_h was 7 due to removal of one outlier.

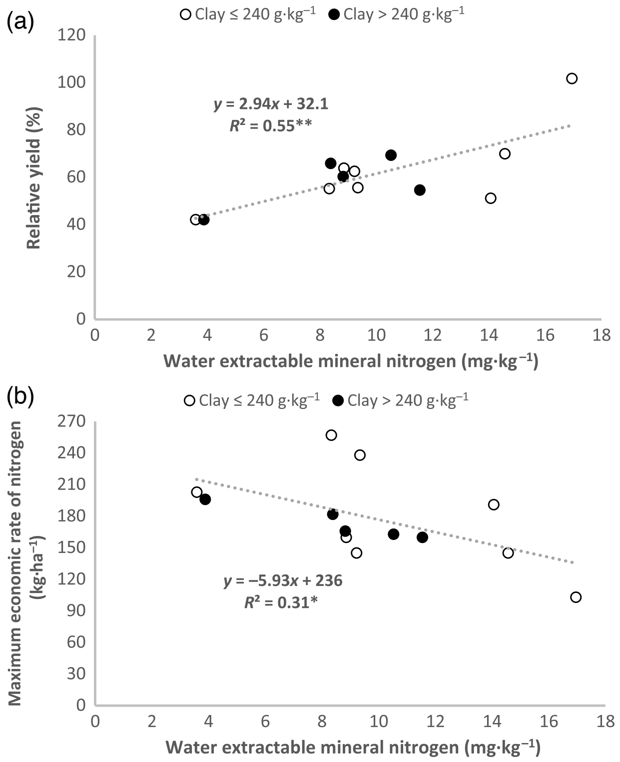
crop N demand, which may result in N losses over the fall, winter, and spring months (Power et al. 1998; Dinnes et al. 2002; Whalen et al. 2019). Ultimately, limiting the amount of residual soil NO_3-N at harvest minimizes potential N losses to the surrounding environment during the non-growing season (Rasouli et al. 2014).

With the relatively low price of N fertilizer in 2014, it was economical to apply higher rates of N for small gains in grain yield. The MERN values were comparable to the range reported by OMAFRA (107–237 kg N·ha^{-1}) for corn response trials in southwestern Ontario in 2013 (GOCorn.net 2010). Other factors that impact N fertilizer recommendations include cropping history (Luce et al. 2011), soil properties (Dharmakeerthi et al. 2005; Subbarao et al. 2006), and soil moisture and temperature (Dessureault-Rompré et al. 2011). For example, in this study, Pinkerton and Teeswater sites had high soil organic C and total N, which probably contributed to a greater SNS (202–269 kg N·ha^{-1}) compared with other field sites. Soils with greater soil organic C concentration have been shown to generally have a greater soil water-holding capacity (Manns et al. 2016), which may have also increased C and N mineralization rates and reduced the likelihood that water stress would limit crop performance.

Labile organic carbon and nitrogen fractions are used for interpretation of variations in nitrogen availability to corn

The WEOC concentrations were comparable to those reported for soils cropped to corn and corn–soybean (*Glycine max* L.) rotations in Ontario, Canada

Fig. 1. Relationship between (*a*) relative yield or (*b*) maximum economic rate of nitrogen and water-extractable mineral nitrogen. Regression is based on whole data set ($n = 13$). *, $P < 0.05$; **, $P < 0.01$.



(Gregorich et al. 2003), and to soil under a corn–soybean–wheat (*Triticum aestivum* L.) rotation near Quebec City, QC, Canada (Thomas et al. 2016*a*). The mean proportion of WEON to total N (1.6%) was smaller than range (2.6%–8.7 %) reported for 30 New Zealand soils (Curtin et al. 2006); however, the mean WEOC to WEON ratio (7.7) was numerically lower than some previous studies (Gregorich et al. 2003; Curtin et al. 2006; Haney et al. 2012), or similar to sandy loam soils (6.7 ± 1.0) fertilized with calcium–ammonium-nitrate fertilizer in Quebec (Thomas et al. 2016*b*). The high proportion of total N as WEON indicates that these soils have a high supply of soluble organic-N compounds, containing biologically available forms of organic-N (Herbert and Bertsch 1995) and therefore may be an important N source for soil organisms and field crops at the selected field sites when they are not fertilized or are under-fertilized. Furthermore, the lower WEOC/WEON ratio may be the result of long-term inorganic-N fertilization without supplemental organic amendment application leading to mining of soil C and production of N rich water-soluble microbial byproducts.

