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ARTICLE

Influence of long-term feedlot manure and inorganic fertilizer application on selected metal and trace elements in a clay loam soil

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Abstract: Long-term application of feedlot manure and inorganic fertilizer to cropland may increase metals and trace elements in soils, and negatively impact agricultural land use. We sampled a surface clay loam soil at Lethbridge in southern Alberta after 16 annual applications (2014) of feedlot manure or inorganic fertilizer, as well as an unamended control. The manure treatments were stockpiled (SM) or composted (CM) feedlot manure with barley straw (ST) or wood-chips (WD), and were applied at 13, 39, and 77 Mg ha^{-1} (dry weight). The soil was analyzed for strong-acid extractable concentrations of selected metals (Al, Fe) and trace elements (As, Ba, Cd, Co, Cr, Cu, Li, Mn, Ni, Pb, Sr, Ti, V, and Zn). Manure type (SM versus CM) had little or no significant ($P > 0.05$) effect on the elements. Significantly greater As, Co, Cu, Fe, Li, and V were found for ST than WD at all or higher rates, and the reverse trend occurred for Cd at the highest rate. Cadmium (ST only), Cu, Sr, and Zn were increased by greater application rates, whereas most of the other elements were decreased. Concentrations were significantly increased by manure (Cu, Sr, and Zn) and inorganic fertilizer (Cd) compared with the unamended soil. Copper, Sr, and Zn were greater for manured than inorganic fertilizer treatments, and the reverse trend occurred for Al, As, Co, Cr, Fe, Li, Ni, and V. Although manure and fertilizer may increase certain elements in the soil, no concentrations exceeded the federal soil guidelines for agricultural land use.

Key words: feedlot manure, inorganic fertilizer, metals, trace elements, triple superphosphate, ammonium nitrate.

Résumé : L'application de fumier et d'engrais inorganique aux terres cultivées pendant une période prolongée pourrait augmenter la concentration des métaux et des oligoéléments dans le sol, ce qui aurait un impact négatif sur la vocation agricole des terres. Les auteurs ont échantillonné un loam argileux superficiel du sud de l'Alberta au terme de 16 applications annuelles (2014) de fumier ou d'engrais inorganique, de même qu'une parcelle témoin non bonifiée. Les traitements consistaient en l'application de 13, 39 ou 77 Mg (poids sec) par hectare de fumier de paille d'orge ou de copeaux de bois, composté ou pas. L'analyse du sol a établi la concentration de certains métaux (Al, Fe) extractibles à l'acide fort et des oligoéléments (As, Ba, Cd, Co, Cr, Cu, Li, Mn, Ni, Pb, Sr, Ti, V, et Zn). Que le fumier soit composté ou pas n'agit guère sur la concentration des éléments ($P > 0,05$). Le fumier de paille d'orge renfermait sensiblement plus d'As, Co, Cu, Fe, Li et V que le fumier de copeaux de bois, à tous les taux d'application ou aux taux les plus élevés, la tendance inverse étant observée pour le Cd, au taux d'application le plus élevé. La concentration de Cd (fumier de paille d'orge seulement), Cu, Sr et Zn augmente avec le taux d'application, alors que celle de la plupart des autres éléments diminue. Comparativement à ce qui s'est produit dans la parcelle non amendée, les concentrations augmentent sensiblement avec l'usage de fumier (Cu, Sr, et Zn) et d'engrais inorganique (Cd). Celle de cuivre, de Sr et de Zn était plus élevée sur les terres bonifiées avec du fumier que celles amendées avec un engrais inorganique, tendance qui s'inverse pour les oligoéléments Al, As, Co, Cr, Fe,

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Abbreviations: CM, composted manure; **CON**, unamended control; **IN**, inorganic fertilizer; **SM**, stockpiled manure; **ST**, straw; **TSP**, triple superphosphate; **WD**, wood-chips.

