NRC Research Press

ARTICLE

Short-term legacy effects of feedlot manure amendments on irrigated barley yield and soil macronutrient supply

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Abstract: Limited research exists on short-term legacy effects of land application of different feedlot manures on barley (*Hordeum vulgare* L.) yield and soil macronutrient (NO_3-N, PO_4-P, K, and SO_4-S) supply. In a study conducted in southern Alberta, feedlot manures with straw (ST) or wood-chip (WD) bedding were either stockpiled or composted and applied annually to a clay loam soil at 13, 39, and 77 Mg ha^{-1} dry wt. for 17 yr. Control treatments without any amendments or with inorganic fertilizer were included. In the second and third year (2016–2017) after discontinuing manure applications in 2014, barley silage yield and soil nutrient supply measured in situ with plant root simulator (PRS®) probes were determined. No significant ($P > 0.05$) treatment effects occurred on barley yield. Significant treatment effects occurred on soil nutrient supply, but these depended on date and interaction with other treatment factors. Manure rate generally increased soil nutrient supply. Soil NO_3-N and PO_4-P supply were 40%–59% lower for composted manure with ST than the other three manure type-bedding treatments, and they were 26%–53% greater for stockpiled than composted manure. This indicated variable manure type effects at different dates. At the two highest rates, soil K supply was 60%–106% greater for ST than WD bedding, and the reverse trend occurred where SO_4-S supply was 40%–174% greater for WD than ST bedding. Overall, short-term legacy effects of feedlot manure type and bedding were more persistent on soil macronutrient supply than barley silage yield.

Key words: feedlot manure type, bedding material, nitrogen, phosphorus, potassium, sulfur.

Résumé : Peu de recherches ont été entreprises pour établir les effets prolongés à court terme de l'épandage de différents types de fumier sur le rendement de l'orge (*Hordeum vulgare* L.) et sur la concentration de macronutriments (N-NO_3, P-PO_4, K, S-SO_4) dans le sol. Les auteurs ont entrepris une étude dans le sud de l'Alberta durant laquelle ils ont appliqué annuellement du fumier de bétail empilé ou composté contenant de la litière de paille (ST) ou des copeaux de bois (WD) sur un loam argileux à raison de 13, de 39 ou de 77 Mg de poids sec par hectare pendant 17 ans. L'expérience incluait un traitement témoin sans amendement ni application d'engrais minéral. La deuxième et la troisième année (2016–2017) après qu'on a arrêté d'épandre du fumier, en 2014, les chercheurs ont mesuré le rendement de l'ensilage d'orge et la concentration d'éléments nutritifs dans le sol *in situ* au moyen de sondes Plant Root Simulator (PRS®). Le traitement n'a aucun effet significatif ($P > 0{,}05$) sur le rendement de la céréale. En revanche, ses effets sur la quantité d'éléments nutritifs présents dans le sol sont significatifs, dépendamment de la date et de l'interaction d'autres paramètres du traitement. En général, le taux d'application du fumier augmente la réserve de nutriments dans le sol. La concentration de N-NO_3 et de P-PO_4 dans le sol est 40 à 59 % plus faible avec le fumier ST composté qu'avec les trois autres types de fumier, et est 26 à 53 % plus importante quand le fumier est empilé plutôt que composté. On en conclut que les effets varient avec la nature du fumier et la date. Au deux taux d'application les plus importants, la concentration de K dans le sol était 60 à 106 % plus élevée avec le fumier ST qu'avec le fumier WD; on observe la tendance inverse pour le S-SO_4, dont la concentration est 40 à 174 % plus élevée pour le fumier WD que pour le fumier ST. Dans l'ensemble, les effets prolongés à court terme du type de fumier et de litière sont plus persistants pour la réserve de macronutriments du sol que pour le rendement de l'orge fourragère. [Traduit par la Rédaction]

Mots-clés : type de fumier, litière, azote, phosphore, potassium, soufre.

Received 28 May 2018. Accepted 5 February 2019.

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Introduction

The termination of long-term application of feedlot manure to irrigated barley grown for silage may result in short-term (<10 yr) legacy effects on soil macronutrient (N, P, K, and S) supply and crop yield during the postapplication period. Legacy effects of manure may occur because of slow decomposition of soil organic matter and release of nutrients, as well as greater inputs of crop residues from higher yields (Larney et al. 2016). We are unaware of any studies on the short-term legacy effects of long-term application of stockpiled or composted feedlot manure containing straw (ST) or wood-chip (WD) bedding applied at increasing application rates on crop yield and soil macronutrient supply during the postapplication phase.

Some studies have reported significant legacy effects of manure application on crop yield compared with unamended control (CON) or inorganic fertilizer (IN) treatments (Wallingford et al. 1975; Mugwira 1979; Lund and Doss 1980; Wen et al. 2003; Larney and Olson 2018). In contrast, others found no significant legacy effects of feedlot manure application on crop yields (Eghball et al. 2004; Larney and Olson 2018), or found significant effects on ST but not grain yield (Indraratne et al. 2009).

Most studies have generally reported significant legacy effects of manure application on soil macronutrients (N, P, K, and S) and other related soil biological and chemical properties (Dormaar and Chang 1995; Ginting et al. 2003; Eghball et al. 2004; Hao et al. 2004, 2008; Indraratne et al. 2009; Larney and Olson 2018; Zhang et al. 2018). Eghball et al. (2004) concluded that short-term legacy effects of feedlot manure or compost application on soil properties were more persistent than on crop production. Based on the previous literature, our expectation was that significant treatment effects might occur on dry matter (DM) yield and soil macronutrient supply during the short-term legacy period.

Considerable research has been conducted on the effect of continual, annual applications of stockpiled or composted feedlot manure with ST or WD bedding on DM yield of barley at a long-term field experiment at Lethbridge, AB (Miller et al. 2004, 2009, 2015), macronutrient (N, P, and S) concentrations in the surface soil (Miller et al. 2005, 2010, 2012*a*, 2012*b*, 2016*a*), and N mineralization and nitrification (Miller et al. 2010, 2012*a*, 2012*b*, 2018*a*; Sharifi et al. 2014). But the possible short-term legacy effect on DM yield and soil macronutrient supply rates after termination of 17 annual applications of these feedlot amendments has not been studied at this Lethbridge site.

Composting or decomposition of organic matter generally decreases the total N content of feedlot manure because of volatilization and runoff losses (Eghball et al. 1997). In contrast, concentrations of total P, K, and soluble salts (e.g., SO_4) generally increase or remain constant during composting because these elements are relatively immobile and not subject to gaseous losses, runoff is minimal, and there is a concentration effect because of reduced mass of DM (i.e., loss of soil organic C as CO_2 during the composting process). Stockpiling of feedlot manure in temporary piles before land application is generally considered an intermediate stage of decomposition between fresh manure and fully composted manure (Larney et al. 2006). Based on the amendments, soil N supply might be greater for stockpiled- than composted-amended soils, and soil P, K, and S supply might be similar or greater for composted- than stockpiled-amended soils. Barley ST bedding generally has a greater content of total N, NO_3-N, total P, available P, and water-soluble K and SO_4-S than WD bedding (Miller et al. 2003). Therefore, manure-amended soils might have a greater nutrient supply for ST than WD bedding during the legacy phase.

The overall objective of our study was to determine if legacy effects of long-term manure application occurred on barley yield and soil macronutrient supply over the short term. The secondary objectives were to examine treatment effects of manure type, bedding material, application rate, and amended versus unamended treatments on yield and macronutrient supply during the legacy period. The study was conducted at a long-term site at Lethbridge, AB, where the historical focus was on continual annual applications. Termination of continuous applications of all amendments in 2014 provided an opportunity to study the legacy effects of manure on crop and soil.

Materials and Methods

Study design

A long-term field experiment with a randomized complete block, factorial design began in the fall of 1998 on a clay loam (29% clay and 42% sand) Dark Brown Chernozemic (Typic Haplustoll) soil at the Lethbridge Research Centre in southern Alberta, Canada. A detailed description of the site and experimental design has been previously reported (Miller et al. 2004, 2009). The organic C content of unamended (control) surface (0–15 cm) soil is approximately 16.4–17.3 g kg^{-1} (Miller et al. 2017*a*).

The NO_3-N (0–60 cm) and soil test P (0–15 cm) content of the unamended CON soil in 1999, 1 yr after the manure applications were initiated in 1998, has been previously reported (Miller et al. 2010). They found that KCl-extractable NO_3-N in the CON treatment (18 mg kg^{-1}) was already close to the maximum recommended agronomic limit (21 mg kg^{-1}) in Alberta, whereas soil test P (<10 mg kg^{-1}, Kelowna extract) was six times below the proposed maximum agronomic limit (60 mg kg^{-1}).

