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Surface-spring-applied compost replenishes plant available phosphorus, but crop uptake depends on soil moisture

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Abstract

Supplying phosphorus (P) to crops on organic farms with low soil test P (STP) remains a major challenge. This study evaluated surface-spring-applied compost effects on spring wheat (*Triticum aestivum* L.) grown under low STP (3 ppm) conditions over 3 years in Manitoba, Canada. Compost application increased grain yield and P uptake in wet but not in drought conditions, where plant-available P remained unattainable to the crop and drought reduced P uptake efficiency (34% vs. 79%). Despite poor crop uptake under drought, spring-applied compost increased mid-season STP, demonstrating that surface-applied compost at time of seeding was effective at replenishing STP.

Key words: broadcasted compost, deficient Olsen-P, wheat, organic production, P infiltration, P cycling

1. Introduction

Plant available phosphorus (P) levels on Canadian organic prairie grain farms are often extremely low (Welsh et al. 2009). On calcareous, high pH soils, the plant-available P pool is measured using Olsen-P extractants (referred to the soil test P (STP)). Correcting P deficiencies (under 5 ppm Olsen-P) is critical for continued productivity of organic farms. Composted cattle manure (referred to as compost throughout) is a popular P source in organic production (Brock et al. 2021), since the composting process reduces volume and increases P concentration compared to raw manure (Zvomuya et al. 2006). Due to cost, large-scale dryland organic farms add compost only to replenish P deficiencies; nitrogen (N) is supplied with legume green manures in rotation (Brock et al. 2021).

Timing and method of compost application are important considerations to optimize nutrient availability in tandem with crop demand while minimizing environmental loss. Compost is known to release a significant portion of its P to the plant-available P pool in the first year after application; up to 71% (Eghball et al. 2002). Similarly, when composted manure was incubated with soil for 2 weeks, 53% of total P was present in plant-available forms (Gagnon et al. 2012).

However, P availability from compost is dependent on incorporation method, soil type, temperature, and moisture (Loecke et al. 2004; Gagnon et al. 2012). For example, Shuai et al. (2014) demonstrated that P availability can decline with time following application, whereas Loecke et al. (2004) reported greater corn yield response to fall-applied composted swine manure compared with spring application. In Manitoba, significant wheat yield responses to cattle compost have been observed in the year of application when compost was tilled in prior to spring seeding (Nicksy et al. 2022).

However, minimizing soil disturbance is an important goal in dryland farming to conserve soil moisture (Halde and Entz 2016), particularly in dry seeding conditions. Soil moisture heavily influences crop P uptake, Brown et al. (2017) reported increased soil moisture resulted in greater P uptake in wheat but not greater N uptake. This raises an important question: how effective is spring-applied compost when it is not soil-incorporated and how do prevailing weather conditions affect its efficacy?

Therefore, the first objective of this study was to evaluate spring wheat (*Triticum aestivum* L.) response to broadcast-applied compost under extremely low STP (3 ppm) conditions and a second objective was to examine how drought versus nondrought conditions influence soil P replenishment and subsequent crop uptake.

2. Materials and methods

2.1. Field experiment

A brief description of the experiment is provided here; a full description is provided by Carkner and Entz (2024). The experiment took place from 2020 to 2022 in Libau, Manitoba (50°24′01″N, 96°72′95″W) in a new location on the farm in each year. The soil was a Gleyed Rego Black Chernozem in the Dencross series (Soil Classification Work-

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ing Group 1998). The experiment was a randomized complete block design with two factors (genotype and compost application) with three replicates in 2020 and four replicates in 2021 and 2022. For our objectives, one spring wheat genotype (cv. *5602HR*) was selected from the larger experiment.