Li, Ni, et V. Bien que le fumier et les engrais rehaussent la concentration de certains éléments dans le sol, celle-ci ne dépasse jamais la concentration recommandée par le gouvernement fédéral pour les terres à vocation agricole. [Traduit par la Rédaction]

Mots-clés : engrais de bovins, engrais inorganique, métaux, oligoéléments, superphosphate triple, nitrate d'ammonium.

Introduction

In 2017, approximately 37% (1.4 million head) of beef cattle in Canada were in 149 feedlots in Alberta and nine were in Saskatchewan (CANFAX Research Services 2017). At least 17 minerals are required by beef cattle, and feeds for growing and finishing cattle in feedlots are often enhanced with certain metals and trace elements such as Co, Cu, Fe, Mn, and Zn (National Research Council 2000). However, up to 90% of these minerals are excreted in the manure (Bolan et al. 2004). The total annual manure production from feedlots in western Canada is about 2.8–3.5 million t, and most of this manure is applied to cropland. An increase of metals and trace elements in manure-amended (MAN) soils to high levels may adversely affect soil microbes, soil invertebrates, crops and plants, livestock, wildlife, and humans (CCME 2006).

Metals and trace elements in feedlot manures are mainly derived from the animal diet, and to a lesser extent from ingestion of soil in unpaved feedlots (Bolan et al. 2004). These chemicals may be lost from feedlot manure by runoff, leaching, volatilization, and volumetric dilution by water and bedding. The behaviour of most metals and trace elements in soils is generally conservative because of strong adsorption to soil solids and low mobility (Sheppard and Sanipelli 2012). However, aqueous metal-organic complexes may dominate the solution chemistry of metals in manure and MAN soils, and these more soluble complexes increase their mobility and availability to plants (Bolan et al. 2004).

Some studies reported an accumulation of total or extractable Cu and Zn in surface soils after 15–28 yr (Kingery et al. 1994), 40 yr (Brock et al. 2006), and 25 yr (Benke et al. 2008) of annual manure application. Others found an accumulation of extractable Cu, Mn, and Zn after 16 yr of annual manure application (van der Watt et al. 1994), or extractable Zn but not Cu enrichment after 11 yr of repeated applications (Chang et al. 1991). Sheppard and Sanipelli (2012) reported mainly total Zn enrichment and to lesser extent several other elements (Co, Cu, Mn, Mo, and Se) on cropland with a history of heavy manure applications. In contrast, Lipoth and Schoenau (2007) found no accumulation of extractable (chelating agent) and total Cu, Cd, and Zn in surface soils after 5–7 yr of repeated applications of swine or beef manure. Therefore, most studies have generally found enrichment of certain total or extractable metals and trace elements (particularly Cu and Zn) in manured cropland, but there are exceptions. Most of these previous studies have generally focused on comparing concentrations of metals and trace elements in manured cropland to unamended or background soils, and some also examined the treatment effect of application rate (Chang et al. 1991; Brock et al. 2006; Lipoth and Schoenau 2007; Benke et al. 2008).

We are unaware of any studies that have been conducted on the long-term (>10 yr) effect of land application of stockpiled (SM) versus composted (CM) beef feedlot manure containing straw (ST) or wood-chip (WD) bedding on concentrations of metals and trace elements in soil cropped to barley for silage. Total Al, Co, Cu, Fe, Mn, and Zn were greater, Cr and Ni contents lower, and Pb contents were similar in composted compared with fresh feedlot manure (Larney et al. 2008). Increased total concentrations from composting were attributed to the concentration effect of lowered total mass of dry matter. Total contents of Al, As, Ba, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn contents were greater in ST than WD composted feedlot manure, and was likely related to fertilizer herbicide–pesticide application on barley (Zvomuya et al. 2005). Therefore, we might expect that these same trends for the two manure types (SM vs CM) and bedding materials (ST vs WD) may be the same for metals and trace elements in amended soils.