The wide range of POMC and POMN values may be attributed to the differences in cropping history (Griffin and Porter 2004; Haynes 2005), or soil properties such as soil texture, given that previous work showed a silty clay soil had 84% greater POMC concentrations than a sandy loam soils in Quebec, Canada (Thomas et al. 2016*a*). The POMN values were lowest where fields were under continuous corn (e.g., AAFC-Ottawa, Woodslee and Elora Research Station). The proportion of total N as POMN was within the range reported in the literature (Gregorich et al. 2006; Sharifi et al. 2007*a*), and the high C/N ratio of this fraction is a characteristic of soils receiving plant residues as the sole source of organic residue (Luce et al. 2011; Sequeira and Alley 2011). The wide range in pool I to SNS ratio, expressed as a percentage, indicates that the sites used in this study had contrasting amounts of readily mineralizable N.

Soil clay content decreases nitrogen availability to corn

Soils with clay content >240 g·kg^{-1} showed weaker relationships between the soil-N tests and RY than soils with clay content ≤240 g·kg^{-1}. These results are consistent with other work that has found clay content explained a substantial proportion of the variation in soil N mineralization (Dessureault-Rompré et al. 2011; Nyiraneza et al. 2012; Villar et al. 2014). Soil mineral N parameters have been related to potentially mineralizable N (N_0) in coarse-textured soils (>300 g sand·kg^{-1}; match with ≤240 g clay·kg^{-1} in this study except for one site) but not fine-textured soils (<300 g sand·kg^{-1}; match with >240 g clay·kg^{-1} in this study except for two sites), whereas total N was related to N_0 in fine-textured soils (Nyiraneza et al. 2012). The higher C content in soils with greater clay content can be attributed to the clay particles physically protecting organic matter from microbial decomposition through physio-chemical interactions and formation of aggregates (Jenkinson 1988; Angers et al. 1997; Six et al. 1999; Kölbl et al. 2006; Yoo and Wander 2006; Chivenge et al. 2011; Nyiraneza et al. 2012). The clay particles also may limit NH_4-N availability for oxidation and nitrification reactions by binding NH_4-N at negatively charged exchanges sites (Drury et al. 1989; Nieder et al. 2011).

Water-extractable mineral nitrogen is a strong nitrogen availability indicator for corn

Overall, laboratory-based soil-N tests that extracted readily available forms of soil N (e.g., WEMN, SMN_p, and PPNT) outperformed the indices that were associated with organic forms of N in soil (e.g., total N, POMN, and WEON) or the C-based indicators (e.g., WEOC, WEOC/N, and POMC/N). The organic-based C and N indicators consist of a combination of readily available and recalcitrant C and N, which may explain their weaker performance.

The PPNT has already been calibrated for corn in Ontario (OMAFRA 2009). Although some corn producers are using precision agriculture practices; others shifted towards using expected yields or visual observations of N deficiency/sufficiency to help predict their fertilizer N rates (O'Halloran et al. 2004). This is due to the large in-field variability that requires a high number of soil samples to be collected per hectare. Furthermore, the PPNT has shown varying success as a predictor of N availability as it is highly dependent on early-season rainfall, which may result in substantial losses due to leaching between the time of sample collection and start of maximum crop N uptake (Sharifi et al. 2009).

