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Decimetric-Scale Two-Dimensional Distribution of Soil Phosphorus after 20 Years of Tillage Management and Maintenance Phosphorus Fertilization

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Improving soil test P assessment at plot scale is essential for productivity in conservation agriculture systems. We characterized the distribution of Mehlich-3 P (P_{M3}) concentrations at the decimetric scale with depth on either side of the sowing row in no-till (NT) and moldboard plow (MP) plots fertilized with 35 kg P ha⁻¹ every 2-yr in a corn-soybean rotation (20-yr). A total of 996 soil samples (83 samples × 2 depths [0–5 and 5–20 cm] × 6 plots [3 blocks each MP and NT]) were collected at corn harvest in 2012. The average P_{M3} concentrations in the 0- to 5-cm layer were 35.7 and 63.4 mg kg⁻¹ in MP and NT, respectively. The P_{M3} concentration in the 5- to 20-cm depth was similar between MP and NT and averaged 32.0 mg kg⁻¹. The horizontal distribution of P_{M3} concentrations in these plots was less sensitive to extrinsic factors including tillage, P fertilization and soil depth. High coefficients of variation were associated with P_{M3} data in both MP (77 and 63% at 0–5 and 5–20 cm, respectively) and NT plots (46 and 66% at 0–5 and 5–20 cm, respectively). It is possible that this strong overall variability overshadowed any P_{M3} pattern that could have been introduced by NT management. Geostatistical semivariance analysis indicated a predominance of random spatial dependence in most plots, except two plots (one MP and one NT) with moderate spatial structures. The 2-D geospatial model related to tillage was not detected by the sampling grid used at this experimental site. Therefore, a similar sampling strategy would be appropriate and could be recommended for these two tillage systems in this long-term corn-soybean rotation.

Abbreviations: Al_{M3}, Mehlich-3 aluminum; CV, coefficient of variation; MP, moldboard plow; NT, no-till; P_{M3} , Mehlich-3 phosphorus; 2-D, two-dimensional.

SOWING CROPS without tillage of soil (the no-till [NT] method) is now an established practice worldwide to mitigate soil erosion and runoff (Friedrich et al., 2012). The implementation of NT management in the current agricultural context has been made possible by the use of herbicides and improved technologies (Pittelkow et al., 2015). It is estimated that approximately 9% (125 Mha) of global arable land is under NT management (Friedrich et al., 2012). In eastern Canada during the 2011 cropping season, the NT acreage was approximately 25%, in comparison with 18.5% in 2001, and further increases are projected by 2020 (Statistics Canada, 2016). A blend of NT management with well-planned crop rotation and residue retention can improve and sustain the productivity of cropland and contribute to overall food security (Pittelkow et al., 2015).

Surveys conducted in various parts of the world have shown that NT practices have raised relevant general concerns about environmental issues surrounding soil and landscape protection and climate change (Dodd and Sharpley, 2016). The major environmental issue to date is the risk of increased leaching of dissolved reactive phosphorus (P) (Simard et al., 2000; Djodjic et al., 2004). To some extent, and de-

Core Ideas

- 2-D distribution of Mehlich-3 P across seeding row had no spatial pattern in no-till and moldboard plow.
- Horizontal distribution of Mehlich-3 P was less sensitive to extrinsic factors.
- Soil-surface P accumulation in no-till is due in part to P recycled by corn and soybean.
- Surface P accumulation in no-till is also due to the replenishment of solution P by residual P.

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spite a reduction in erosion and sediment loss with NT, P enrichment of the particles transported due to legacy P can also result in increased particulate P loss (Rodrigues et al., 2016). Puustinen et al. (2005) found that the transport of dissolved reactive P on clayey sloped fields in a boreal climate increased by 348% under NT management in comparison with plowed soils.

A literature review on P distribution in the soil profile of fertilized NT cropland shows greater soil test P concentrations in the top 5-cm layer and, to some extent, down to the 10-cm depth, as well as a marked depletion of P in subsequent sublayers (Abdi et al., 2014; Cade-Menun et al., 2010). Messiga et al. (2012) observed low soil test P concentration in the 10- to 20-cm layer of fertilized NT plots in comparison with MP plots, indicating that under NT, P was depleted in this layer. This gradient of P concentration is due in part to year-to-year broadcast or band application of P fertilizer at or near the same sowing row, to the absence of mixing of P fertilizers with soil and crop residues left on the soil surface after harvest, and to the subsequent leaching of P from crop residues (Duiker and Beegle, 2006). Phosphorus stratification has implications for crop nutrition, since P depletion in the rooting zone, where P is needed by plant roots, may reduce crop yield (Lupwayi et al., 2006). Several strategies have been suggested to address this issue, including strategic tillage (Dang et al., 2015) and the collection of separate soil samples from different layers to capture the vertical variability found in the rooting zone and thus ensure better fertilizer P recommendations and placement methods (Cade-Menun et al., 2010).