In addition to manure, long-term application of inorganic fertilizers (IN) to cropland may cause an accumulation of metals and trace elements in surface soils (Charter et al. 1993; Raven and Loeppert 1997; EPA 1999; McBride and Spiers 2001). Metal and trace element concentrations are generally greater for commercial phosphate fertilizers, followed by organic amendments, and then lesser for commercial N fertilizers (Raven and Loeppert 1997). Little research has compared concentrations of metals and trace elements in soils with feedlot manure versus IN. Wei et al. (2006) reported that total Fe, Mn, and Zn concentrations in soil after 18 yr under five different cropping systems were generally greater for IN and manure treatments than IN only. Sheppard et al. (2009*b*) found that predicted annual loading to cropland was greater for fertilizers than manure for total As, Cd, and Pb, but the reverse trend occurred for Cu, Se, and Zn.

The main objective was to study the long-term influence of manure type (SM vs CM), bedding material (ST vs WD), and application rate (13, 39, and 77 Mg ha^{-1} dry weight) on concentrations of selected metals and trace elements in soil after 16 annual applications. A secondary objective was to compare these elements in amended versus unamended soils, as well as in MAN versus inorganic fertilized soils. Our hypothesis was that metals and trace element concentrations in soils might be greater for CM than SM and ST than WD. Further, soil enrichments of selected metals or trace elements would occur when these elements are present in greater concentrations in the manure compared with the soil, whereas soil dilutions would occur for the metals or trace elements which are present in lower concentrations in the manure compared with the soil.

Materials and Methods

The experimental plots were initiated to study the influence of selected feedlot amendments on agronomy, soil, and the environment. This field site is a clay loam soil located in Lethbridge (49°38′N, 112°48′W), southern Alberta. The treatments have been previously described in more detail (Miller et al. 2015). The treatments are SM or CM with either ST or WD applied at three rates (13, 39, and 77 Mg ha^{-1} dry basis), one IN treatment, and one unamended control (CON). The SM and CM were derived from the same fresh manure (FM) source. The SM was stockpiled for up to 2 mo prior to land application, and has been referred to as FM in some previous studies. The CM was composted using the windrow method (Larney et al. 2003) with turning about seven times over a 90 d period (active phase), followed by a curing phase (no turning) for a further 90–120 d.

The treatments (randomized complete block) were replicated four times for a total of 56 treatment plots (6 m × 25 m). Both fertilizers were applied on the same date as the organic amendments. The ST was unchopped barley ST. The WD bedding (Sunpine Forest Products, Sundre, AB, Canada) was a mixture of 50% wood-chips, bark, and post peelings, and 50% fine sawdust. The tree species were a 4:1 mixture of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and white spruce (*Picea glauca* (Moench) Voss). The ratio of bedding to manure was approximately 1:4 (Larney et al. 2008). ST or WD bedding was added to separate feedlot pens during the winter as required and depending on precipitation. Therefore, the manure and bedding were mixed in the feedlot pens, and the manure containing the bedding was removed when the pens were cleaned.

Organic amendments were annually applied in the fall (October) after harvest since 1998 using a box-style, solid-manure spreader and incorporated to a depth of about 20 cm using a offset disc harrows. The amendment rates were consistent with the actual wet application rates applied by feedlots in this area. The application rates (13, 39, and 77 Mg ha^{-1} dry basis) were lower than the application rates (60, 120, and 180 Mg ha^{-1} wet basis) used at an adjacent long-term (since 1973) irrigated experiment (Chang et al. 1991) but were higher than agronomic application rates based on N (9–23 Mg ha^{-1} dry basis) or P (1–7 Mg ha^{-1} dry basis) used for irrigated cereal silage plots in southern Alberta (Olson et al. 2010). In our study, the 13 Mg ha^{-1} rate was closer to the agronomic rate, whereas the 39 and 77 Mg ha^{-1} rates were likely excess rates. The IN treatment was 100 kg N ha^{-1} as NH_4NO_3 applied as 34–0–0 and 17 kg P ha^{-1} as triple superphosphate (TSP) applied as 0–46–0. Barley was seeded in all plots in May or early June and harvested as silage at the soft-dough stage in August. The barley was irrigated with a side-roll irrigation system to achieve optimum growth.