The WEMN is the N form that is readily available in the soil solution with a consistent positive correlation with RY and negative correlation with MERN among soil textures. The high importance of WEMN in supplying N to grain corn can be attributed to long-term history of N fertilization in this region. The WEMN represented an average of 22% of the WEN, which is comparable to the 15% found for soils under unfertilized corn monoculture, and the 20% for soils under a corn–soybean rotation receiving mineral fertilizer (Gregorich et al. 2003). Literature on WEN is rare as most studies report only the organic portion (Curtin et al. 2006; Haney et al. 2012; Luce et al. 2014; Thomas et al. 2016*a*). The WEON is hypothesized to contain mobile forms of bioavailable organic-N that is the by-product of microbial decomposition of crop residues and organic amendments (Murphy et al. 2000; Gregorich et al. 2003). The composition and, therefore, biodegradability of the WEON pool is important as this pool can also be composed of recalcitrant compounds that are resistant to further microbial decomposition (Smolander et al. 1995; Gregorich et al. 2003; Wander 2004).

It is apparent that the WEMN is a reliable index of the SNS for corn in soils primarily fertilized with inorganic-N sources. However, similar to PPNT, WEMN is highly mobile in soil, may show great in-field variability and can be affected by early season rainfall. Our findings reject our hypothesis; therefore, labile organic-N fractions were not significant predictors of soil-available N to grain corn in Ontario. However, our findings suggest that WEMN outperformed PPNT and corn N calculator methods in predicting soil-available N (Tables 5 and 6). Future research may focus on readily available pools of N in the main soil texture classes to develop regional-based indicators for N availability under field conditions.

Conclusion

The mineral N in the soil at planting (SMN_p) was estimated to represent about 30% of the SNS available to a corn crop during the growing season in Ontario. Across the entire dataset, WEMN was the only indicator that strongly correlated with both RY and MERN; indicating that in soils with a long-term history of N fertilization, mineral forms of N in soil solution may be used to make fertilizer N recommendations for corn in Ontario. Using WEMN instead of KCl-extractable mineral N, can reduce the cost of analysis while generating more reliable recommendations. However, the variability due to the soil properties and weather conditions will still exist and requires careful attention. Evidence from this research suggests that grouping soils based on soil texture improved predictions of corn-available N in the soils with clay <240 $g \cdot kg^{-1}$. A multi-year calibration of the WEMN soil test with more field sites and development of a fertilizer recommendation table for this test are recommended.

Acknowledgements

Funding for this project was provided by the Grain Farmers of Ontario (GFO). The majority of the sites selected in this experiment were part of the Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA) corn response trials. Technical support was provided by Scott Baker and Melissa Johnston. Dr. Mehdi Sharifi's position at Trent University at the time of this research was funded by Canadian Research Chairs (CRC) program of Canada Foundation for Innovations (CFI) and by Agriculture and Agri-Food Canada during the preparation of this manuscript.

References

Angers, D.A., Recous, S., and Aita, C. 1997. Fate of carbon and nitrogen in water-stable aggregates during decomposition of ^{13}C ^{15}N-labelled wheat straw in situ. Eur. J. Soil Sci. **48**: 295–300. doi:10.1111/j.1365-2389.1997.tb00549.x.

Beauchamp, E., Kay, B., and Pararajasingham, R. 2004. Soil tests for predicting the N requirement of corn. Can. J. Soil Sci. **84**: 103–113. doi:10.4141/S03-023.

Blackmer, A., Pottker, D., Cerrato, M., and Webb, J. 1989. Correlations between soil nitrate concentrations in late spring and corn yields in Iowa. J. Prod. Agric. **2**: 103–109. doi:10.2134/jpa1989.0103.

Cabrera, M., and Beare, M. 1993. Alkaline persulfate oxidation for determining total nitrogen in microbial biomass extracts. Soil Sci. Soc. Am. J. **57**: 1007–1012. doi:10.2136/sssaj1993.03615995005700040021x.

Chantigny, M.H., MacDonald, J.D., Beaupré, C., Rochette, P., Angers, D.A., Massé, D., and Parent, L.-E. 2009. Ammonia volatilization following surface application of raw and treated liquid swine manure. Nutr. Cycl. Agroecosyst. **85**: 275–286. doi:10.1007/s10705-009-9266-7.