Given that P fertilizers are applied at a shallow depth (about 4 to 5 cm below the soil surface), and that sowing row positions do not change over time, NT management can also result in a lateral distribution of P. This is often overlooked compared to the common evaluation of P concentration gradients with depth. Evidence of such two-dimensional (2-D) spatial variability, both vertical and horizontal, in NT was highlighted in a 2-yr study under a corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation with crops planted at 76-cm row spacing (Fernández and Schaefer, 2012). Those authors observed no change in soil test P concentrations under NT for broadcast application across all sampling positions with respect to the crop row for the top 30 cm of the soil. In contrast, increases in soil P levels were observed at the crop row relative to interrow positions at maintenance or recommended fertilizer P rates for subsurface-band fertilization (at 15 cm below the soil) (Farmaha et al., 2012; Fernández and Schaefer, 2012) or injection (at 10 cm below the soil) (Duiker and Beegle, 2006). Continuous band applications of P in the same soil volume result in a substantial localized increase in soil P test levels and depletion in the rest of the rooting zone.

The long-term NT site (from 1992 onward) at the L'Acadie Experimental Farm of Agriculture and Agri-Food Canada's Saint-Jean-sur-Richelieu Research and Development Centre (Saint-Jean-sur-Richelieu RDC), in the province of Quebec, Canada, has been the object of extensive research over the past decade. At this site, granular P fertilizers are surface-band-applied as triple superphosphate (5 cm from the seeding row) year to year at or

near the same sowing row using a disk opener (3–4 cm deep) according to local recommendations (CRAAQ, 2010). Water, Mehlich-3 P (P_{M3}), and other soil P fraction accumulations were observed in the surface soil layer under NT in comparison with moldboard plow (MP) (Messiga et al., 2012; Shi et al., 2013). In addition, Messiga et al. (2012) found that P stratification down the soil profile in NT was influenced by P rates. However, it is not clear if continuous surface-band application of P at maintenance P rates in the same location results in significant horizontal variability between the sowing row and the interrow space and whether this distribution would influence soil P assessment and thus soil sampling procedures and subsequent fertilizer P recommendations. We hypothesized that the year-to-year surface-band application of fertilizer at maintenance P rates at or near the same sowing row and the absence of mixing of P fertilizers can induce a spatial structure for soil P in NT-managed soils that can be detected on either side of the sowing row. The objective of this study was to characterize the decimetric spatial variability of soil P on either side of the sowing row in both NT and MP plots using classical and 2-D geostatistical analyses (semivariograms).

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted at an existing long-term experimental site established in 1992 at the L'Acadie (45°18' N, 73°21' W) Experimental Farm of Agriculture and Agri-Food Canada's Saint-Jean-sur-Richelieu RDC, in the province of Quebec, Canada (Ziadi et al., 2014). Briefly, the soil is a poorly drained deep clay loam classified as Humic Orthic Gleysol (Typic Haplaquept under the US Soil Taxonomy [Soil Survey Staff, 2010]). It originated from a fluvial deposit and evolved from a fine-textured greyish-to-brown parent material. The topography is flat with slope less than 1% and tile drainage was installed. The field was cropped to alfalfa (*Medicago sativa* L.) before its conversion to a corn–soybean rotation in 1992. The topsoil (0–15 cm) initially had organic matter of 38 g kg⁻¹, P_{M3} of 135 kg P ha⁻¹, a phosphorus saturation index (P/Al)_{M3} of 4.3%, and pH water of 6.3 (Ziadi et al., 2014). The mean annual temperature at the study site is 6.3°C with 1100 mm of total annual precipitation. The experimental design was a split plot with tillage practices (MP and NT) assigned to main plots and a factorial of three nitrogen (N) rates (0, 80, and 160 kg ha⁻¹) and three P rates (0, 17.5, and 35 kg ha⁻¹) assigned to subplots with four replicates. The experimental plots were 25 m long by 4.5 m wide (six rows of corn). The MP treatment consisted of one MP operation (20 cm deep) in fall after harvest, followed by disking and harrowing (10 cm deep) each spring before seeding. For the NT treatment, the plots were ridge-tilled from 1992 to 1997 and flat-direct-seeded from 1998 onward, with crop residues left on the ground after harvest. Granular triple superphosphate was band-applied (5 cm from the seeding row) to only the corn phase of the rotation using a disk opener (3–4 cm deep) according to local recommendations. The P treatments were band-applied in a single application at planting as commercial triple superphosphate (0–