Water-extractable K (7.3 mg kg^{-1}) and SO_4-S (27.0 mg kg^{-1}) in the surface (0–15 cm) soil of the unamended CON treatment in 2013 have also been previously reported (Miller et al. 2016*a*), but there are no agronomic limits for these water-extractable nutrients.

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The majority of unamended soils in Alberta generally contain sufficient plant-available K to satisfy crop growth (McKenzie and Pauly 2013). Irrigated soils in southern Alberta generally contain adequate S for optimum crop growth because irrigation water contains about 30 kg SO_4-S ha^{-1} for every 30 cm depth of irrigation water applied (McKenzie 2013).

The treatment factors were two manure types (stockpiled vs. composted feedlot manure), two bedding materials (ST vs. WD), and three application rates (13, 39, and 77 Mg ha^{-1}). There were also an unfertilized CON and an inorganic fertilizer (IN) treatment, and all 14 treatments were replicated four times. No IN was co-applied with the manure-amended treatments. The IN treatment consisted of 100 kg N ha^{-1} as NH_4NO_3 (34–0–0) and 17 kg P ha^{-1} as triple superphosphate (0–46–0). The fertilizers were annually broadcast and incorporated (≈8 cm depth) separately but on the same date in the spring prior to seeding. Fertilizers were applied on 19 and 20 Apr. in 2016 and 2017, respectively. The feedlot manure was applied annually for 17 yr (1998–2014) and then discontinued thereafter. Therefore, our study of 2 yr legacy period in 2016 and 2017 was 2–3 yr after the last manure application in 2014. The IN treatment, however, was continuous every year from 1998 to 2017, which included the legacy period of postmanure applications (2015–2017).

The beef cattle manure originated from a research feedlot at the Lethbridge Research and Development Centre that utilized practices similar to commercial feedlots (Miller et al. 2003). The diet of the beef cattle for the feeding period (200 d) generally consisted of 70% barley silage and 30% barley grain for the backgrounding (initial) period (70–80 d), followed by 85%–90% barley grain and 10%–15% barley silage for the remainder of the feeding period (100–120 d). Fresh beef feedlot manure was stockpiled for up to 2 mo before land application, and some previous studies on this same experiment refer to the stockpiled manure as fresh manure. Feedlot manure was composted by the windrow method (Larney et al. 2003). The windrows were turned about seven times during a 90 d period (active phase), with a subsequent curing phase (no turning) for 90–120 d.

The ST bedding was unchopped barley ST from local producers near Lethbridge. The WD bedding was a mixture of 50% fine sawdust and 50% wood chips, bark, and post peelings. The WD were obtained from Sundre Forest Products (West Fraser Mills Ltd.®) in Sundre, AB, Canada. The trees were a 4:1 mixture of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and white spruce [*Picea glauca* (Moench) Voss]. The feedlot manure amendments applied to the plots were about a 4:1 ratio of manure to bedding material (Larney et al. 2008).

The application rates of 13–77 Mg ha^{-1} (dry wt.) were selected to elicit treatment responses on soil and crop and were generally similar to actual rates used by commercial feedlots. Olson et al. (2010) applied feedlot manure with ST bedding to a Dark Brown Chernozemic soil (loam) in southern Alberta at N-based rates of 9–23 Mg ha^{-1} (dry wt.) for stockpiled manure and from 36 to 55 Mg ha^{-1} for composted (windrow) manure. The 13 Mg ha^{-1} rate in our study was the only rate that was similar or lower than their agronomic N-based rate, whereas the 39 and 77 Mg ha^{-1} rates were generally greater (i.e., excess rates) than their N-based rates for this area.

Feedlot manure was annually applied to plots in the fall (late October to late November) and incorporated to 20 cm depth using an offset-disc cultivator. Irrigated, six-row feed barley grown for silage was seeded on all plots each year since 1999. The barley cultivars were 'Duke' grown from 1999 to 2004, 'Kasota' grown from 2005 to 2007, and 'Vivar' grown from 2008 to 2017. The crop was seeded between 15 May and 17 May in 2016 and 2017. It was harvested between 2 Aug. and 9 Aug. (2016–2017) as silage at the soft-dough stage, or Zadock's growth stage 85, at between 60% and 70% moisture content. Aboveground DM yields of barley were determined using a silage harvester, with subsequent oven-drying of a subsample at 60 °C for 7 d.

Triplicate cation and anion plant root simulator (PRS®) probes containing ion exchange membranes were installed (with no root exclusion cylinder) in the surface soil (3.0–8.5 cm depth) of each of the 56 plots for 1 wk periods in 17–24 June and 20–27 July 2016, and in 12–19 June 2017. The PRS probe consists of an ion-exchange membrane 1.6 cm wide × 5.5 cm length that is encapsulated in a 2.8 cm wide × 15.5 cm long plastic casing. Incubations during June (31–38 d after seeding) 2016 coincided with the stem elongation stage of cereal growth, incubations in July (64–71 d after seeding) 2016 with heading–ripening stages, and incubations in June (28–35 d after seeding) 2017 with tillering – stem elongation stages. After incubation, the PRS probes from all three experiments were removed, cleaned, rinsed with distilled water, and shipped to the Western Ag Innovations laboratory for analysis. Nitrate-N was analyzed by colorimetry using an automated flow injection analysis system, and PO_4-P, SO_4-S, and K were analyzed using inductively coupled plasma (ICP) spectrometry (ICP-OES 8300®, Perkin Elmer, Waltham, MA, USA) method (Soltanpour et al. 1996). Although ICP measures total P and S, PO_4-P and SO_4-S are the dominant ions adsorbed by the PRS probes.

Plant roots can compete with PRS probes for mobile nutrients such as NO_3. Soil N supply using PRS probes under vegetation with active plant roots may be lower compared with when root exclusion cylinders are used. Our method of installing PRS probes in vegetated soil with active roots during the growing season was consistent with previous studies on N supply (Bair et al. 2008; King 2015; Miller et al. 2017*b*).

Daily precipitation was obtained from an Agriculture and Agri-Food Canada weather station <330 m from the

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field experiment. Irrigation of the barley crop was applied using a wheel move, sprinkler system, and all treatments received the same amount of water during a single irrigation event. Total precipitation and irrigation 30 d prior to PRS probe installation was greatest in July 2016, followed by June 2016, and June 2017 (Table 1). The total rainfall and irrigation applied during the PRS incubation period (1 wk) was greatest in June 2017, followed by June 2016, and then July 2016. The irrigation applied during the incubation period was greatest in June 2016, followed by June 2017, and then July 2016. No irrigation was applied in July 2016 because of the higher-than-normal precipitation received 30 d prior to PRS installation.

Data analysis

Two separate MIXED model analyses (SAS Institute Inc. 2005) as previously used (Miller et al. 2004, 2009) were conducted. The first analysis determined the effect of all 14 individual treatments, including the CON and IN treatments, on the dependent variables (crop yield and macronutrient supply). Estimate statements (quantitative contrasts) were also used to compare manure-amended versus unamended CON and IN treatments. The second analysis determined the effect of the main treatment factors (manure type and bedding) on the dependent variables. The CON and IN treatments were omitted from this analysis, as there was only one level of these factors. A Least Significant Difference test was used to identify significant ($P \leq 0.05$) differences among the treatments. If required, dependent variables were log-transformed prior to analysis to meet assumptions of normality. Pearson's correlation analysis ($P \leq 0.05$) was used to assess possible relationships between the macronutrients and DM yield.

Results and Discussion

Barley DM yield

Dry matter yields in 2016 ranged from 7.1 to 8.3 Mg ha^{-1} for the manure-amended treatments and were 7.3 Mg ha^{-1} for the CON and 7.9 Mg ha^{-1} for the IN treatment (data not shown). In 2017, DM yields ranged from 6.9 to 9.1 Mg ha^{-1} for the manure-amended treatments and were 6.0 Mg ha^{-1} for the CON and 8.0 Mg ha^{-1} for the IN treatment. There were no significant ($P > 0.05$) treatment effects of manure type, bedding, rate, or interaction effects on DM yields in 2016 and 2017 (data not shown). Previous studies on this same experiment also reported no yield response to these treatments after one to three continuous applications (Miller et al. 2004) and nine continuous applications (Miller et al. 2009), but after 12 continuous applications, DM yields were significantly lower for composted manure with WD than the other three manure type-bedding treatments and were greater for ST-13 and WD-77 compared with WD-13 treatment (Miller et al. 2015).

Table 1. Total precipitation and irrigation for the 30 d period prior to PRS installation and during the PRS installation period (1 wk incubation) for the two sampling dates in 2016 and one sampling date in 2017.