Chivenge, P., Vanlauwe, B., Gentile, R., and Six, J. 2011. Organic resource quality influences short-term aggregate dynamics and soil organic carbon and nitrogen accumulation. Soil Biol. Biochem. **43**: 657–666. doi:10.1016/j.soilbio.2010.12.002.

Curtin, D., Wright, C., Beare, M., and McCallum, F. 2006. Hot water-extractable nitrogen as an indicator of soil nitrogen availability. Soil Sci. Soc. Am. J. **70**: 1512–1521. doi:10.2136/sssaj2005.0338.

Curtin, D., Beare, M.H., Lehto, K., Tregurtha, C., Qiu, W., Tregurtha, R., and Peterson, M. 2017. Rapid assays to predict nitrogen mineralization capacity of agricultural soils. Soil Sci. Soc. Am. J. **81**: 979–991. doi:10.2136/sssaj2016.08.0265.

Dahnke, W., and Olson, R. 1990. Soil test correlation, calibration, and recommendation. Pages 45–71 in R.L. Westerman, ed. Soil testing and plant analysis. Soil Science Society of America, Madison, WI, USA.

De Jong, R., Drury, C., Yang, J., and Campbell, C. 2009. Risk of water contamination by nitrogen in Canada as estimated by the IROWC-N model. J. Environ. Manage. **90**: 3169–3181. doi:10.1016/j.jenvman.2009.05.034. PMID:19592153.

Dessureault-Rompré, J., Zebarth, B.J., Chow, T.L., Burton, D.L., Sharifi, M., Georgallas, A., et al. 2011. Prediction of soil nitrogen supply in potato fields in a cool humid climate. Soil Sci. Soc. Am. J. **75**: 626–637. doi:10.2136/sssaj2010.0305.

Dharmakeerthi, R., Kay, B., and Beauchamp, E. 2005. Factors contributing to changes in plant available nitrogen across a variable landscape. Soil Sci. Soc. Am. J. **69**: 453–462. doi:10.2136/sssaj2005.0453.

Dinnes, D.L., Karlen, D.L., Jaynes, D.B., Kaspar, T.C., Hatfield, J.L., Colvin, T.S., and Cambardella, C.A. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. **94**: 153–171. doi:10.2134/agronj2002.1530.

Drury, C., Beauchamp, E., and Evans, L. 1989. Fixation and immobilization of recently added in selected Ontario and Quebec soils. Can. J. Soil Sci. **69**: 391–400. doi:10.4141/cjss89-039.

Fox, R., Roth, G., Iversen, K., and Piekielek, W. 1989. Soil and tissue nitrate tests compared for predicting soil nitrogen availability to corn. Agron. J. **81**: 971–974. doi:10.2134/agronj1989.00021962008100060025x.

Gee, G., and Bauder, J. 1986. Particle size analysis. Pages 383–411 in A. Klute, ed. Methods of soil analysis. Part 1: Physical and mineralogical methods. American Society of Agronomy, Inc., Madison, WI, USA.

GOCorn.net. 2010. Growing Ontario's corn. Grain farmers of Ontario. [Online]. Available from www.GOCorn.net.

Gregorich, E., Beare, M., Stoklas, U., and St-Georges, P. 2003. Biodegradability of soluble organic matter in maize-cropped soils. Geoderma, **113**: 237–252. doi:10.1016/S0016-7061(02)00363-4.

Gregorich, E., Beare, M., McKim, U., and Skjemstad, J. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Sci. Soc. Am. J. **70**: 975–985. doi:10.2136/sssaj2005.0116.

Griffin, T., and Porter, G. 2004. Altering soil carbon and nitrogen stocks in intensively tilled two-year rotations. Biol. Fertil. Soils, **39**: 366–374. doi:10.1007/s00374-004-0725-7.

Haney, R.L., Franzluebbers, A.J., Jin, V.L., Johnson, M.-V., Haney, E.B., White, M.J., and Harmel, R.D. 2012. Soil organic C: N vs. water-extractable organic C: N. Open J. Soil Sci. **2**: 269–274 doi:10.4236/ojss.2012.23032.