The site had been organically managed since 2008 and continuously hayed with no fertilizer application since 2006. The crop prior to each experimental year was a green manure mixture that was incorporated with a field cultivator at full flower (approximately mid-August). The following year, seedbeds were prepared using a field cultivator and heavy diamond harrows prior to seeding. Seeds were sown into moist soil using a disk drill with 15 cm row spacing (Fabro Industries, Swift Current, SK) at a target plant population of 350 live plants m^{-2}. Seeding dates were 7 May, 28 April, and 24 May in 2020, 2021, and 2022, respectively. Experimental units were 0.61 m × 6 m in 2020, and 1.5 m × 6 m in 2021 and 2022. Two rows of fall rye (*Secale cereale* L. cv. *Hazlet*) were seeded between each experimental unit. Spring wheat border plots were seeded on either side of each replicate to avoid edge effects. The nutrient status of the applied composts (7.7 g kg^{-1} N, 6 g kg^{-1} P in 2020, and 29 g kg^{-1} N, 7 g kg^{-1} P in 2021 and 2022) were determined by Agvise Laboratories (North Dakota, USA). Compost was surface applied prior to or just after seeding at a rate of 25 kg available P ha^{-1}, assuming 50% P availability (50 kg P ha^{-1} as applied) (Eghball et al. 2002). No compost was applied to the control plots. Experimental units were harvested using a Hege plot combine (Hege model 125, Waldenburg, Germany) and dried on forced air beds for 72 h. Harvest took place on 19 August, 11 August, and 10 September in 2020, 2021, and 2022, respectively.

Grain samples were cleaned using a Carter Day dockage tester (model 31624/W-3301) with sieve size 0.26–0.28 cm × 1.98 cm.

Spring soil samples for the initial site characterisation were taken prior to seeding using a Dutch auger at 0–15 and 15–30 cm depth in each year. In all years, soils were low in STP (3–4 ppm), adequate in N (24.5–28.5 ppm), and high pH (8.1–8.4) (Supplementary Table S1). Consistent grain protein concentration increases under control versus compost treatments in a related study (Carkner and Entz 2024) established that P was the yield-limiting nutrient. A second soil sampling (denoted as mid-season) in the 0–15 cm soil zone occurred on 8 July, 5 July, 15 July in 2020, 2021, and 2022, respectively.

2.2. Plant biomass and phosphorus determination

Plant biomass was sampled at stem elongation, anthesis, and the hard dough (mature) stage at ground level. Samples were dried at 70 °C for 36 h and weighed. Dried threshed mature biomass samples were finely ground (1 mm) using a Wiley mill (Thomas Scientific, Pennsylvania, USA). Grain samples were a composite sample of harvested grain of each experimental unit and finely ground (1 mm). Ground subsamples of straw and grain for total P concentration were analyzed by Agvise Laboratories in North Dakota, USA. Total plant P accumulation represents mature straw and grain P accumulation combined. Olsen-P ppm was converted to land-based kg P ha^{-1} based on the assumption of 15 cm soil depth, and a bulk density of 1.2 g cm^{-3}. Phosphorus uptake efficiency (PuptE) represents net total plant P accumulation (kg ha^{-1}) per P that was assumed to be available to the crop based on indigenous soil tests and applied compost P availability (kg ha^{-1}) (eq. 1).

$$\text{PUptE (\%)} = \frac{\text{Total plant P accumulation}}{\text{Total land} - \text{based soil P (Indigenous and added)}} \times 100 \quad (1)$$

2.3. Data analyses

Data were analyzed using PROC Mixed with Statistical Analysis Software program 9.4 with years combined to detect compost effects and year × compost interactions. Compost was a fixed effect, and replicate (year) and year were random effects. Significant compost × year interactions were further investigated by analyzing years separately. PROC Univariate and Shapiro–Wilks statistic were used to detect normality. Values greater than 0.9 were assumed to be normally distributed. Differences among compost levels were tested using the least significant difference test and considered significant at $P < F$ 0.05.