46–0). Nitrogen treatments consisted of two split band-applications, first at seeding with additions of 0, 48, and 48 kg N ha⁻¹ as urea, and second at approximately the eight-leaf stage with additions of 0, 32, and 112 kg N ha⁻¹ side-dressed as ammonium nitrate. All plots received potassium at 41.5 kg ha⁻¹ (0–0–60) band-applied at planting in 1992 and 2007; this application was based on soil analysis and local recommendations (CRAAQ, 2010). There were six rows in each subplot, with corn sown at 74 × 10³ plants ha⁻¹ and soybean sown at 45 × 10⁴ plants ha⁻¹.

Soil Sampling

Six experimental plots receiving 35 kg P ha⁻¹ and 160 kg N ha⁻¹, the local recommended rates, before corn seeding were selected within the experimental set-up for this study (MP and NT tillage practices replicated in three blocks). Each plot was treated as an individual field for the spatial variability study: MP₁ (MP from the first block), MP₂ (MP from the second block), MP₃ (MP from the third block), NT₁ (NT from the first block), NT₂ (NT from the second block), and NT₃ (NT from the third block). A nested grid sampling scheme was implemented on the two middle rows of each of the six units to limit border effects (Nyiraneza et al., 2011). The principal grid (2.5-m × 0.38-m distance between each of the 35 sampling points) consisted of seven transects (perpendicular to row direction) and five transects (located in three interrows and two corn rows, i.e., third and fourth rows in the plot) (Fig. 1). Three of the seven transects had more intensive inter-row sampling points (0.076-m distance between the sampling points perpendicular to the row; 16 additional sampling points per transect). Each sampling point was sampled at the 0- to 5- and the 5- to 20-cm soil depths after corn harvest in October 2012. A total of 996 soil samples (83 samples per depth and experimental plot × 2 depths × 6 experimental units) were collected for the spatial variability study (Fig. 1). The soils were air-dried, sieved through a 2-mm sieve as suggested for soil P testing methods, and analyzed.

Soil Analysis

The soils were extracted with a Mehlich-3 solution according to Ziadi and Tran (2007). The P_{M3} and Mehlich-3 aluminum (Al) (Al_{M3}) concentrations (mg kg⁻¹) were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) (Optima 4300 DV spectrometer; PerkinElmer, Shelton, CT).

Statistical and Geostatistical Analysis

Data were analyzed in the classical way using descriptive statistics in SAS v.9.3 (SAS Institute, 2010) to investigate P_{M3}, Al_{M3} and (P/Al)_{M3} and their spatial variability. The minimum,

Fig. 1. Distribution of sampling points in the experimental plot.

maximum, mean, median, coefficient of variation (CV), and standard error of the mean (SEM) were determined for each location and depth. The CV and SEM were calculated using Eq. [1] and [2], respectively:

$$CV = \frac{\sqrt{\frac{\sum (X - \bar{X})^2}{n}}}{\bar{X}} \times 100 \quad [1]$$

$$SEM = \frac{\sqrt{\frac{\sum (X - \bar{X})^2}{n}}}{\sqrt{n}} \quad [2]$$

where X is the measured parameter, $\bar{X}$ is the mean value of the sample population, and n is the size of the sample population.

The mixed procedure of SAS v.9.3 (SAS Institute, 2010) was used to assess the effects of tillage, depth, and sampling location. Block was used as random effect, and tillage, depth, sampling location, and the two- and three-way interactions involving the three factors were used as fixed effects.