Haynes, R. 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biol. Biochem. **32**: 211–219. doi:10.1016/S0038-0717(99)00148-0.

Haynes, R. 2005. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. Adv. Agron. **85**: 221–268.

Hendershot, W.H., Lalande, H., and Duquette, M. 2008. Ion exchange and exchangeable cations. Pages 197–206 in M.R. Carter and E.G. Gregorich, eds. Soil sampling and methods of analysis. CRC Press, Boca Raton, FL, USA.

Herbert, B.E., and Bertsch, P.M. 1995. Characterization of dissolved and colloidal organic matter in soil solution: a review. Pages 63–88 in W.W. McFee and J.M. Kelly, eds. Carbon forms and functions in forest soils. Soil Science Society of America, Inc., Madison, WI, USA.

Jenkinson, D. 1988. Determination of microbial biomass carbon and nitrogen in soil. Pages 368–386 in J.R. Wilson, ed. Advances in nitrogen cycling in agricultural ecosystems. CAB International, Wallingford, England.

Jokela, W., and Randall, G. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. **81**: 720–726. doi:10.2134/agronj1989.00021962008100050004x.

Kölbl, A., Von Lützow, M., and Kögel-Knabner, I. 2006. Decomposition and distribution of ^{15}N labelled mustard litter (*Sinapis alba*) in physical soil fractions of a cropland with high-and low-yield field areas. Soil Biol. Biochem. **38**: 3292–3302. doi:10.1016/j.soilbio.2006.04.010.

Luce, M.S., Whalen, J.K., Ziadi, N., and Zebarth, B.J. 2011. Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils: chapter two. Adv. Agron. **112**: 55. doi:10.1016/B978-0-12-385538-1.00002-0.

Luce, M.S., Whalen, J.K., Ziadi, N., Zebarth, B.J., and Chantigny, M.H. 2014. Labile organic nitrogen transformations in clay and sandy-loam soils amended with ^{15}N-labelled faba bean and wheat residues. Soil Biol. Biochem. **68**: 208–218. doi:10.1016/j.soilbio.2013.09.033.

Ma, B., Subedi, K., and Zhang, T. 2007. Pre-sidedress nitrate test and other crop-based indicators for fresh market and processing sweet corn. Agron. J. **99**: 174–183. doi:10.2134/agronj2006.0028.

Magdoff, F. 1991. Understanding the Magdoff pre-sidedress nitrate test for corn. J. Prod. Agric. **4**: 297–305. doi:10.2134/jpa1991.0297.

Magdoff, F., Ross, D., and Amadon, J. 1984. A soil test for nitrogen availability to corn. Soil Sci. Soc. Am. J. **48**: 1301–1304. doi:10.2136/sssaj1984.03615995004800060020x.

Manns, H.R., Parkin, G.W., and Martin, R.C. 2016. Evidence of a union between organic carbon and water content in soil. Can. J. Soil Sci. **96**: 305–316. doi:10.1139/cjss-2015-0084.

McGonigle, K.F., Lantry, S.A., Odom-Maryon, T.L., Chai, A., Vasilev, S.A., and Simpson, J.F. 1996. Histopathologic effects of tamoxifen on the uterine epithelium of breast cancer patients: analysis by menopausal status. Cancer Lett. **101**: 59–66. doi:10.1016/0304-3835(96)04114-6. PMID:8625283.

Morris, T.F., Murrell, T.S., Beegle, D.B., Camberato, J.J., Ferguson, R.B., Grove, J., et al. 2018. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. Agron. J. **110**: 1–37. doi:10.2134/agronj2017.02.0112.

Murphy, D., Macdonald, A., Stockdale, E.A., Goulding, K., Fortune, S., Gaunt, J., et al. 2000. Soluble organic nitrogen in agricultural soils. Biol. Fertil. Soils, **30**: 374–387. doi:10.1007/s003740050018.

Nieder, R., Benbi, D.K., and Scherer, H.W. 2011. Fixation and defixation of ammonium in soils: a review. Biol. Fertil. Soils, **47**: 1–14. doi:10.1007/s00374-010-0506-4.