Time period	June 2016 (mm)	July 2016 (mm)	June 2017 (mm)
Total 30 d prior to incubations	99.5	184.5	75.2
Total during incubation (irrigation during incubation)	38.8 (38.1)	25.6 (0)	55.3 (25.4)
Total	138.3	210.1	130.5

There were no significant differences in DM yields among the 14 treatments in 2016 and 2017, and the estimate comparisons showed no significant differences between manure-amended versus unamended CON or IN treatment for each year (data not shown). Although not significant, the DM yields were still greater for the manure-amended treatments than the CON by 0.5 Mg ha^{-1} ($P = 0.57$) in 2016 and by 1.9 Mg ha^{-1} ($P = 0.07$) in 2017. The finding of similar DM yields for amended and unamended treatments during the short-term legacy period was in contrast to the continuous application phase, in which DM yields were generally greater for amended than unamended treatments (Miller et al. 2004, 2009, 2015).

No significant legacy effects of manure on DM yield may have been due to climatic, soil, and crop factors influencing crop yield potential (Havlin et al. 1999), low nutrient uptake by the crop, the inherently high soil organic matter and high soil nutrient levels, as well as manure-induced soil salinity. Chang et al. (1993) reported that the timing and amount of precipitation in the current and previous year were important in determining barley response to manure treatments. Sharifi et al. (2014) also reported that increased soil N mineralization at the 39 and 77 Mg ha^{-1} rates during the continuous period of this experiment did not translate into greater barley yield or N uptake. They attributed this to the abundant soil N supply and high proportion of mineral N inherent in these Dark Brown Chernozemic soils, and the high soil electrical conductivity (EC) of soils amended at higher rates (close to crop tolerance threshold). Eghball et al. (2004) also reported high corn yields on an unamended Mollisol with about 29 g kg^{-1} organic C. Therefore, the nutrient supply from soils with inherently high soil organic matter content may be sufficient to maximize DM yield by mineralization of soil nutrients such as N, P, and S.

Miller et al. (2016*a*) reported that the EC of the surface (0–15 cm) soil after 15 annual applications of amendments for the two higher application rates ranged from 2.3 to 7.0 dS m^{-1} and was 0.8 dS m^{-1} for the CON and 1.5 dS m^{-1} for the IN treatment. The salt tolerance

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Table 2. Treatment factor effects on nutrient supply rates of NO_3-N, PO_4-P, K, and SO_4-S in a surface clay loam soil in 2016 and 2017 after 17 annual applications (until 2014) of feedlot amendments followed by 2 (2016) and 3 (2017) yr of no applications.

	Prob > F[a]											
	NO_3-N			PO_4-P			K			SO_4-S		
Treatments	June 2016	July 2016	June 2017	June 2016	July 2016	June 2017	June 2016	July 2016	June 2017	June 2016	July 2016	June 2017
Type (T)	**	***	NS	NS	NS	***	**	NS	**	NS	NS	NS
Bedding (B)	NS	NS	NS	NS	NS	NS	***	***	***	***	***	***
Rate (R)	***	**	**	*	***	***	***	***	***	**	***	*
T × B	*	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS
T × R	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
B × R	NS	*	NS	NS	NS	NS	NS	NS	*	*	***	NS
T × B × R	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
Estimate[b]												
CON vs. AMEND	−271***	−79.6**	−166**	−71.8**	−44.8***	−141***	−106.3***	−105.4***	−104.9***	−55.5*	−20.8**	−21.0NS
IN vs. AMEND	−226***	−74.6**	−59.7NS	−56.0*	−42.1***	−116***	−107.1***	−105.4***	−105.1***	−34.0NS	−28.2***	−18.3NS

Note: The unamended control (CON) and inorganic (IN) fertilizer treatments were omitted for factorial analysis because there was only one level of these treatments. Estimate comparisons are also shown for CON and IN treatments versus manure-amended (AMEND) treatments. T, manure type (SM, stockpiled manure; CM, composted manure); B, bedding (WD, wood-chip bedding; ST, straw bedding); R, application rate (13, 39, and 77 Mg ha^{-1} dry basis). NS, not significant.

[a]Prob > F for MIXED model analysis of variance analysis. Significant treatment effect at 0.05 (*), 0.01 (**), and 0.001 (***) levels.

[b]Estimate comparison values are significantly different at the 0.05 (*), 0.01 (**), and 0.001 (***) probability levels. Estimate values are negative when unamended CON or IN treatments are less than AMEND treatments, and are positive when CON or IN are greater than AMEND treatments.

Table 3. Influence of application rate on nutrient supply of NO_3-N, PO_4-P, K, and SO_4-S for a clay loam soil in 2016 after 17 annual applications of feedlot amendments and 1 yr of no application.

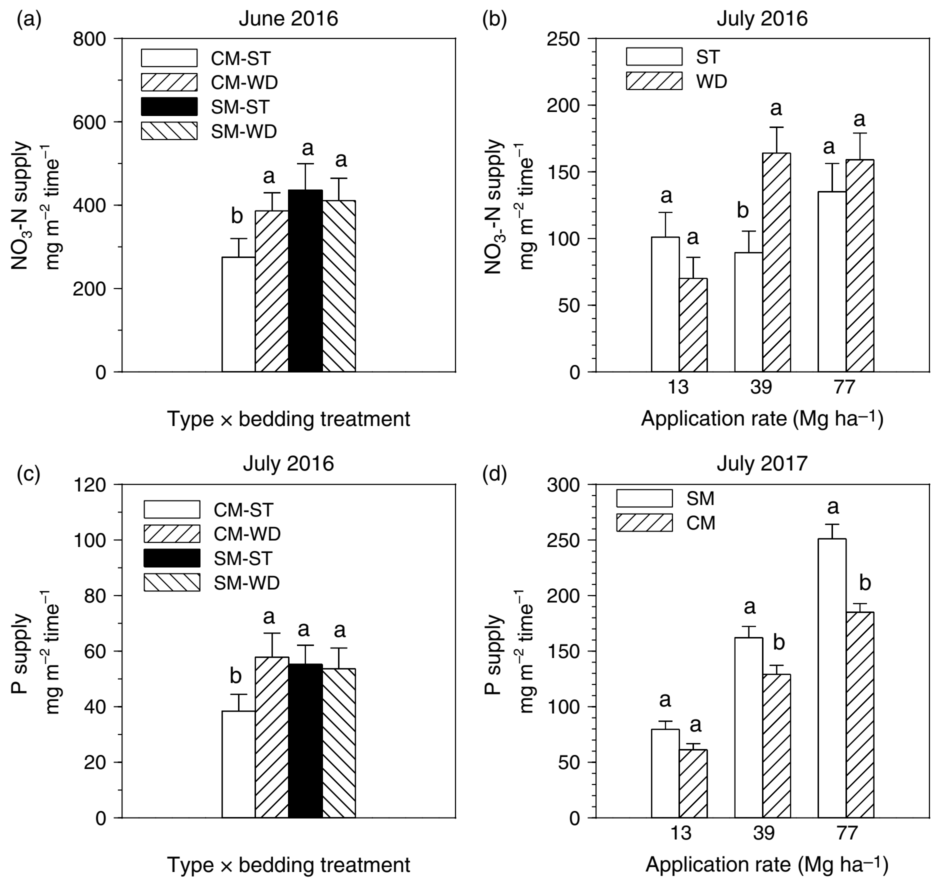
Application rate (Mg ha^{-1})	NO_3-N (mg m^{-2} wk^{-1})		PO_4-P (mg m^{-2} wk^{-1})		K (mg m^{-2} wk^{-1})	SO_4-S (mg m^{-2} wk^{-1})
	June 2016	June 2017	June 2016	July 2016	July 2016	June 2017
13	202 ± 17.8c	220 ± 23.0b	47.7 ± 6.5b	25.4 ± 3.7b	233 ± 24.8c	74.4 ± 7.8b
39	380 ± 34.0b	319 ± 26.9a	97.8 ± 12.9a	61.5 ± 5.1a	705 ± 51.5b	97.6 ± 7.7a
77	548 ± 35.5a	346 ± 28.1a	79.3 ± 13.2ab	66.9 ± 4.8a	1003 ± 63.8a	95.2 ± 6.3a

Note: Values are the means ± standard error. Within a column, means not sharing a lowercase letter differ significantly at the $P < 0.05$ level.

threshold for barley is 8.0 dS m^{-1} for chloride-dominant soils (Maas 1990), but more recent research for sulfate-dominated systems has found that barley yield can decline by 15% at EC of 5.0 dS m^{-1} (Steppuhn and Raney 2005). Wallingford et al. (1975) applied extremely high rates (123–529 Mg ha^{-1} dry wt.) of beef feedlot manure to a silty clay loam soil, and they found that corn-forage yields were improved at lower and medium rates but declined at higher rates because of salt injury. Although no soluble salts were added to the manure-amended treatments during the legacy period, it is still possible that the legacy effects of manure on soil salinity may have persisted into the legacy period.

