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Long term impact of tillage practices and biennial P and N fertilization on maize and soybean yields and soil P status

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ABSTRACT

The benefits of no till (NT) management in the short to medium terms need to be examined over decades of continuous cropping. Our objectives were to (i) assess the long term effects of tillage practices (no-till (NT) and mouldboard plough [MP]) and biennial P × N fertilizer rates applied to the maize phase of a two-year maize–soybean rotation on grain yield, Mehlich-3 P (P_{M3}), and Olsen P (P_{Ol}), and (ii) determine whether NT practice affects the relationships between P_{M3}, P_{Ol} and P budgets. The study site was established in 1992 on a clay loam soil of the St-Blaise series (Dark Grey Gleysol). The experimental design is a split plot with NT and MP assigned to main plots and nine combinations of 3 P (0, 17.5, and 35 kg P ha^{-1}) and 3 N (0, 80, and 160 kg N ha^{-1}) additions assigned to subplots. Maize and soybean grain yield response to P additions was obtained only twice between 1992 and 2010. On average, grain yields were reduced by 10–25% in NT compared to MP treatments in 11 years. The dynamics over years of P_{M3} and P_{Ol} (0–15 cm) in unfertilized P treatment was similar in NT and MP. In contrast, P fertilized NT maintained greater P_{M3} and P_{Ol} than MP. This difference in soil tests P was due to greater P accumulation in the 0–5 cm and 5–10 cm soil layers of NT. Under MP, soil tests P and P budgets over the P treatments were linearly related and for this specific MP treatment, we calculated that a P budget of ±100 kg P ha^{-1} would change P_{M3} by 12 kg ha^{-1} and P_{Ol} by 7 kg ha^{-1}. Under NT, a cubic model fitted closely to the experimental data due principally to a more than proportional change in soil tests P relative to P budgets in fertilized P treatments. We conclude that additions of P fertilizer in NT systems changes the dynamics of P in the rooting zone, suggesting the importance of approaches to monitor P dynamics specifically tailored for NT systems that integrates the variability caused by the absence of mixing the fertilizer, residues, and soil.

1. Introduction

Conservation tillage practices (e.g. no-till, NT) have become increasingly common in recent years. No-till is widely used under various rotation systems (Duiker and Beegle, 2006; Kelley and Sweeney, 2007; Kimmell et al., 2001) and monoculture (Borges and Mallarino, 2000). The benefits of NT production systems (Lafond et al., 2011; Mallarino et al., 2009; Messiga et al., 2011) and economic performance (Holm et al., 2006) are well recognized.

One major constraint of NT management systems, however, is the stratification of P and other nutrients with depth (Cade-Menun et al., 2010; Mallarino and Borges, 2006; Robbins and Voss, 1991). Stratification produces high concentrations of P at the soil surface (0–5 cm) but decreasing concentrations lower in the soil profile. Phosphorus accumulation at the soil surface is the result of minimal mixing of surface-applied fertilizers and crop residues with soil, limited vertical movement of P in most soils, and cycling of P from deep soil layers to shallow layers through nutrient uptake by roots and deposition from crop residues (Borges and Mallarino, 2000). Phosphorus stratification in NT is of concern because lower concentrations at depth in the rooting zone may reduce crop yields (Lupwayi et al., 2006) and high concentrations near the soil surface increase the runoff of dissolved P (Sharpley and Smith, 1994).

In eastern Canada, soil sampling in agricultural soils for fertilizer recommendations is made at 0–17.5 cm soil depth [Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ, 2003, 2010)]. In conventionally tilled management systems, this soil layer is homogeneous due to mixing of applied fertilizers, crop

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residues, and soil. For maize (*Zea mays* L.) production in conventionally tilled systems in eastern Canada, P fertilizer recommendation is based on Mehlich-3 soil P saturation index (PSI) or the ratio of P to aluminium (Al) in the Mehlich-3 soil test [$(P/Al)_{M3}$] (Pellerin et al., 2006). For soils with adequate soil P [$(P/Al)_{M3}$ ratios of 0.04], maize grain yield response to P fertilizer is usually not significant and P additions lower than P removal may be applied without any significant grain yield loss (Pellerin et al., 2006). The lack of maize response to P fertilizers in conventionally tilled soils with adequate P is common to various soil types (Mallarino et al., 1991; Wortmann et al., 2009).

Soybean (*Glycine max* L. Merr.) behaves as a P-mining crop even in low-P soils (Pellerin et al., 2006). Yet, soybean response to P fertilizer application is infrequent in eastern Canada and farmers are reluctant to apply P fertilizers to soybean when cropped in rotation with maize or other field crops (CRAAQ, 2003, 2010). In other areas, however, the lack of soybean grain yield response to P fertilizer is usually associated with soils with high initial soil test P (Borges and Mallarino, 2000; Wittry and Mallarino, 2004).

Several long term studies on unfertilized and fertilized conventionally tilled soils under field crops have shown that soil test P change in the rooting zone is linearly related to the P budget (Boniface and Trocmé, 1988; Messiga et al., 2010a; Zhang et al., 1995). In some soils, however, two relationships are observed, one for positive and one for negative P budget values (Ciampitti et al., 2011). For such soils, the rates of P accumulation with excess P and depletion with P deficit are different. It has also been shown that different initial soil P status will result in different rates of decrease in soil test P for a unit P deficit (Power et al., 2005; Zhang et al., 2004). Soils with high initial soil test P will show a steep decline in soil test P with a unit deficit P budget compared to soils with low initial soil test P (Giroux et al., 2002).