Nyiraneza, J., N'Dayegamiye, A., Chantigny, M.H., and Laverdière, M.R. 2009. Variations in corn yield and nitrogen uptake in relation to soil attributes and nitrogen availability indices. Soil Sci. Soc. Am. J. **73**: 317–327. doi:10.2136/sssaj2007.0374.

Nyiraneza, J., Ziadi, N., Zebarth, B.J., Sharifi, M., Burton, D.L., Drury, C.F., et al. 2012. Prediction of soil nitrogen supply in corn production using soil chemical and biological indices. Soil Sci. Soc. Am. J. **76**: 925–935. doi:10.2136/sssaj2011.0318.

O'Halloran, I., Von Bertoldi, A., and Peterson, S. 2004. Spatial variability of barley (*Hordeum vulgare*) and corn (*Zea mays* L.) yields, yield response to fertilizer N and soil N test levels. Can. J. Soil Sci. **84**: 307–316. doi:10.4141/S03-041.

OMAFRA. 2009. Agronomy guide for field crops. Publication 811. OMAFRA.

Osterholz, H., Kirchman, D.L., Niggemann, J., and Dittmar, T. 2016. Environmental drivers of dissolved organic matter molecular composition in the Delaware Estuary. Front. Earth Sci. **4**: 95. doi:10.3389/feart.2016.00095.

Power, J.F., Koerner, P., Doran, J.W., and Wilhelm, W. 1998. Residual effects of crop residues on grain production and selected soil properties. Soil Sci. Soc. Am. J. **62**: 1393–1397. doi:10.2136/sssaj1998.03615995006200050035x.

Ransom, C.J., Kitchen, N.R., Camberato, J.J., Carter, P.R., Ferguson, R.B., Fernández, F.G., et al. 2020. Corn nitrogen rate recommendation tools' performance across eight US midwest corn belt states. Agron. J. **112**: 470–492. doi:10.1002/agj2.20035.

Rashid, M., Khalil, S., Ayub, N., Alam, S., and Latif, F. 2004. Organic acids production and phosphate solubilization by phosphate solubilizing microorganisms (PSM) under in vitro conditions. Pak. J. Biol. Sci. **7**: 187–196. doi:10.3923/pjbs.2004.187.196.

Rasouli, S., Whalen, J.K., and Madramootoo, C.A. 2014. Reducing residual soil nitrogen losses from agroecosystems for surface water protection in Quebec and Ontario, Canada: best management practices, policies and perspectives. Can. J. Soil Sci. **94**: 109–127. doi:10.4141/cjss2013-015.

SAS Institute, Inc. 2011. SAS online doc. Version 9.3. SAS institute Inc. Cary, NC, USA.

Sequeira, C.H., and Alley, M.M. 2011. Soil organic matter fractions as indices of soil quality changes. Soil Sci. Soc. Am. J. **75**: 1766–1773. doi:10.2136/sssaj2011.0067.

Sharifi, M., Zebarth, B., Burton, D., Grant, C., and Cooper, J. 2007*a*. Evaluation of some indices of potentially mineralizable nitrogen in soil. Soil Sci. Soc. Am. J. **71**: 1233–1239. doi:10.2136/sssaj2006.0265.

Sharifi, M., Zebarth, B.J., Burton, D.L., Grant, C.A., Porter, G.A., Cooper, J.M., et al. 2007*b*. Evaluation of laboratory-based measures of soil mineral nitrogen and potentially mineralizable nitrogen as predictors of field-based indices of soil nitrogen supply in potato production. Plant Soil, **301**: 203–214. doi:10.1007/s11104-007-9438-7.

Sharifi, M., Zebarth, B.J., Burton, D.L., Grant, C.A., and Porter, G.A. 2008. Organic amendment history and crop rotation effects on soil nitrogen mineralization potential and soil nitrogen supply in a potato cropping system. Agron. J. **100**: 1562–1572. doi:10.2134/agronj2008.0053.