The 2-D geostatistical analyses (semivariance and block kriging) were performed on P_{M3} (mg kg^{-1}) data for each of the six experimental units and depths (MP₁ at 0–5 cm, MP₁ at 5–20 cm, MP₂ at 0–5 cm, MP₂ at 5–20 cm, MP₃ at 0–5 cm, MP₃ at 5–20 cm, NT₁ at 0–5 cm, NT₁ at 5–20 cm, NT₂ at 0–5 cm, NT₂ at 5–20 cm, NT₃ at 0–5 cm, and NT₃ at 5–20 cm) with GS⁺ v.9 software (Robertson, 2008; Webster and Oliver, 2007). The prediction of spatial dependence or continuity of P_{M3} at non-sampling points required a theoretical semivariogram that was constructed on the basis of experimental semivariograms. Experimental semivariograms, the main component of kriging, were calculated with Eq. [3]:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^n \{Z(x_i) - Z(x_i + h)\}^2 \quad [3]$$

where $\gamma(h)$ is the semivariogram for the lag distance h ; n is the number of sample pairs separated by the lag distance h ; $Z(x_i)$ is the measured P_{M3} at the i th location; $Z(x_i + h)$ is the measured P_{M3} at the $(i + h)$ th location; and i is the index to design location.

Various models were fitted to the semivariogram to estimate simulated P_{M3} for non-sampling points. Model selections for semivariograms were performed on the basis of a goodness-of-model-fit criterion. The corresponding nugget (C_0), partial sill (C), sill ($C_0 + C$), and range values of the best-fitting theo-

retical model were calculated. The values of the nugget/sill ratios [$C_0/(C_0 + C)$] were used to evaluate the spatial dependence or structure of the P_{M3} data (Oliver and Webster, 2014), where $C_0/(C_0 + C)$ less than 25% suggests that the variable has a strong spatial dependence, $C_0/(C_0 + C)$ between 25 and 75% suggests that the variable has a moderate spatial dependence, and $C_0/(C_0 + C)$ above 75% suggests that the variable has a low spatial dependence. Block kriging interpolation technique was used to produce the spatial distribution maps of P_{M3} for the studied plots.

RESULTS

Mehlich-3 Phosphorus and Aluminum and Phosphorus Saturation Ratio

The P_{M3} and Al_{M3} concentrations and the $(P/Al)_{M3}$ were affected only by tillage, and the extent varied with sampling depth (Table 1). Mehlich-3 P concentrations across the three MP plots ranged from 10.6 to 285.0 mg kg^{-1} in the 0- to 5-cm layer and from 9.1 to 185.7 mg kg^{-1} in the 5- to 20-cm layer (Fig. 2a). In the three NT plots, P_{M3} concentrations ranged from 14.0 to 209.6 mg kg^{-1} in the 0 to 5-cm layer and from 5.8 to 184.8 mg kg^{-1} in the 5- to 20-cm layer (Fig. 2a). Average P_{M3} concentrations in the 0- to 5-cm layer were 35.7

Fig. 2. (a) Mehlich-3 P, (b) Mehlich-3 Al and (c) P saturation index $(P/Al)_{M3}$ in moldboard plow (MP) and no-till (NT) systems in relation to soil depth (0–5 and 5–20 cm). SEM represents standard error of the mean.

Table 1. Results of the analysis of variance of Mehlich-3 P (P_{M3}) and Al (Al_{M3}) concentrations and P saturation ratio $(P/Al)_{M3}$ in a corn-soybean rotation under moldboard plow and no-till soils.

	df	P values		
		P_{M3}	Al_{M3}	$(P/Al)_{M3}$
Tillage	1	<0.001	0.003	<0.001
Depth	1	<0.001	0.028	<0.001
Tillage × Depth	1	0.007	0.002	<0.001
Absolute position	10	0.721	0.859	0.232
Absolute position × Tillage	10	0.648	0.788	0.706
Absolute position × Depth	10	0.749	0.999	0.600
Absolute position × Tillage × Depth	10	0.980	0.999	0.892