Our finding of no significant legacy effect of manure on DM yields was consistent with some other studies (Eghball et al. 2004; Larney and Olson 2018). The former authors found no manure treatment effects on corn yield for a silty clay loam soils 2–4 yr after the last manure application following four annual applications. Larney and Olson (2018) reported no manure treatment effects on spring wheat grain yields on a non-eroded loam to clay loam soil 3–20 yr after the last manure application. In contrast, others have reported significant amendment treatment effects on yield during legacy periods on silty clay loam (Mugwira 1979), loamy sand to sandy loam soils (Lund and Doss 1980), loam to sandy loam soils (Wen et al. 2003), clay loam soils (Drury et al. 2014), and loam to clay loam soils (Larney and Olson 2018). Others found a significant legacy effect on ST but not grain yield after a 16 yr legacy period on clay loam soil (Indraratne et al. 2009). Some studies, however, also reported improved crop yields despite relatively high (14–21 g kg^{-1}) soil organic C (Wen et al. 2003; Drury et al. 2014).

Fig. 1. Influence of manure type × bedding on NO_3-N supply in June 2016 (*a*), bedding × rate effect on NO_3-N supply in July 2016 (*b*), type × bedding on P supply in July 2016 (*c*), and type × rate effect on P supply in July 2017 (*d*). Vertical bars are means plus 1 standard error. Different lowercase letters above the vertical bars indicate significant differences ($P \leq 0.05$) among treatments.



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Nitrate-N

Significant ($P \leq 0.05$) treatment effects on NO_3-N supply (Tables 2 and 3; Figs. 1*a* and 1*b*) indicated persistence of short-term legacy effects of manure. There was a significant manure type effect on NO_3-N supply in July 2016 (Table 2), where mean values were 53% greater for stockpiled (145 ± 13.7 mg m^{-2} wk^{-1}) than composted manure (94.7 mg m^{-2} wk^{-1}). The finding of greater NO_3-N supply for stockpiled than composted manure in July 2016 was consistent with more readily available and intermediate mineralizable N, and N turnover rate in the soil for stockpiled than composted manure after 8 yr during the application phase of this same experiment (Sharifi et al. 2014). It was unlikely that greater soil water content for stockpiled than composted treatment increased NO_3-N supply because manure type generally had little or no effect on volumetric soil water content of surface soils after 15–17 continuous applications (Miller et al. 2018*b*). It should be noted that this trend was not consistent with the amendment composition that had 32% greater NO_3-N content for composted than stockpiled manure (Miller et al. 2009). The different trends in NO_3-N supply for the soil and amendment may have been caused by masking of the amendment effect by incorporation into the soil and subsequent N transformations in the soil. These N transformations may have included mineralization, immobilization, nitrification, leaching, plant uptake, and denitrification (Havlin et al. 1999). In addition, inherently high soil NO_3-N and mineral N (Sharifi et al. 2014) in the unamended CON soil may have contributed to masking of amendment effects. It is unlikely that denitrification contributed to greater NO_3-N supply for stockpiled than composted manure because maximum daily denitrification rates were 97% greater for stockpiled than composted manure with ST bedding (Miller et al. 2012*a*). Leaching of NO_3 was also an unlikely cause because NO_3-N in leachate at 30 cm depth was similar for composted and stockpiled manure with ST bedding (Miller et al. 2011). Greater N uptake by the crop was probably not a contributing factor because crude protein uptake was greater for stockpiled than composted manure (Miller et al. 2015).

Application rate had a significant effect on NO_3-N supply in June 2016 and 2017 (Table 2). As expected, mean values in June 2016 were greatest for 77 Mg ha^{-1} rate,

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followed by 39 Mg ha^{-1} rate, and then 13 Mg ha^{-1} rate, and all three means were significantly different (Table 3). Mean values in June 2017 were significantly greater at 39 and 77 Mg ha^{-1} rates than at 13 Mg ha^{-1} rate. The positive influence of application rate on NO_3-N supply was attributed to more total N and NO_3-N applied in the amendments at higher rates.

Qian and Schoenau (2000*a*) also reported that application rate of liquid swine manure to soils increased available N supply (PRS) during the application phase, but the increase in NO_3-N supply was not proportional to the increase in application rate. They suggested that excessive rates may increase the C:N ratio of soil, resulting in N immobilization, and soil N mineralization may be slower at higher than lower rates. Hammermeister et al. (2003) found that mean NO_3-N supply during the application phase was significantly greater at the higher rate of amendment application compared with two lower rates for four of eight sampling times.

There was a significant type × bedding interaction on NO_3-N supply in June 2016 (Table 2), where mean values were significantly lower for composted manure with ST compared with the other three manure type-bedding treatments by 40%–59% (Fig. 1*a*). This finding was not consistent with the trend in NO_3-N content of the amendments (Miller et al. 2009) but may be more reflective of the subsequent mineralization rates years after the amendments were applied. Greater N uptake for composted manure with ST than the other three manure type-bedding treatments during the continuous period (Miller et al. 2009) may have also contributed to lower NO_3-N for this treatment.

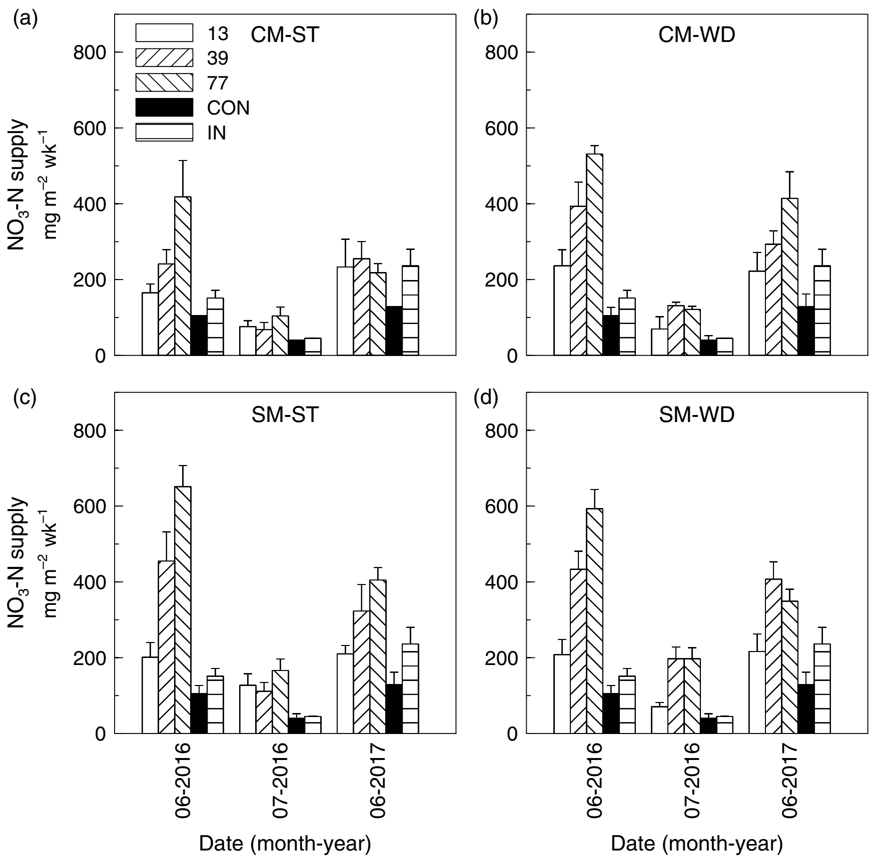
There was also a significant bedding × rate effect on NO_3-N supply in July 2016 (Table 2). Mean values were significantly greater by 1.8 times for WD than ST at 39 Mg ha^{-1} rate but were similar for the two bedding materials at 13 and 77 Mg ha^{-1} rates (Fig. 1*b*). This finding was unexpected because the ST amendment had greater NO_3-N (by 45%) and C:N ratio (by 55%) than the WD amendment, suggesting a greater potential for N immobilization with WD (Miller et al. 2009). In addition, soil NO_3-N concentration was generally greater for ST than WD (Miller et al. 2010; Sharifi et al. 2014), and soil N mineralization and nitrification was greater for ST than WD (Sharifi et al. 2014; Miller et al. 2018*a*). Significantly greater NO_3-N transport through the soil (0–30 cm) under ST than WD (Miller et al. 2013*b*), and greater protein (N) crop uptake for ST than WD in certain years during the continuous period (Miller et al. 2015) may have contributed to greater NO_3-N supply in the surface soil for WD than ST at the 39 Mg ha^{-1} rate in July 2016.

Nitrate-N supply in the surface soil was generally significantly greater for the manure-amended than unamended CON and IN treatments (estimate comparisons) for all three dates during the legacy phase (Table 2). The one exception was in June 2017 when it was similar for manure-amended and IN treatments. This was surprising because KCl-extractable NO_3-N concentrations in the unamended CON (in 1999) were already close to the agronomic limit (Miller et al. 2010). But it is possible that soil NO_3-N levels were considerably lower in the CON in 2016 and 2017 than in 1999. Greater NO_3-N supply for manure-amended than IN treatments was likely due to continual N mineralization and nitrification in the manure-amended soils. Similar findings have previously been reported for NO_3-N during the legacy phase (Wallingford et al. 1975; Mugwira 1979; Indraratne et al. 2009; Larney and Olson 2018), but some have found no legacy effects (Eghball et al. 2004).