Sharifi, M., Zebarth, B., Porter, G., Burton, D., and Grant, C. 2009. Soil mineralizable nitrogen and soil nitrogen supply under two-year potato rotations. Plant Soil, **320**: 267–279. doi:10.1007/s11104-009-9892-5.

Sims, G., Ellsworth, T., and Mulvaney, R. 1995. Microscale determination of inorganic nitrogen in water and soil extracts. Commun. Soil Sci. Plant Anal. **26**: 303–316. doi:10.1080/00103629509369298.

Six, J., Elliott, E., and Paustian, K. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. **63**: 1350–1358. doi:10.2136/sssaj1999.6351350x.

Smolander, A., Kitunen, V., Priha, O., and Mälkönen, E. 1995. Nitrogen transformations in limed and nitrogen fertilized soil in Norway spruce stands. Plant Soil, **172**: 107–115. doi:10.1007/BF00020864.

Subbarao, G., Ito, O., Sahrawat, K., Berry, W., Nakahara, K., Ishikawa, T., et al. 2006. Scope and strategies for regulation of nitrification in agricultural systems — challenges and opportunities. Crit. Rev. Plant Sci. **25**: 303–335. doi:10.1080/07352680600794232.

Thomas, B.W., Sharifi, M., Whalen, J.K., and Chantigny, M.H. 2015. Mineralizable nitrogen responds differently to manure type in contrasting soil textures. Soil Sci. Soc. Am. J. **79**: 1396–1405. doi:10.2136/sssaj2015.03.0124.

Thomas, B.W., Whalen, J.K., and Sharifi, M. 2016*a*. Short-term nitrogen dynamics in soil amended with poultry litter containing woodchip bedding. Can. J. Soil Sci. **96**: 427–434. doi:10.1139/cjss-2015-0113.

Thomas, B.W., Whalen, J.K., Sharifi, M., Chantigny, M., and Zebarth, B.J. 2016*b*. Labile organic matter fractions as early-season nitrogen supply indicators in manure-amended soils. J. Plant Nutr. Soil Sci. **179**: 94–103. doi:10.1002/jpln.201400532.

Villar, N., Aizpurua, A., Castellón, A., Ortuzar, M.A., Moro, M.B.G., and Besga, G. 2014. Laboratory methods for the estimation of soil apparent N mineralization and wheat N uptake in calcareous soils. Soil Sci. **179**: 84–94. doi:10.1097/SS.0000000000000047.

Wander, M. 2004. Soil organic matter fractions and their relevance to soil function. Soil organic matter in sustainable agriculture. CRC Press, Boca Raton, FL, USA. pp. 67–102.

Whalen, J.K., Kernecker, M.L., Thomas, B.W., Sachdeva, V., and Ngosong, C. 2013. Soil food web controls on nitrogen mineralization are influenced by agricultural practices in humid temperate climates. CAB Rev. **8**: 1–18. doi:10.1079/PAVSNNR20138023.

Whalen, J.K., Thomas, B.W., and Sharifi, M. 2019. Novel practices and smart technologies to maximize the nitrogen fertilizer value of manure for crop production in cold humid temperate regions. Adv. Agron. **153**: 1–85. doi:10.1016/bs.agron.2018.09.002.

Wu, T.-Y., Ma, B., and Liang, B. 2008. Quantification of seasonal soil nitrogen mineralization for corn production in eastern Canada. Nutr. Cycl. Agroecosyst. **81**: 279–290. doi:10.1007/s10705-007-9163-x.

Yoo, G., and Wander, M.M. 2006. Influence of tillage practices on soil structural controls over carbon mineralization. Soil Sci. Soc. Am. J. **70**: 651–659. doi:10.2136/sssaj2005.0036.

Zebarth, B., Drury, C., Tremblay, N., and Cambouris, A. 2009. Opportunities for improved fertilizer nitrogen management in production of arable crops in eastern Canada: a review. Can. J. Soil Sci. **89**: 113–132. doi:10.4141/CJSS07102.

Zsolnay, A. 2003. Dissolved organic matter: artefacts, definitions, and functions. Geoderma, **113**: 187–209. doi:10.1016/S0016-7061(02)00361-0.