3. Results and discussion

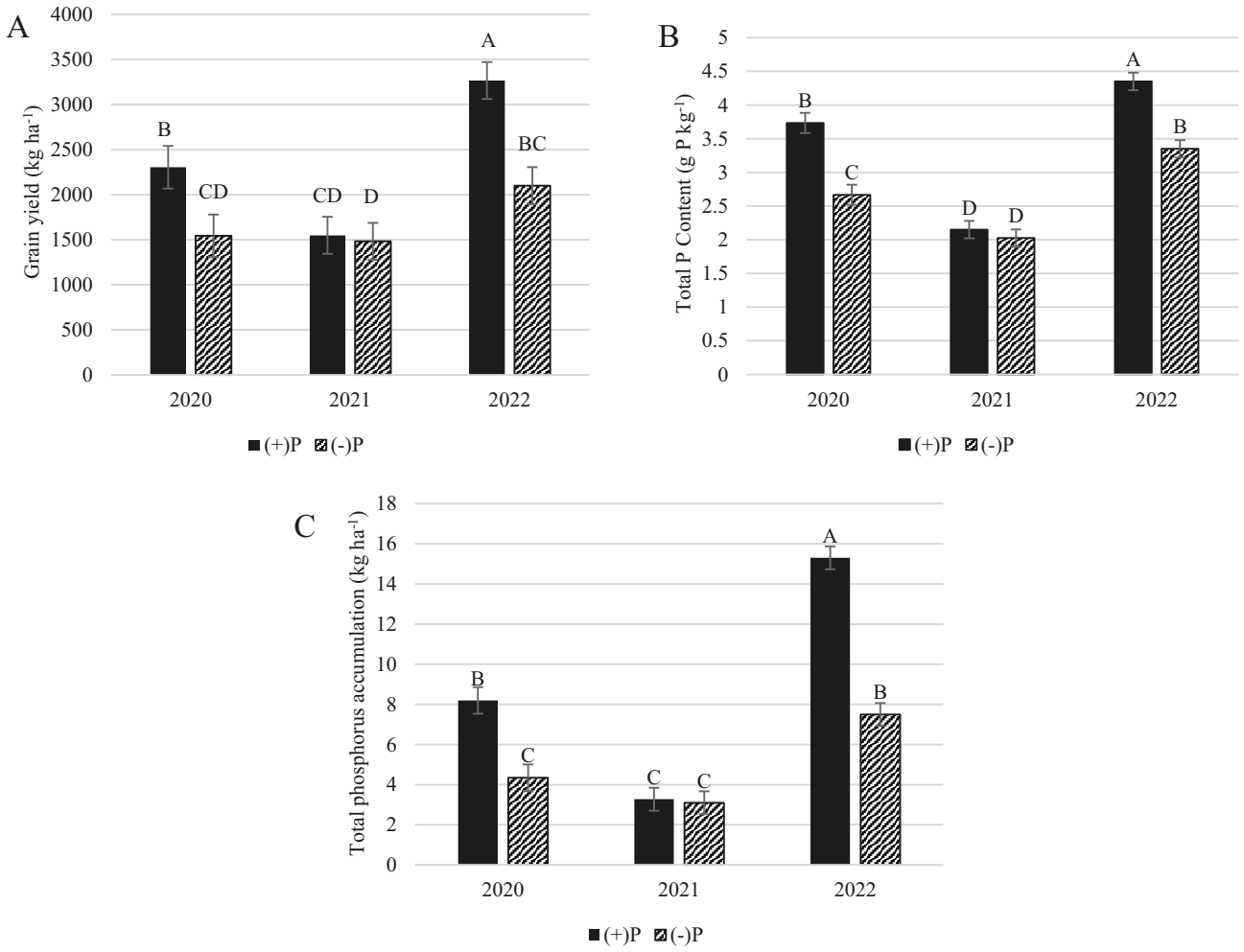
3.1. Environmental conditions

Seasonal precipitation and temperature data were obtained through the Selkirk weather station maintained by Manitoba Agriculture (50°17′71″N, 96°79′28″W) (Supplementary Table S2). From May to August, the experiments received approximately 66%, 62%, and 125% of 30-year average rainfall in 2020, 2021, and 2022, respectively. In 2021, drought caused widespread crop failure in the area (Manitoba Agriculture 2022). Precipitation occurred 3 weeks after seeding and a significant rainfall event took place at stem elongation; however, no precipitation occurred from stem elongation to maturity.

3.2. Crop yield and P uptake in response to compost application

Averaged over all years, compost application significantly increased anthesis biomass (by 1689 kg ha^{-1}) and grain yield (Supplementary Table S3). Grain yields ranged from 1425 to 3267 kg ha^{-1}, comparable to Nicksy et al. (2022) who worked at the same site on low STP soils. A compost × year interaction ($P = 0.044$) revealed that the yield response was

Fig. 1. (A) Compost × year interaction of spring wheat grain yield, (B) compost × year interaction of spring wheat total phosphorus content, and (C) compost × year interaction of spring wheat total phosphorus accumulation from 3 years (2020, 2021, and 2022) collected under organic conditions in Libau, Manitoba from under limited soil test Olsen-P (3 ppm). (−)P, unamended control; (+)P, compost amended at 50 kg P ha^{-1}. Means followed by the same letter are not significantly different within groups of treatments by an Analysis of variance test ($P \leq 0.05$).



significantly less pronounced in 2021 compared to 2020 and 2022 (Fig. 1A). Precipitation from May to July was 336 mm higher in 2022 than 2021, leading to the interaction.