and 63.4 mg kg⁻¹ in MP and NT, respectively. In contrast, P_{M3} concentration in the 5- to 20-cm layer was similar between MP and NT and averaged 32.0 mg kg⁻¹. Under MP, the CVs of P_{M3} concentration were 77 and 63% in the 0- to 5- and 5- to 20-cm layers, respectively. Under NT, the CVs of P_{M3} concentration were 46 and 66% in the 0- to 5- and 5- to 20-cm layers, respectively. Mehlich-3 Al concentrations across the three MP plots ranged from 1127 to 1338 mg kg⁻¹ in the 0- to 5-cm layer and from 1116 to 1290 mg kg⁻¹ in the 5- to 20-cm layer (Fig. 2b). In the three NT plots, Al_{M3} concentrations ranged from 922 to 1433 mg kg⁻¹ in the 0- to 5-cm layer and from 990 to 1351 mg kg⁻¹ in the 5- to 20-cm layer. Average Al_{M3} concentrations in the 0- to 5-cm layer were 1214 and 1160 mg kg⁻¹ in MP and NT, respectively. In contrast, Al_{M3} concentration in the 5- to 20-cm layer was similar between MP and NT and averaged 1206 mg kg⁻¹. Under MP, the CVs of Al_{M3} concentration were 3.2 and 2.9% in the 0- to 5- and 5- to 20-cm layers, respectively. Under NT, the CVs of Al_{M3} concentration were 8.2 and 5.5% in the 0- to 5- and 5- to 20-cm layers, respectively. The (P/Al)_{M3} ratios across the three MP plots ranged from 0.90 to 21.80% in the 0- to 5-cm layer and from 0.74 to 2.72% in the 5- to 20-cm layer (Fig. 2c). In the three NT plots, the (P/Al)_{M3} ratios ranged from 1.25 to 16.62% in the 0- to 5-cm layer and from 0.45 to 14.51% in the 5- to 20-cm layer. The average (P/Al)_{M3} ratios in the 0- to 5-cm layer were 2.91 and 5.50% in MP and NT, respectively. In contrast, the (P/Al)_{M3} ratios in the 5- to 20-cm depth were similar between MP and NT and averaged 2.66%. Under MP, the CVs of the (P/Al)_{M3} ratio were 80 and 64% in the 0- to 5- and 5- to 20-cm layers, respectively. Under NT, the CVs of the (P/Al)_{M3} ratio were 43 and 67% in the 0- to 5- and 5- to 20-cm layers, respectively.

Spatial Prediction of Mehlich-3 Phosphorus

Anisotropy was not evident in the directional semivariograms of P_{M3} for any of the six studied experimental units and two depths. Therefore, isotropic models were fitted to the experimental semivariograms of P_{M3} concentrations across the six studied experimental plots and two depths. In the MP and NT plots, the pure nugget model was obtained as the dominant best fit for all except the 5- to 20-cm depth of the MP₃ plot and the 0- to 5-cm of the NT₁ plot, where exponential models best described the experimental semivariogram (Table 2). The semivariogram models displayed positive nugget effects, which may be a result of sampling errors, random inherent variability, or short-range variability. The degree of spatial dependence in the six studied plots and two depths was evaluated by the nugget/sill ratio. The nugget/sill ratio was 50% for the 5- to 20-cm depth in the MP₃ plot and 100% for the rest of the MP plots and depths. Similarly, the nugget/sill ratio was 41% for the 0- to 5-cm depth in the NT₁ plot and was 100% for the rest of the NT plots and depths. On average, spatial dependence was low in most plots except for MP₃ at 5 to 20 cm (Fig. 3) and NT₁ at 0 to 5 cm (Fig. 4), where moderate spatial dependence was obtained. The range, a measure of the spatial continuity between two sampling points, was determined only for the spherical model and equalled 125 cm for MP₃ at 5 to 20 cm and 127 cm for NT₁ at 0 to 5 cm (Table 2). All models were evaluated using cross-validation analysis (Table 2). The cross-validation coefficients of determination (*R*²) were 0.30 for MP₃ at 5 to 20 cm and 0.82 for NT₁ at 0 to 5 cm but were 0.0 for the other experimental units and depths. In addition, the root mean square error values were large and varied between 8.90 and 40.56 in the MP plots and between 18.56 and 29.32 in the NT plots, indicating poor model prediction.

Table 2. Semivariogram and kriging parameters describing the spatial variability of Mehlich-3 P concentrations at 0 to 5 and 5 to 20 cm layers of a corn-soybean rotation under moldboard plow (MP) and no-till (NT) soils.