Surface (0–15 cm) soil samples were taken (one per plot) using truck-mounted Giddings soil core sampler in the fall of 2014 after harvest, air-dried, and then shipped to ALS Environmental Laboratory in Saskatoon, SK, Canada. This year of sampling was after 16 annual applications of feedlot amendments and IN. This depth of sampling was chosen because it included most of the depth (20 cm) of manure incorporation. A sample of each of the four amendments (CM-ST, CM-WD, SM-ST, and SM-WD) taken in the fall of 2014 was also sent to this lab for analysis. Concentrations of metals (Al, As, Ba, Cd, Co, Cr, Cu, Fe, Li, Mn, Ni, Pb, Sr, Ti, V, and Zn) in soil and amendments were determined using ALS Test Code Method MET-200.2-CCMS-SK. This analysis was performed using CSR (Contaminated Sites Regulation) Analytical Method "Strong Acid Leachable Metals (SALM) in soil" (British Columbia Ministry of the Environment 2009), and procedures adapted from EPA Method 200.2 "Sample preparation procedure for spectrochemical determination of total recoverable elements" (EPA 1999). The soil or amendment sample was dried at 40 °C, and then ground to <2 mm particle size using a stainless-steel flail grinder. A 1 g subsample was then digested with concentrated HNO_3 and HCl for 2 h in an open-vessel digester at 95 °C. Instrumental analysis of the digested extract was conducted by collision-cell inductively coupled plasma mass spectrometry (modified from EPA Method 6020A).

These concentrations are referred to as strong-acid (HNO_3-HCl) extractable (SAE) concentrations. Mineral-acid extractions are used to predict the bioavailability of manure-borne metals and trace elements (Bolan et al. 2004). Digestion with HNO_3–HCl leaches sulfides, some oxides, and some silicates, and is considered a measure of long-term availability in soils (Sheppard et al. 2009*a*). The metal and trace element contents of NH_4NO_3 and TSP fertilizers used in our study were not determined because the concentrations of most of these elements in these same fertilizers have been previously reported (McBride and Spiers 2001). We assumed that the elemental analysis of these IN would be relatively similar for the fertilizers we applied.

Total carbon was determined on surface (0–15 cm) soil samples collected in the fall of 2015. The soil was air-dried, finely ground (<150 μm), and then analyzed using the Dumas automated combustion technique (McGill and Fiqueiredo 1993) and a CNS analyzer (Carla Erba, Milan, Italy). The pH of surface (0–15 cm) soil was determined on saturation paste extracts (water) of samples collected in early May of 2013.

Table 1. Concentrations of metals (Al, Fe) and selected trace elements in the four feedlot amendments applied to a clay loam soil in southern Alberta.

	Feedlot amendments				Inorganic fertilizers	
Chemical	SM-WD	SM-ST	CM-WD	CM-ST	NH_4NO_3	TSP
Al	6.8	4.3	7.3	7.3	ND	ND
As	3.2	3.0	3.6	4.6	<1	11
Ba	298	180	287	185	<1	30
Cd	0.46	0.3	0.53	0.3	<0.1	8.1
Cr	9.9	11.5	10.2	14.3	<1	83
Co	3.2	3.5	3.2	4.9	<0.1	4.2
Cu	37.3	39.5	26.9	28.6	12.0	4.0
Fe	6.2	7.0	7.0	10.3	ND	ND
Pb	8.8	4.7	9.0	6.3	0.2	5.7
Li	6.5	6.5	6.9	8.7	<0.1	2.0
Mn	317	267	351	309	ND	ND
Ni	8.8	9.8	8.7	14.1	<1	20
Sr	95.0	56.1	90.1	60.2	<1	538
Ti	81.6	38.3	92.8	40.7	ND	ND
V	12.6	13.0	14.0	19.2	<1	143
Zn	165	164	133	109	5.0	82