These observations were mainly made on conventionally tilled soils with homogenous P distribution in the ploughed layer. Whether these relationships remain true for P stratified NT soils is still not clear. Indeed, in NT soils the majority of studies have been focussing only on the benefits of this management practice on P retention in soils through reduction of losses through water and wind erosion (Messiga et al., 2011; Sharpley and Smith, 1994), the influence of the resulting P stratification on surface soil P movement (Blevins et al., 1990; Kimmell et al., 2001), and the distribution of P forms and chemistry in the soil profile (Cade-Menun et al., 2010). The objectives of this study were to (i) assess the long term effects of tillage practices (NT and mouldboard plough [MP]) and biennial P × N fertilizer rates applied to the maize phase of a two-year maize–soybean rotation on grain yield and soil tests P (P_{M3} and Olsen P [P_{Ol}]), and (ii) determine whether NT practice affects the relationships between P budgets and soil test P.

2. Materials and methods

2.1. Site description

The long-term crop rotation experiment was established in 1992 at the L'Acadie Research Station (45°18′N; 73°21′W), Agriculture and Agri-Food Canada. The soil of this field was a deep clay loam soil (364 g kg^{-1} of clay and 204 g kg^{-1} of sand in the Ap horizon) of the St-Blaise series (Dark Grey Gleysol). This deep soil originated from a fluvial deposit and evolved from a fine–textured greyish-to-brown parent material. The soil was tile-drained with slope less than 1% and was cropped with alfalfa (*Medicago sativa*) before 1992. Chemical characteristics of the topsoil (0–15 cm) at the onset of the experiment were, on average: organic matter 38 g kg^{-1}, Mehlich-3 P 135 kg P ha^{-1}, PSI 4.3%, and pH_{water} 6.3 (Légère et al., 2008; Tremblay et al., 2003). The mean annual temperature at the study site is 6.3 °C with 1100 mm of total annual precipitation.

2.2. Experimental design and treatments

The experimental design was a split plot with NT and MP assigned to main plots and nine fertilization combinations consisting of three N (0, 80, and 160 kg N ha^{-1}) and three P (0, 17.5, and 35 kg P ha^{-1}) levels assigned to subplots. Experimental treatments were replicated in four blocks, with individual plots measuring 25-m long and 4.5-m wide. From 1992 to 1994 plots were maintained under continuous maize production. Since 1995, a two-year soybean and maize rotation was practiced. The MP treatment consisted of one MP operation in the fall after harvest to a depth of 20 cm, followed by disking and harrowing to 10 cm each spring before seeding. For the NT treatment, plots were ridge tilled from 1992 to 1997 and flat direct seeded from 1998 onward. For direct seeding, crop residues were left on the ground after harvest. The nine fertilization combinations (N × P) were applied annually between 1992 and 1994. Thereafter, fertilizer application was made only to the maize phase of the rotation according to local recommendation. Fertilizers were band-applied (5 cm from the seeding row) using a disk opener (3–4 cm deep). The P treatments were applied in a single application at planting as triple super phosphate (0–46–0). An initial portion of the N treatments were band-applied at seeding in additions of 0, 48, and 48 kg N ha^{-1} as urea, and with additions of 0, 32, and 112 kg N ha^{-1} side-dressed as ammonium nitrate to reach the target recommendation (0, 80, and 160 kg N ha^{-1}), at approximately the eight-leaf stage.

There were six rows by sub-plot unit and maize was sown at 74×10^3 and soybean at 45×10^4 plants ha^{-1}. Soybean seeds were inoculated with a commercial granular formulation of *Bradyrhizobium japonicum*. Herbicides were selected according to provincial recommendations; the rate for each crop has been similar since 1992 (Légère et al., 2008). Herbicide and cultivar were used based on local recommendations (Conseil des Productions Végétales du Québec (CPVQ, 1992); CRAAQ, 2003, 2010).

2.3. Soil sampling and measurements

To study soil P status changes, soil cores were sampled from 2001 to 2008 in the arable layer (0–15 cm) between the rows in each plot in spring before fertilizer application and sowing. Four soil cores were composited per experimental plot in plastic bags, then air dried, passed through a 2 mm sieve and stored at room temperature. Soil P status was determined using two soil test P indicators. Mehlich-3 extractable P was determined on all samples by shaking 2.5 g of soil with a 25 mL of Mehlich-3 solution (pH 2.3) for 5 min (Mehlich, 1984) and the concentrations were assessed with an Inductively Coupled Plasma Optical Emission Spectrometer (Optima 4300 DV, PerkinElmer Corp., Norwalk, CT). Olsen extractable P was determined on all samples by shaking 1.0 g of soil with 20 mL of 0.5 mol L^{-1} sodium bicarbonate solution (pH 8.5) for 30 min (Olsen et al., 1954; Morel et al., 2000) and the concentrations were determined by the malachite green method (van Veldhoven and Mannaerts, 1987) using a spectrophotometer (Jenway 6320D) (at 610 nm) with a 1-cm long optical cell.

Soil pH, Al, and total P were determined only in soil samples collected in 2003 and 2006. Soil pH was measured in distilled water with a 1:2 soil:solution ratio (Hendershot et al., 1993). Aluminium was determined in Mehlich-3 extracts with an Inductively Coupled Plasma Optical Emission Spectrometer (Optima 4300 DV, PerkinElmer Corp., Norwalk, CT). Total soil P concentration was determined on samples collected in 2006 using a method adapted from Nelson (1987). Briefly, 0.1 g of finely ground soil (0.2 mm) was mixed in a 50-mL boiling flask with 0.5 g $K_2S_2O_8$ and 10 mL 0.9 M