Nitrate-N supply for the four manure type-bedding treatments declined during the growing season of 2016 and then was higher in June 2017 (Fig. 2). A decrease in NO_3-N supply during the growing season of 2016 was likely due to crop depletion of NO_3-N from the soil solution, and lower soil water content caused by increasing crop water use during the growing season. Johnson et al. (2007) reported that vegetation decreased N supply by plant uptake, and maximum rates of N uptake by barley occur at stem elongation (Malhi et al. 2006). King (2015) also reported a decline in soil NO_3-N supply during the growing season in a Black Chernozemic soil where solid cattle manure was applied using different methods. It is also possible that greater percolation of NO_3 below the surface soil by irrigation during the growing season, and increased denitrification immediately after irrigation or heavy rainfall events, may have also contributed to a decrease in NO_3-N supply over time. It is unlikely that reduced nitrification over the growing season contributed to this trend as soil NH_4-N supply, which is a major factor influencing nitrification (Havlin et al. 1999), was below detection limits in June and July of 2016. The greater soil NO_3-N supply in June 2017 was likely related to higher soil water content during the incubation period (Table 1), as well as increased mineralization and nitrification during the postharvest period in the fall of 2016 and preseeding period in the spring of 2017.

The NO_3-N supply at the 13 Mg ha^{-1} application rate for the four manure type-bedding treatments was not significantly different from the IN treatment for all three sampling dates. This suggested that the 13 Mg ha^{-1} rate, which was closest to the agronomic N-based rate, supplied soil NO_3-N that was similar to that for IN. In contrast, soil NO_3-N supply at application rates of 39 and 77 Mg ha^{-1} was generally significantly greater than the IN treatment, suggesting a potential for excessive soil NO_3-N supply and subsequent losses by leaching and denitrification. Similar findings were reported for NO_3-N concentrations in the soil profile (0–1.5 m) during the continuous application period (Miller et al. 2010). In comparison, Olson et al. (2010) reported annual N-based agronomic rates for feedlot manure (ST bedding) to a Dark Brown Chernozemic soil at Lethbridge that ranged from 9 to 23 Mg ha^{-1} (dry wt.) for stockpiled manure and from 36 to 55 Mg ha^{-1} for composted manure with ST bedding.

Fig. 2. Mean NO_3-N supply at three sampling dates (June and July 2016, June 2017) in a clay loam soil amended with 13, 39, and 77 Mg ha^{-1} (dry wt.) of composted manure with straw (CM-ST) treatment (*a*), composted manure with wood-chips (CM-WD) treatment (*b*), stockpiled manure with straw (SM-ST) treatment (*c*), and stockpiled manure with wood-chips (SM-WD) treatment (*d*). Nitrate-N supply rates for the unamended control (CON) and inorganic fertilizer (IN) treatments are also presented.



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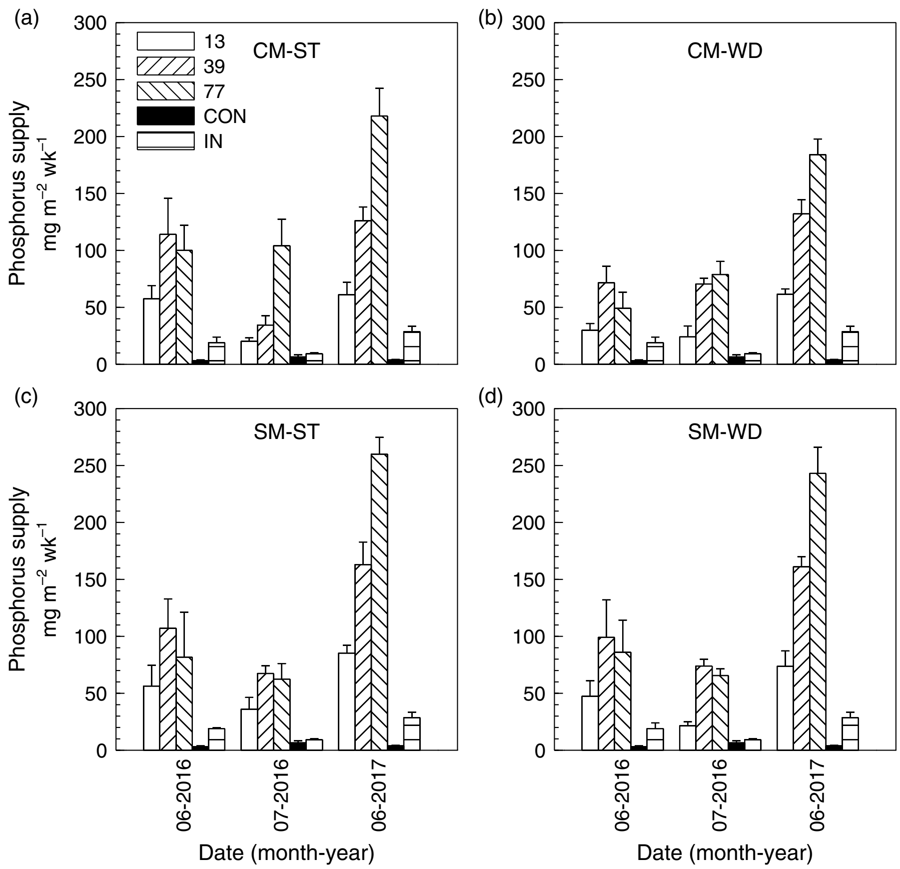
Phosphorus (PO_4-P)

Significant treatment effects on PO_4-P supply during the postapplication period indicated that legacy effects of manure still persisted. Application rate had a significant effect on PO_4-P supply in June and July 2016 (Table 2). Mean PO_4-P supply in June 2016 did not follow the same trend as for application rates, and was greatest for 39 Mg ha^{-1} rate, followed by 77 Mg ha^{-1} rate, and then 13 Mg ha^{-1} rate (Table 3). Mean values in July 2016 were significantly greater for 77 and 39 Mg ha^{-1} rates than the 13 Mg ha^{-1} rate as would be expected (Table 3). Other studies using PRS probes have reported a significant rate effect of amendment on PO_4-P supply during the application phase (Hammermeister et al. 2003), or no application rate effect during this phase (Qian and Schoenau 2000*b*; Stumborg and Schoenau 2008).

Similar to NO_3-N supply, there was a significant type × bedding effect on PO_4-P supply in July 2016 (Table 2), where mean values were significantly lower for composted manure with ST than the other three manure type-bedding treatments by 40%–51% (Fig. 1*c*). This finding was not consistent with the trend of available P in the amendments (Miller et al. 2009). Lower P supply for composted manure with ST may have been due to the higher P sorption index of this treatment in finer (<0.47–2.0 mm) aggregate sizes (Miller et al. 2012*b*), which may have reduced available P. In addition, significantly greater P uptake by barley for composted manure with ST than the other three manure type-bedding treatments after nine continuous applications (Miller et al. 2009) may have been a contributing factor.

There was also a significant type × rate effect on PO_4-P supply in July 2017 (Table 2) where mean values were significantly greater for stockpiled than composted manure at the two highest rates by 26%–36% (Fig. 1*d*). This was not consistent with the amendments where available P was similar for stockpiled (4.0 g kg^{-1}) and composted manure (4.2 g kg^{-1}) types (Miller et al. 2009). This finding may have possibly been due to masking of amendments by the soil and subsequent P transformations (mineralization, immobilization, adsorption, desorption, dissolution, precipitation, plant uptake, and leaching) in the soil (Havlin et al. 1999). It is unlikely that plant uptake, sorption, and leaching contributed to greater P supply for stockpiled than composted manure because P crop uptake, P sorption, and P in leachate were generally similar for these two manure types (Miller et al. 2009, 2011, 2012*b*).

Fig. 3. Mean PO_4-P supply in a clay loam soil at three sampling dates (June and July 2016, June 2017) amended with 13, 39, and 77 Mg ha^{-1} (dry wt.) of composted manure with straw (CM-ST) treatment (*a*), composted manure with wood-chips (CM-WD) treatment (*b*), stockpiled manure with straw (SM-ST) treatment (*c*), and stockpiled manure with wood-chips (SM-WD) treatment (*d*). The PO_4-P supply rates for the unamended control (CON) and inorganic fertilizer (IN) treatments are also presented.



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Mean PO_4-P supply was significantly greater for amended than unamended CON or IN treatments (estimate comparisons) for all three dates (Table 2). This positive treatment response was consistent with low soil test P in the unamended CON treatment (Miller et al. 2010). Similar findings have been reported for available P of amended surface soils during postapplication periods on silty loam (Eghball et al. 2004) and clay loam soils (Hao et al. 2008; Indraratne et al. 2009), whereas contrasting findings were found on a loam to clay loam soil by Larney and Olson (2018).