Note: All concentrations are in mg kg^{-1}, except for Al and Fe, which are in g kg^{-1}. The amendment samples are taken in the fall of 2014 prior to land application. Concentrations of metals and trace elements in NH_4NO_3 and triple superphosphate (TSP) fertilizer (taken from McBride and Spiers 2001) are also shown. SM, stockpiled feedlot manure; CM, composted feedlot manure; ST, straw bedding; WD, wood-chip bedding.

Statistical analyses

Two MIXED model analyses (Littell et al. 1998; SAS Institute Inc. 2005) were conducted. The first analysis determined the effect of all 14 individual treatments, including the control and IN treatment, on the dependent variables. The data were first examined using Proc Univariate procedure to determine if a logarithmic transformation was required. Estimate statements were also used to compare the unamended CON versus MAN treatments, CON versus inorganic (IN) treatment, and IN versus MAN treatments. The second analysis determined the effect of the main treatment factors manure type, bedding material, manure application rate, and year on the dependent variables. For this latter analysis, the control and IN treatments were omitted, as there was only one level of each of these factors. Correlation analysis in SAS was conducted using the CORR procedure. A significance level of $P \leq 0.05$ was used for the MIXED model and correlation analysis.

Results

Metals and trace elements in the amendments

The SAE concentrations of metals (Al and Fe) and selected trace elements in the four amendments applied to our plots in the fall of 2014, and concentrations in the INs as reported previously (McBride and Spiers 2001) are shown in Table 1. Concentrations of Ba, Sr, and Zn were greatest for the SM-WD amendment compared with the other three amendments; Cu was greatest in the SM-ST amendment. Concentrations of Cd, Pb, Mn, and Ti were greatest in the CM-WD amendment than the other three amendments; As, Cr, Co, Fe, Li, Ni, and V were greatest in the CM-ST amendment. The concentration of Al was greatest in CM-WD and CM-ST amendments compared with other two amendments.

When averaged over the two bedding materials, concentrations of Ba, Cu, and Zn were lower for CM than SM amendments; Cd and Sr were similar in the two manure types; and the other 11 elements were greater for CM than SM amendment (data not shown). When averaged across the two manure types, concentrations of nine elements (Al, Ba, Cd, Mn, Pb, Sr, Ti, and Zn) were lower for ST than WD bedded amendments; As had similar concentrations in ST and WD; and seven elements (Co, Cr, Cu, Fe, Li, Ni, and V) had greater concentrations for ST than WD.

Effect of all 14 treatments on metals and trace elements in soil

The SAE concentrations of total trace elements in soil for all 14 treatments did not exceed the agricultural land use guidelines for total As, Ba, Co, Cr, Cu, Ni, Pb, V, and Zn (Tables 2 and 3). Concentrations of Cu, Sr, and Zn were significantly greater for the MAN treatments than the unamended CON. In contrast, Al, As, Ba, Co, Cr, Fe, Li, Ni, and V were significantly lower for the MAN than

Table 2. Treatment effects on strong-acid extractable concentrations[a] of trace elements in soil (0–15 cm depth) after 16 yr (2014) of application.