Total plant P content ranged from 2.1 to 4.4 g P kg^{-1} (Fig. 1B). Total plant P accumulation ranged from 3.2 to 15.3 kg ha^{-1} overall (Fig. 1C; Supplementary Table S3), higher than a similar study in the region which ranged from 6.3 to 10.7 kg ha^{-1} (Nicksy et al. 2022). Phosphorus plant content and accumulation response to compost varied significantly depending on year (compost × year interaction, $P \leq 0.0001$) (Figs. 1B and 1C). No response in either P content or accumulation was observed under drought conditions in 2021, whereas a significant response to compost was detected in 2020 (increase of 5.7 kg ha^{-1}, respectively), with the largest difference in 2022 (increase of 12.1 kg ha^{-1}) for P accumulation (Fig. 1B). Compost increased plant P content in 2020 and 2022 by 1 g P kg^{-1} (Fig. 1B). PuptE was greatest in 2022 (79%), and lowest in 2021 (34%) (Supplemental Table S3). Phosphorus uptake in wheat is proportional to water availability, which could be related to greater root growth and movement of P into the roots via mass flow (Clarke et al. 1990; Brown et al. 2017); these findings reinforce the critical role of precipitation in facilitating P uptake.

We conclude that under adequate moisture conditions, surface- and spring-applied compost at seeding increased yield and P uptake of organic wheat grown on very P deficient soils, but wheat did not respond to compost under extreme drought conditions. Therefore, our results provide a practical guide to P management in dryland organic wheat systems.

3.3. Disconnect between P movement into soil and crop uptake under wet versus drought conditions

The evidence presented in this study clearly shows that spring-applied compost did not increase wheat yield under drought conditions. Based on this outcome, we tracked downward movement of P and uptake in the soil–plant system when compost was used under adequate moisture versus

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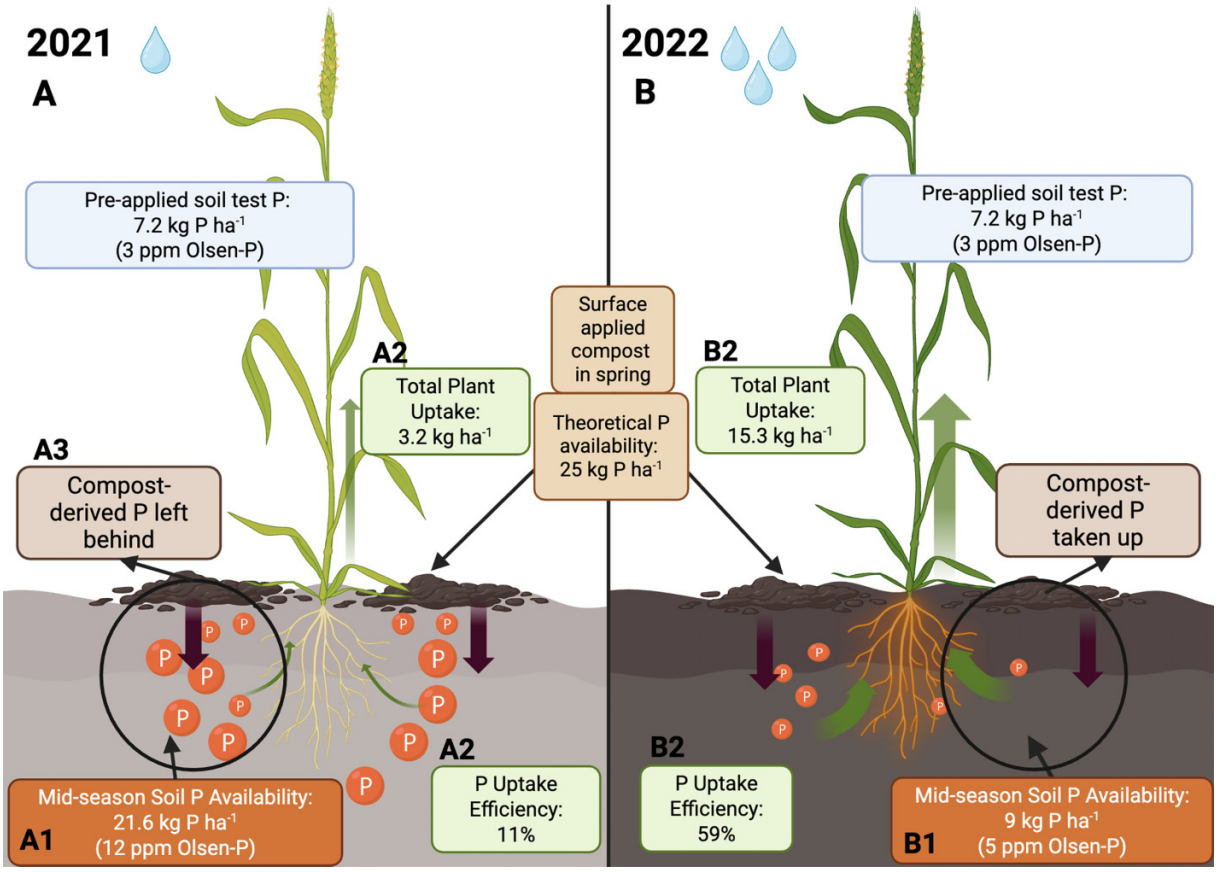
Fig. 2. A schematic description of the stranded-P hypothesis under drought (A) and wet (B) conditions. Under deficient P conditions, when compost is surface and spring-applied, infiltration is possible under drought conditions in 2021, demonstrated by high mid-season available P (A1). However, crop uptake was arrested (poor plant P accumulation and P uptake efficiency (A2)), thereby leaving P in the soil (A3). In contrast, under wet conditions in 2022, mid-season soil P availability was reduced (B1) because P was taken up by the crop as demonstrated by higher plant P accumulation and higher P up-take efficiency (B2). P, phosphorus. Created in BioRender.com