Plot	Depth	N†	Semivariogram parameters							Kriging parameters			
			Model‡	Nugget (C ₀)	Partial sill (C)	Sill (C ₀ + C)	C ₀ /C ₀ +C	Spatial class§	Range	<i>R</i> ²	Cross validation		RMSE¶
											<i>R</i> ²		
	cm						%		cm				
Moldboard plow	MP ₁	0–5	83	PN	452	0	452	100	L	–	0	0.20	19.35
		5–20	83	PN	93	0	93	100	L	–	0	0.03	10.28
	MP ₂	0–5	83	PN	153	0	153	100	L	–	0	0.06	13.06
		5–20	83	PN	68	0	68	100	L	–	0	0.00	8.90
	MP ₃	0–5	83	PN	1644	0	1644	100	L	–	0	0.00	40.56
		5–20	83	Exp.	40	40	80	50	M	125	0.30	0.00	8.98
No-till	NT ₁	0–5	83	Exp.	200	285	485	41	M	127	0.82	0.08	20.11
		5–20	83	PN	298	0	298	100	L	–	0	0.04	18.56
	NT ₂	0–5	83	PN	733	0	733	100	L	–	0	0.03	28.79
		5–20	83	PN	748	0	748	100	L	–	0	0.01	29.32
	NT ₃	0–5	83	PN	752	0	752	100	L	–	0	0.01	28.35
		5–20	83	PN	490	0	490	100	L	–	0	0.01	23.03

† Sample size.

‡ Exp., exponential; PN, pure nugget.

§ L, random spatial dependence (>75%); M, moderate (25–75%); S, strong (<25%) (Oliver and Webster, 2014).

¶ RMSE, root mean squared error.

DISCUSSION

Mehlich-3 Phosphorus and Aluminum

We did not detect any differences in the horizontal distribution of P_{M3} on either side of the sowing rows in the 0- to 5- and 5- to 20-cm layers in the MP- and NT-managed plots (Fig. 5).

Fig. 3. Prediction map of the spatial distribution of Mehlich-3 P (P_{M3}) concentrations (mg kg^{-1}) in the 5- to 20-cm soil depth after 20 yr of moldboard plow management and maintenance phosphorus fertilization. The green bands represent six corn rows. The dark lines perpendicular to the green bands represent seven transects. The dark stars represent 83 sampling points.

Geostatistical semivariance analysis further supported this result, indicating a predominance of random spatial dependence in most of studied plots regardless of tillage management and soil depth. The semivariogram models displayed positive nugget effects, which may be a result of sampling errors, random inherent variability, or short-range variability.

Pure nugget and exponential models were defined for NT and MP, although the first model was predominant. Pure nugget models indicate that the P_{M3} concentration is not spatially correlated. The 2-D geostatistical semivariance analysis is in line with the general statistical analysis indicating that the horizontal distribution of P_{M3} concentration in these plots was less sensitive to extrinsic factors including tillage, P fertilization and depth. Random spatial dependence indicates a lack of structural variability and a predominance of random factors (Nyiraneza et al., 2011). Previous studies reported moderate spatial dependence for extractable P (Chang et al., 1999; Nyiraneza et al., 2011) using grid dimensions varying from 0.18 to 15 ha. The wide range obtained in MP_3 at 5 to 20 cm (Fig. 3) and NT_1 at 0 to 5 cm (Fig. 4) suggests the presence of some autocorrelation that limited the accuracy of predictions in the two types of tillage management. The occurrence of P_{M3} concentrations above critical agro-environmental levels (CRAAQ, 2010) can be observed in plots MP_3 at 5 to 20 cm (Fig. 3) and NT_1 at 0 to 5 cm (Fig. 4) in this site. However, considering the moderate spatial structure of P_{M3} it is difficult to derive based on our results any distribution pattern that could be generalized to other MP or NT sites. Nyiraneza et al. (2011) also found range values for P extracted with anion exchange membranes varying from 40 to 711 cm. For most model selections, the R^2 values indicated a poor fit regardless of the type of management. In this study, the cross-validation R^2 values were very low for MP and NT, regardless of depth. Therefore, the 2-D geospatial model related to fertilization and tillage mode was not detected by the sampling grid. The mismatches detected between the observed and predicted P_{M3} concentrations could be explained by the small sample size used in this study. We used 83 data points to construct the semivariograms, and Webster and Oliver (1992) indicated that semivariograms computed from fewer than 100 pieces of data are unreliable. The number of samples used in this study was limited by the small size of the experimental plots (25 m x 4.5 m) and the intensive sampling that is performed year to year for other studies (Messiga et al., 2012; Poirier et al., 2009; Shi et al., 2013).