Treatment	Al	Fe	As	Ba	Cd	Co	Cr	Cu
CON	15.9 ± 0.6	17.4 ± 0.3	7.1 ± 0.2	499 ± 20.3	0.3 ± 0.01	7.1 ± 0.2	21.7 ± 0.7	16.2 ± 0.3
IN	14.7 ± 0.2	16.9 ± 0.3	7.0 ± 0.2	467 ± 29.9	0.4 ± 0.02	7.1 ± 0.2	22.6 ± 0.4	15.8 ± 0.3
SM-ST-13	15.5 ± 0.4	16.9 ± 0.3	7.1 ± 0.2	481 ± 22.9	0.3 ± 0.01	7.3 ± 0.2	21.6 ± 0.8	20.0 ± 0.8
SM-ST-39	12.8 ± 0.6	14.7 ± 0.4	5.7 ± 0.2	479 ± 19.8	0.3 ± 0.02	6.4 ± 0.2	18.0 ± 0.5	24.5 ± 0.3
SM-ST-77	11.9 ± 0.3	14.0 ± 0.3	5.2 ± 0.2	418 ± 16.1	0.3 ± 0.01	6.0 ± 0.1	16.9 ± 0.5	29.4 ± 1.1
CM-ST-13	13.7 ± 0.2	15.9 ± 0.2	6.5 ± 0.2	440 ± 7.4	0.3 ± 0.01	6.7 ± 0.3	19.5 ± 0.2	18.9 ± 1.0
CM-ST-39	13.8 ± 0.4	15.6 ± 0.3	5.9 ± 0.1	454 ± 10.7	0.3 ± 0.01	6.5 ± 0.0	19.0 ± 0.3	25.5 ± 0.7
CM-ST-77	12.1 ± 0.1	14.9 ± 0.4	5.6 ± 0.2	391 ± 20.3	0.3 ± 0.01	6.1 ± 0.1	17.2 ± 0.4	29.0 ± 1.3
SM-WD-13	14.7 ± 0.2	16.5 ± 0.1	6.6 ± 0.0	488 ± 12.9	0.3 ± 0.01	6.8 ± 0.0	21.0 ± 0.3	18.3 ± 0.4
SM-WD-39	13.2 ± 0.4	14.9 ± 0.1	5.9 ± 0.2	444 ± 20.3	0.4 ± 0.01	6.4 ± 0.1	18.7 ± 0.6	22.5 ± 0.7
SM-WD-77	11.3 ± 0.5	13.3 ± 0.4	5.3 ± 0.3	400 ± 5.5	0.4 ± 0.02	5.9 ± 0.3	16.8 ± 0.8	25.3 ± 2.7
CM-WD-13	14.2 ± 0.4	16.3 ± 0.5	6.6 ± 0.2	477 ± 24.1	0.3 ± 0.01	6.8 ± 0.1	20.6 ± 0.7	18.9 ± 0.6
CM-WD-39	13.2 ± 0.3	15.1 ± 0.3	6.1 ± 0.2	421 ± 28.1	0.4 ± 0.02	6.4 ± 0.2	19.6 ± 0.7	21.7 ± 0.6
CM-WD-77	10.6 ± 0.5	13.0 ± 0.4	5.0 ± 0.2	407 ± 8.4	0.4 ± 0.02	5.6 ± 0.1	16.4 ± 0.6	26.2 ± 1.7
DL[b]	0.05	0.050	0.1	1.0	0.1	1.0	0.5	1.0
Agr. Guide[c]	NA	NA	12.0	750	1.4	40	64	63
Estimate[d]								
CON vs MAN	2.8*	2.3*	1.19*	57*	−0.02	0.74*	3.0*	−7.1*
CON vs IN	1.1*	0.5	0.18	32.3	−0.06*	0	−0.9	0.5
IN vs MAN	1.7*	1.8*	1.02*	25.0	0.04*	0.74*	3.8*	−7.6*

Note: Values are the mean ± standard error. Treatments: CON, control; IN, inorganic fertilizer; SM, stockpiled beef manure; CM, composted beef manure; MAN, manured; ST, barley straw; WD, wood-chips; application rates of 13, 39, and 77 Mg ha^{-1}.

[a]All concentrations are in mg kg^{-1}, except for Al and Fe, which are in g kg^{-1}.

[b]DL, detection limit.

[c]Canadian soil quality guidelines for the protection of environmental and human health with respect to agricultural land use (CCME 1999). NA, not available.

[d]Estimate values are negative when treatment 1 (CON, IN) < treatment 2 (MAN, IN), and are positive when treatments 1 > treatments 2. For example, a negative estimate value for CON vs MAN indicates that mean value for MAN is greater than CON.