The PO_4-P supply for the four manure type-bedding treatments was relatively low and constant during the growing season of 2016 and then was higher in June 2017 (Fig. 3). The low and constant PO_4-P supply during the growing season was not consistent with the maximum rate of P uptake by barley occurring at the tillering to stem elongation stages (Malhi et al. 2006). Low and constant PO_4-P supply in June and July 2016 suggested low but continual P mineralization from the manure, limited P uptake by the barley during the growing season, or both. In addition, the interaction of soil water with various factors controlling PO_4-P supply in soil may have been a contributing influence. Soil moisture is a major factor influencing macronutrient supply for PRS probes in soil because diffusion paths become shorter and less tortuous (Qian and Schoenau 2002). It is also possible that the losses of soil P by crop uptake may have been offset by mineralization of organic P, resulting in low and constant soil PO_4-P supply during the growing season of 2016. King (2015) also reported a decline in PO_4-P supply to PRS probes during the application phase in manure-amended soils. The higher PO_4-P supply in June 2017 may have been due to greater precipitation and irrigation during the incubation period (Table 1), mineralization of organic P during the fall and early spring when no crop was growing, dissolution from P mineral compounds, and desorption of P from minerals.

The PO_4-P supply at the 13 Mg ha^{-1} application rate for the four manure type-bedding treatments was not significantly different from the IN treatment for all three sampling dates. This suggested that the 13 Mg ha^{-1} application, which was closest to agronomic N-based rate, supplied soil P that was similar and closest to IN. In contrast, the PO_4-P supply at application rates

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of 39 and 77 Mg ha^{-1} was generally significantly greater than the inorganic treatment, suggesting a potential for excessive soil P supply and subsequent possible losses by surface runoff and leaching. Similar findings were also reported for soil test P concentrations in the soil profile after nine continuous applications (Miller et al. 2010). In comparison, Olson et al. (2010) reported annual agronomic P-based rates for feedlot manure (ST bedding) to a Dark Brown Chernozemic soil at Lethbridge that ranged from 0.8 to 7.2 Mg ha^{-1} (dry wt.) for stockpiled manure and from 3.6 to 5.4 Mg ha^{-1} for composted manure. They also had to co-apply inorganic N fertilizer with P-based rates of manure to meet annual crop N requirements.

Potassium

Significant treatment effects on K supply during the postapplication period was evidence that legacy effects of manure still persisted. There was a significant type × bedding × rate effect on K supply in June 2016 (Table 2). Mean K values at 13 and 77 Mg ha^{-1} were significantly greater for stockpiled and composted manure with ST treatments compared with WD treatments (Fig. 4*a*). Mean K values at 39 Mg ha^{-1} were significantly greater for composted manure with ST treatment than the other three manure type-bedding treatments and were consistent with this amendment having the highest water-extractable K content (Miller et al. 2016*a*). Manure type effects were evident at 13 Mg ha^{-1} where K supply was significantly greater for composted than stockpiled manure with WD and also at 39 Mg ha^{-1} where K supply was significantly greater for composted than stockpiled manure with ST.

A significant bedding × rate effect occurred for K supply in June 2017 (Table 2), where mean values were significantly greater for ST than WD by 60%–106% at all three rates (Fig. 4*b*). There was also a significant type × bedding effect on K supply in June 2017 (Table 2), where mean values were significantly greater for composted manure with ST than the other three manure type-bedding treatments (Fig. 4*c*). For this interaction, K supply was significantly greater for composted than stockpiled manure with ST bedding. In addition, K supply was greater for ST than WD by 70%–87% with both manure types.

Overall, soil K supply was generally greater for composted than stockpiled manure despite only 5% greater water-extractable K in composted than stockpiled amendments (Miller et al. 2016*a*). Masking of amendment effects and K transformations in soil such as adsorption and desorption of exchangeable K, crop uptake, and leaching (Havlin et al. 1999) may have contributed to greater composted than stockpiled manure supply. It was unlikely that leaching contributed because K in leachate was greater for composted than stockpiled manure with ST bedding (Miller et al. 2013*a*). Similar cation exchange capacity of soil for the two manure types (Miller et al. 2016*b*) also suggested that K sorption was not a likely cause. Greater soil K supply for ST than WD was consistent with 81% greater K in ST than WD amendments and significantly greater water-extractable K in the surface soil after 15 continuous applications (Miller et al. 2016*a*).

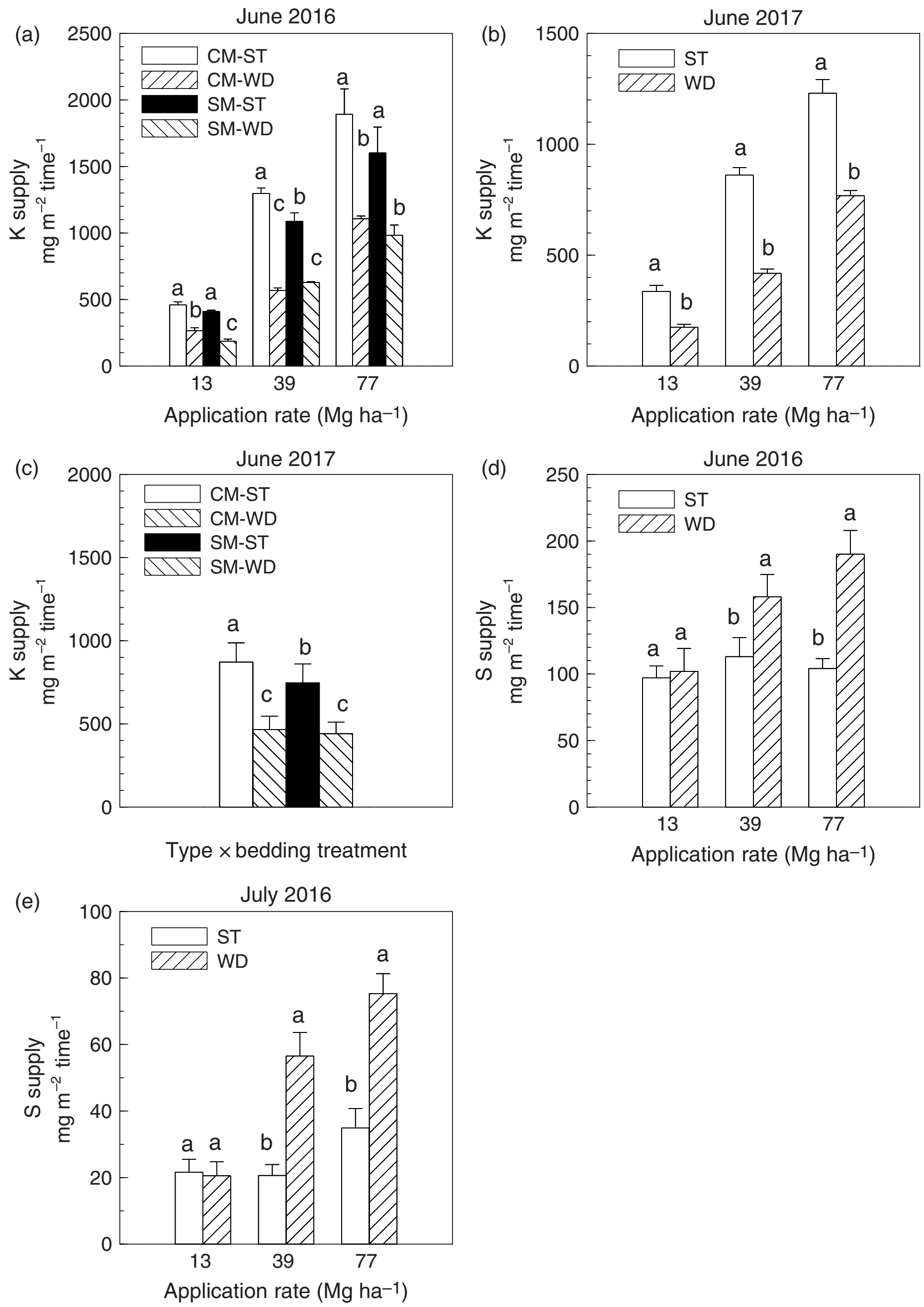
Mean K supply was significantly greater for the manure-amended than the IN and unamended CON treatments (estimate comparisons) for all three dates (Table 2). This finding was unexpected because the majority of unamended soils in Alberta contain sufficient plant-available K to satisfy crop growth (McKenzie and Pauly 2013). But it was consistent with the extremely high water-extractable K content (6.1–12.4 g kg^{-1}) of the manure amendments (Miller et al. 2016*a*) compared with the IN treatment where no K was applied during the application period. Wallingford et al. (1975) also reported that extractable K was greater for amended surface soils compared with unamended treatment during the legacy phase (3 yr) following a single application of beef feedlot manure.