Fig. 5. Horizontal distribution of Mehlich-3 P on either side of the sowing row at 0 to 5 cm (a) and 5 to 20 cm (b) in corn-soybean under moldboard plow (MP) and no-till (NT) soils. Soil samples were collected after harvest in fall 2012. Error bars represent standard deviation of the mean.

range of P budgets to include the variability associated with fertilization practices in cereal–legume rotations in Eastern Canada.

The absence of horizontal P_{M3} variability under NT could further be explained by the dynamics of the residual P fraction as assessed by P fractionation. Results obtained by Shi et al. (2013) in the same studied plots showed that the residual P fraction under P fertilization was less in the NT plots than in the MP plots after 16 yr of cultivation. Those authors concluded that over the long-term, the residual P fraction replenishes the solution P ions and therefore contributes to the greater labile P levels observed in the P-fertilized NT. A similar process occurs in P-unfertilized plots. Syers et al. (2008) found that even after decades of cropping without P additions, soils were still able to release measurable P and sustain agricultural production. Long-term studies on various soils showed that crop yield does not decrease over time without P fertilization, which supports the assumption of a greater presence of P in the solid phase (Messiga et al., 2012, 2015). The transfer of P ions at the solid–solution interface is controlled by rapid and slow reactions, with equilibration periods lasting up to 5 yr owing to solid-state and pore diffusion (Messiga et al., 2012, 2015). Therefore, as plant roots deplete the P on either side of the sowing rows not affected by the band-applied fertilizer P, the residual P fraction partly contributes to replenishing the labile P pool. This labile P pool is made up mainly of resin P and NaHCO_3 –inorganic P fractions, thus overshadowing the P_{M3} variability that could have been introduced by band-applied fertilizer P. Insight obtained from further studies

looking at the differential dynamics of residual P and labile P in the sowing row and on either side of it would be valuable.

The P_{M3} concentrations and $(P/Al)_{M3}$ ratio values and trends are also in line with previous studies conducted at this site and elsewhere that showed greater accumulations of soil test P in the topsoil of NT plots in comparison with MP plots, a process that is also described as P stratification. Messiga et al. (2010) used soil cores (0–5 cm) collected from this site in September 2007 and showed that after one and three freeze–thaw cycles, water-extractable P and P_{M3} concentrations were greater under NT than under MP. In another study considering the long-term impact of tillage practices and P fertilization on soil P status, Messiga et al. (2012) used samples collected in 2010 to highlight greater soil test P accumulations in the 0- to 5-cm depth under NT than under MP. Studies conducted at other sites on P distribution in the soil profile of fertilized NT plots also showed greater soil test P concentrations in the top 5-cm layer and, to some extent, down to 10 cm, as well as a depletion of P in sublayers where most of the roots develop (Cade-Menun et al., 2010; Lupwayi et al., 2006). In this long-term experiment, P fertilizers are band-applied in the NT plots, and the P budgets are close to equilibrium. This suggests that P accumulation at the soil surface across NT plots is due in part to P recycled by corn and soybean plants (Eckert and Johnson, 1985). The agronomic implications of P stratification in the soil profile of NT-managed soils are well documented and include reduced P uptake and lower crop yield due to the depletion of P in lower layers where plant roots develop (Lupwayi et al., 2006). Our results also suggest that there may be less need for starter P fertilizer in long-term NT management owing to the high available P levels in the 0- to 5-cm depth where the seeds are placed. The environmental implications of P stratification include enhanced P losses in runoff due to P concentrations in the topsoil that are above critical environmental risk values (Duiker and Beegle, 2006).

CONCLUSIONS

The 2-D distribution of P_{M3} concentrations with soil depth and perpendicularly to the seeding row did not show a spatial pattern in the NT and MP plots. Therefore, the 2-D geospatial model related to tillage mode was not detected by the sampling grid used in this experiment. The horizontal distribution of P_{M3} concentration in these plots was less sensitive to extrinsic factors including tillage, P fertilization and depth. It is possible that the mismatches between the observed and predicted P_{M3} concentrations could be explained by the small sample size used in this study. Interestingly, the P_{M3} concentrations were greater in the 0- to 5-cm layer than in the 5- to 20-cm layer in the NT plots. Given that P fertilizers are band-applied in the NT plots and that the P budgets are close to equilibrium in this long-term experiment, P accumulation at the soil surface across the NT plots is due in part to P recycled by corn and soybean plants and to the replenishment of the solution P ions by the residual P fraction. According to the sampling design used in this experiment, we conclude that NT and MP soil management requires the same sampling strategy for establishing P fertilization recommendations.

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