*, Means are significantly different at $P \leq 0.05$.

CON treatments. Mean concentrations of Mn, Pb, and Ti were similar for the MAN and CON treatments. Concentrations of all elements were similar for the IN treatment and CON. The two exceptions were Al, where it was significantly lower for IN than CON treatment, and Cd, which had the reverse trend. Concentrations of Al, Cd, Fe, As, Co, Cr, Li, Ni, and V were significantly greater for the IN treatment compared with the MAN treatments, and the reverse trend occurred for Cu, Sr, and Zn. In contrast, Ba, Mn, Pb, and Ti were similar for the IN and MAN treatments.

Treatment factor effects on metals and trace elements in soil

For the main treatment factors, manure type had no significant effect on SAE concentrations of Ba, Co, Cu, Li, Mn, Ni, Pb, Sr, and Zn in soil (Tables 4 and 5). Bedding had a significant ($P \leq 0.05$) effect on Co, Cu, and Li, where concentrations were 3%–11% greater for ST than WD. In contrast, bedding had no influence on Al, Ba, Cr, Mn, Ni, Pb, Sr, Ti, and Zn. Application rate had a significant effect on Ba, Co, Cu, Li, Ni, Sr, and Zn, but no significant effect on Mn and Pb. Concentrations of Ba were significantly greater at 13 and 39 Mg ha^{-1} rates compared with 77 Mg ha^{-1} rate. Cobalt, Li, and Ni concentrations were significantly decreased with each greater application rate, and the reverse trend occurred for Cu, Sr, and Zn.

There was no significant manure type × bedding effects on SAE concentrations for any of the trace elements (Tables 4 and 5). There was significant type × rate effects for Al, Cr, Fe, Ti, and V. Although a significant type × rate effect occurred for Fe, the mean concentrations were similar for SM and CM at each application rate (data not shown). Concentrations of Al, Cr, and Ti were 6%–12% greater for SM than CM at the 13 Mg ha^{-1} rate, but were similar at the 39 and 77 Mg ha^{-1} rates (Fig. 1). There was also a significant bedding × rate effect on Fe and Cd (Table 4). Mean Fe values were 14% greater for ST than WD at the 77 Mg ha^{-1} rate, and Cd was 33% greater for WD than ST at two higher rates (Fig. 2). Finally, there were significant three-way interaction effects (manure type × bedding × rate) on soil As and V concentrations. Mean As and V values were 9% greater for SM than CM with ST at the 13 Mg ha^{-1} rate, and were 12% greater for ST than WD with composted manure at 77 Mg ha^{-1} rate (Fig. 3).

Correlations among elements versus total C and pH in soil

Significant and positive correlations occurred between Cu, Pb, Sr, and Zn and Cd with total C (Table 6).

Table 3. Treatment effects on strong-acid concentrations[a] of trace elements in soil (0–15 cm depth) after 16 yr (2014) of application.