The K supply at 39 and 77 Mg ha^{-1} rates generally declined over the growing season of 2016 and then was either higher or similar in June 2017 (Fig. 5). In contrast, the K supply at 13 Mg ha^{-1} rate showed a slight decrease during the growing season of 2016 and then remained relatively constant. The K supply for IN and CON treatments was low and constant for all sampling dates. The decrease in K supply at the two higher manure rates over the growing season of 2016 was likely due to greater crop uptake and declining soil water content. As expected, the K supply at all three manure rates for the four manure type-bedding amendments was significantly greater than the IN and unamended CON treatments where no inorganic K was applied. Pratt (1984) cautioned that excessive K concentrations in the soils amended with feedlot manure is a serious concern for soil dispersion and soil structural decline. More recent research has also noted that the effect of high K (and Mg) on soil permeability has been underestimated (Oster et al. 2016). Further research is needed to study soil K supply in manured soils and its possible detrimental effects on soil structure and water flow.

Sulfur (SO_4-S)

No significant manure type effects on SO_4-S (Table 2) indicated that this effect did not persist into the legacy phase. In contrast, significant bedding and rate effects suggested persistence legacy effects for these two treatment factors. There was a significant bedding × rate effect on SO_4-S supply in June and July 2016. For both dates, the SO_4-S supply was similar for ST and WD at the 13 Mg ha^{-1} rate, and it was significantly greater for WD than ST at the 39 and 77 Mg ha^{-1} rates by 40%–83% in June and by 116%–174% in July 2016 (Figs. 4*d*, 4*e*). There was a significant bedding effect on SO_4-S supply in June 2017 (Table 2), where mean values were

Fig. 4. Influence of manure type × bedding × rate on K supply in June 2016 (*a*), bedding × rate bedding effect on K supply in June 2017 (*b*), type × bedding effect on K supply in June 2017 (*c*), and bedding × rate effect on S supply in June (*d*) and July (*e*) 2016. Vertical bars are means plus 1 standard error. Different lowercase letters above the vertical bars indicate significant differences ($P \leq 0.05$) among treatments.



significantly greater for WD (105 ± 4.8 mg m^{-2} wk^{-1}) than ST (72.9 ± 5.8 mg m^{-2} wk^{-1}) by 44%.

Similar SO_4-S supply for composted and stockpiled manure was consistent with similar total S (water extractable) in the composted (1.9 g kg^{-1}) and stockpiled manure (1.8 g kg^{-1}) amendments (Miller et al. 2016*a*). But greater SO_4-S supply for WD than ST at certain rates or when averaged over all rates was not consistent with greater total S for ST (2.3 g kg^{-1}) than WD (1.4 g kg^{-1}) amendment (Miller et al. 2016*a*). It is possible that masking of amendment effect by the soil and subsequent S transformations (mineralization, immobilization, leaching, and plant uptake) in the soil (Havlin et al. 1999) may have been contributing factors. Leaching was an unlikely contributor to similar S supply for the two manure types because S in leachate was greater for composted than stockpiled manure (Miller et al. 2013*a*).

A significant rate effect occurred for SO_4-S supply in June 2017 (Table 2). Mean values were significantly

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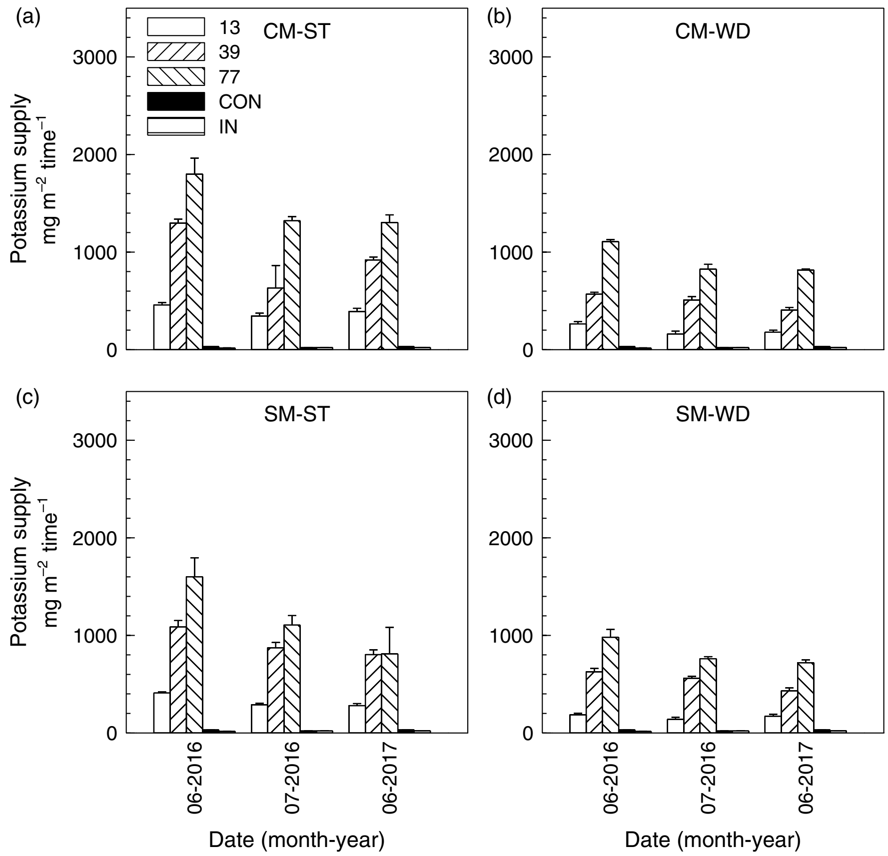
Fig. 5. Mean K supply in a clay loam soil at three sampling dates (June and July of 2016, June 2017) amended with 13, 39, and 77 Mg ha^{-1} (dry wt.) of composted manure with straw (CM-ST) treatment (*a*), composted manure with wood-chips (CM-WD) treatment (*b*), stockpiled manure with straw (SM-ST) treatment (*c*), and stockpiled manure with wood-chips (SM-WD) treatment (*d*). The K supply rates for the unamended control (CON) and inorganic fertilizer (IN) treatments are also presented.



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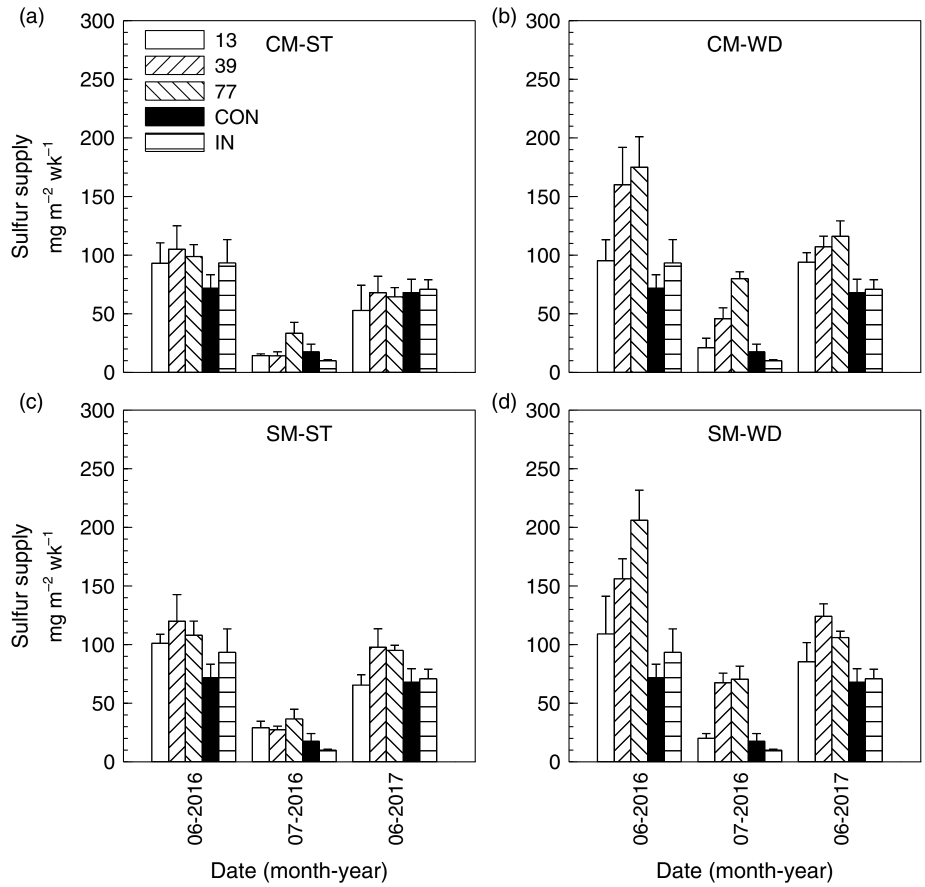
greater for the 39 (97.6 ± 7.7 mg m^{-2} wk^{-1}) and 77 (95.2 ± 6.3 mg m^{-2} wk^{-1}) Mg ha^{-1} rates than the 13 Mg ha^{-1} rate (74.4 mg m^{-2} wk^{-1}) by 28%–31%. Hammermeister et al. (2006) reported no rate effect of poultry manure compost on SO_4-S supply in PRS probes in unvegetated soil pots during the application phase.