drought conditions. To elucidate the relationship between compost-derived soil P replenishment, growing season precipitation, and crop P uptake, we measured STP prior to application and at mid-season, and total plant P accumulation.

Field experiments conducted in 2021 and 2022 were located on the same soil type (approximately 100 m apart), had identical initial STP levels (3 ppm Olsen-P), and the same compost source. Consequently, growing season precipitation was the only difference between field experiments. In both years, mid-season STP did not change in the control treatments, whereas compost application increased STP. In 2021, compost increased STP to 12 ppm Olsen-P, while in 2022 STP increased to 5 ppm Olsen-P (Supplementary Table S1).

In both years, the theoretical P availability from compost was estimated at 25 kg P ha^{-1}. In the wet year of 2022, mid-season compost-applied STP was 5 ppm Olsen-P (equivalent to 9 kg P ha^{-1}, based on 15 cm soil depth, and a bulk density of 1.2 g cm^{-3}) (Fig. 2). STP was lower than the estimated available P, suggesting substantial crop uptake as evidenced by total plant P accumulation of 15.3 kg P ha^{-1} (Fig. 1B).

In contrast, during the drought year of 2021, mid-season STP level was 12 ppm Olsen-P (21.6 kg P ha^{-1}). Elevated STP suggests that compost-derived P moved downward into the soil despite dry conditions. Two precipitation events (16.8 and 37.4 mm) occurred within 6 weeks of compost application in 2021 and were likely sufficient to facilitate P movement into the soil profile. However, despite a sizeable pool of plant available P at anthesis in 2021, wheat uptake was constrained. Plant P accumulation in 2021 was only 3.2 kg P ha^{-1}, compared with 15.3 kg P ha^{-1} in 2022, and the estimated PuptE was 11% versus 59% in the wetter year (Fig. 2). Poor P accumulation in 2021 was related to the lack of precipitation between stem elongation and maturity. Therefore, early season precipitation increased STP from compost-derived P, but later-season moisture limitations restricted crop access, leaving P in the soil.

Support for this interpretation is provided by Eichler-Löbermann et al. (2007), who reported strong correlations between compost application and available soil P fractions (r = 0.73–0.77) but weaker correlations with P uptake and grain yield (r = 0.38–0.44). Although this P is likely available

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for subsequent crops as legacy P, year-2 uptake was not assessed in the present study.

In summary, our study provides information on the P flows from compost in an organic wheat production system with minimal spring tillage. Surface-applied compost alleviated P deficiency under high moisture conditions. However, under drought, compost-derived P moved downward into the soil but was not taken up by wheat, leaving P behind.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Visualization: MKC
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Competing interests

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjps-2025-0228.

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