The SO_4-S supply was significantly greater for the manure-amended than unamended CON in June and July 2016 but not for June 2017. The SO_4-S supply was significantly greater for the manure-amended than IN treatment in July 2016 but not for the other two dates. Significantly greater SO_4-S supply for the manure-amended than the CON and IN treatments for certain dates was consistent with the relatively high total S content (1.3–2.4 g kg^{-1}) of these four feedlot amendments (Miller et al. 2016*a*), and with no S fertilizer applied with the IN and CON treatments during the application phase. This positive treatment response was somewhat surprising given the relatively high content of SO_4-S in irrigated soils of southern Alberta (McKenzie 2013), but more SO_4-S was likely added to the soil from the amendments than irrigation water. Miller et al. (2016*a*) reported significantly greater water-soluble SO_4-S in surface soil for manure-amended than unamended CON and IN treatments after 15 continuous applications. Hammermeister et al. (2006) reported similar SO_4-S supply in PRS probes during the application phase for poultry-manure-amended treatments compared with unamended and inorganic fertilized (at equivalent N rates) treatments using unvegetated soil pots.

The SO_4-S supply generally decreased over the growing season of 2016 and then was higher in June 2017 (Fig. 6). The decrease in SO_4-S supply during the growing season of 2016 was attributed to increased crop uptake, decreased soil water content, and immobilization of S by organic matter. Our finding of a decrease in SO_4-S supply during the growing season was in contrast to Johnson et al. (2007), who reported that SO_4-S supply to PRS probes in soil was increased by vegetation. They speculated this was caused by rhizosphere-enhanced decomposition of soil organic matter, as well as increased desorption of S by organic anions exuded by the rhizosphere. The SO_4-S supply for the composted manure with ST treatment was similar to the IN treatment at all three application rates. In contrast, the SO_4-S supply for the other three manure type-bedding treatments was similar to IN treatment for 13 Mg ha^{-1} rate (agronomic N based) at all three dates.

Fig. 6. Mean SO_4-S supply in a clay loam soil at three sampling dates (June and July 2016, June 2017) amended with 13, 39, and 77 Mg ha^{-1} (dry wt.) of composted manure with straw (CM-ST) treatment (*a*), composted manure with wood-chips (CM-WD) treatment (*b*), stockpiled manure with straw (SM-ST) treatment (*c*), and stockpiled manure with wood-chips (SM-WD) treatment (*d*). The SO_4-S supply rates for the unamended control (CON) and inorganic fertilizer (IN) treatments are also presented.



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Correlations between crop yield and soil nutrient supply

For the composted manure treatment, there was no significant ($P \leq 0.05$) correlation between DM yield and the four macronutrients (NO_3-N, PO_4-P, K, and SO_4-S) in the soil for June and July of 2016. In June 2017 for the composted manure treatment (averaged over two beddings and three rates or six treatments), there was a significant negative correlation between DM yield and NO_3-N supply ($r = -0.62$, $n = 23$) as well as S supply ($r = -0.57$, $n = 23$). There were no significant correlations between DM yield and macronutrient supply for the stockpiled manure treatment at any of the three dates. For the IN treatment, there was a significant positive correlation between DM yield and NO_3-N supply ($r = 0.95$, $n = 4$) in June 2016. For the CON treatment, there was a significant positive correlation between DM yield and K supply [$r = 0.97$, $n = 4$ (reps)] in June 2016, and a significant negative correlation between DM yield and SO_4-S supply ($r = -0.95$) in June 2017.

Few significant correlations between DM yield and nutrient supply suggested that increased soil macronutrient supply did not result in greater yield. This finding was consistent with Sharifi et al. (2014) who reported that increased soil mineralizable N did not translate into greater barley DM yield or plant N uptake after eight continuous applications. Although N and P crop uptake was significantly greater for amended than unamended CON during the continuous application period (Miller et al. 2009), it is possible that nutrient uptake may have diminished during the legacy period.

Overall short-term legacy effects on yield and soil macronutrient supply

Our overall findings on crop yield and soil macronutrient supply supported the conclusion of Eghball et al. (2004) that short-term (≤3 yr) legacy effects of feedlot manure were more persistent on soil properties than crop yield. The most likely explanation is that soil nutrients have a more direct linkage to the amendment (i.e., soil amendment) than crop yield (i.e., crop–soil amendment), with crop uptake being the critical link to transfer the legacy effect of the amendment from soil to crop yield. In addition, inherently high soil organic matter and soil nutrient supplies, as well as manure-induced soil salinity that was close to crop tolerance may have been contributing factors.

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Our finding of significant manure effects on soil macronutrient supply during the legacy period was generally consistent with previous findings that reported significant manure treatment effects on soil biochemical properties during shorter term (<10 yr) legacy periods (Ginting et al. 2003; Eghball et al. 2004; Wyngaard et al. 2016) and longer term (>10 yr) legacy periods (Hao et al. 2004, 2008; Indraratne et al. 2009; Larney et al. 2016, Larney and Olson 2018; Zhang et al. 2018). Larney et al. (2016) attributed the legacy effect of manure application to the lingering retention of soil organic matter and nutrients initially applied, and the benefits of extra residue additions from higher yield responses to the manure. They also noted that the former mechanism will likely dominate over the latter during the initial stages of the legacy period but will reverse over time. Zhang et al. (2018) reported that the legacy effect of organic amendments on soil microbes was due to decomposition of organic matter, plant growth, and changing edaphic factors.

McLauchlan (2006) noted that the longevity of legacy effects will depend on the magnitude of the alteration of soil C and nutrient levels, and legacy effects on soil will generally persist for much longer than the continuous application period. Indraratne et al. (2009) calculated mean recovery times for soil nutrients to return to pre-manure or initial conditions when feedlot manure was annually applied for 14 yr to an irrigated clay loam soil at 60 Mg ha^{-1} (wet wt.). The recovery times for NO_3-N, soil test P, and soluble salts (EC) were estimated to be 30, 96, and 31 yr, respectively.

Conclusions

Feedlot producers shifting from long-term and continuous annual applications of these manure amendments to discontinued applications may not encounter significantly lower barley DM yields, but significant differences in soil macronutrient supply may still occur 2–3 yr after the last application. Significant treatment effects occurred on soil nutrient supply but depended on date and interaction with other treatment factors. Manure rate generally increased soil nutrient supply. Soil N and P supply were 40%–59% lower for composted manure with ST than the other three manure type-bedding treatments, and soil N and P supply were 26%–53% greater for stockpiled than composted manure. Therefore, composting generally had variable effects on soil N and P supply compared with stockpiled manure that were dependent on date. At the two highest rates, soil K supply was 60%–106% greater for ST than WD bedding, and the reverse trend occurred where SO_4-S supply was 40%–174% greater for WD than ST bedding. Our results suggest that soil nutrient supply was sufficient for maximum DM yield in the unfertilized CON for the 2 yr of this study, and that the greater nutrient supply observed in most fertilized or previously manured treatments was in excess of crop requirements. The high supply rates of N, P, K, and S in the amended soil may pose a risk to the environment through off-site transport.

As expected, temporal variations in macronutrient supply occurred during the growing season and from year-to-year, and they were likely related to soil nutrient transformations and soil moisture. For the four manure type-bedding treatments, the N and P supply in the soil at 13 Mg ha^{-1} or agronomic N-based rate was most suitable for supplying adequate levels of these soil nutrients. In comparison, the N and P supply at 39 and 77 Mg ha^{-1} rates (excess rates) were generally significantly greater than IN, suggesting the potential for environmental losses of these nutrients.

Future research could conduct more detailed studies on treatment effects on yield and soil nutrient supply as the legacy period increases. A possible hypothesis could be that yield and nutrient-supplying power should decline with increasing legacy period. In addition, research is required to study the macronutrient supply in the soil and nutrient uptake of irrigated barley silage and other annual crops at each different stage of crop growth such as early leaf, tillering, stem elongation, heading, and ripening. Soil nutrient supplies in amended soils could also be compared under agronomic N- and P-based application rates. Finally, little research has been conducted on the legacy effects of manure application on soil micronutrients such as Fe, Mn, Cu, and Zn.

Acknowledgements

We thank Mallory Owen for assistance with installing, removing, cleaning, and shipping the PRS probes; and for maintaining the field experiment in 2017. We also thank the Associate Editor (Andrew Vanderzaag), and the reviewers for their constructive comments and suggestions that helped to improve the manuscript.

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