Treatment	Li	Mn	Ni	Pb	Sr	Ti	V	Zn
CON	11.0 ± 0.3	369 ± 15.2	20.2 ± 0.4	11.4 ± 0.7	36.8 ± 0.9	86.0 ± 5.2	37.8 ± 0.8	68.2 ± 2.6
IN	10.6 ± 0.2	351 ± 15.8	20.3 ± 0.3	10.5 ± 0.2	39.7 ± 2.4	73.7 ± 4.3	36.4 ± 0.5	64.2 ± 1.7
SM-ST-13	10.7 ± 0.1	378 ± 9.7	20.3 ± 0.7	10.3 ± 0.3	38.5 ± 2.1	89.3 ± 5.5	37.6 ± 1.1	81.9 ± 1.9
SM-ST-39	9.6 ± 0.4	357 ± 13.1	17.0 ± 0.4	9.4 ± 0.4	46.3 ± 2.2	79.6 ± 4.2	31.0 ± 1.0	106 ± 0.7
SM-ST-77	9.0 ± 0.1	353 ± 4.1	16.0 ± 0.2	9.0 ± 0.4	49.4 ± 1.6	72.0 ± 3.7	28.5 ± 0.8	129 ± 5.6
CM-ST-13	10.2 ± 0.4	373 ± 18.2	18.5 ± 0.6	10.4 ± 0.3	41.2 ± 2.3	81.9 ± 4.1	33.1 ± 0.5	79.4 ± 3.2
CM-ST-39	9.8 ± 0.2	370 ± 7.1	17.5 ± 0.1	9.3 ± 0.2	44.5 ± 0.9	88.6 ± 3.6	33.0 ± 0.6	111 ± 3.2
CM-ST-77	9.4 ± 0.2	358 ± 9.8	16.4 ± 0.1	8.7 ± 0.04	49.6 ± 2.5	73.4 ± 5.1	30.0 ± 0.4	126 ± 6.5
SM-WD-13	10.0 ± 0.2	379 ± 6.8	19.0 ± 0.3	10.3 ± 0.2	39.3 ± 3.7	88.9 ± 7.0	35.3 ± 0.5	81.0 ± 0.9
SM-WD-39	9.5 ± 0.4	373 ± 17.5	17.5 ± 0.4	9.7 ± 0.4	43.5 ± 2.0	83.4 ± 4.1	31.9 ± 0.9	100 ± 4.5
SM-WD-77	8.7 ± 0.2	378 ± 13.2	16.2 ± 0.9	23.2 ± 14.4	49.1 ± 2.1	65.8 ± 3.0	27.8 ± 1.0	106 ± 8.8
CM-WD-13	9.9 ± 0.3	368 ± 7.1	19.1 ± 0.7	10.2 ± 0.1	38.5 ± 2.4	76.8 ± 3.7	34.6 ± 1.2	80.0 ± 2.1
CM-WD-39	9.7 ± 0.1	363 ± 1.2	18.1 ± 0.6	9.5 ± 0.3	43.5 ± 2.2	85.2 ± 2.0	32.2 ± 0.8	92.7 ± 5.3
CM-WD-77	8.9 ± 0.2	389 ± 17.3	15.5 ± 0.3	8.3 ± 0.1	51.7 ± 2.0	71.4 ± 3.9	26.5 ± 1.0	123 ± 9.0
DL[b]	2.0	1.0	1.0	1.0	1.0	5.0	1.0	5.0
Agr. Guide[c]	NA	NA	50	70	NA	NA	130	200
Estimate[d]								
CON vs MAN	1.4*	−1.2	2.6*	0.7	−7.8*	6.3	6.0*	−33*
CON vs IN	0.4	17.3	−0.2	0.9	−2.9	−6.0	1.4	4.0
IN vs MAN	1.01*	−18.5	2.8*	−0.2	−4.9*	−6.0	4.6*	−37*

Note: Values are the mean ± standard error. Treatments: CON, control; IN, inorganic fertilizer; SM, stockpiled beef manure; CM, composted beef manure; MAN, manured; ST, barley straw; WD, wood-chips; application rates of 13, 39, and 77 Mg ha^{-1}.

[a]All concentrations are in mg kg^{-1}.

[b]DL, detection limit.

[c]Canadian soil quality guidelines for the protection of environmental and human health with respect to agricultural land use (CCME 1999). NA, not available.

[d]Estimate values are negative when treatment 1 (CON, IN) < treatment 2 (MAN, IN), and are positive when treatments 1 > treatments 2. For example, a negative estimate value for CON vs MAN indicates that mean value for MAN is greater than CON. *, Means are significantly different at $P \le 0.05$.

Table 4. Treatment effects on strong-acid extractable concentrations of trace elements in soil (0–15 cm depth) after 16 yr (2014) applications of feedlot amendments.

Treatment	Al	Fe	As	Ba	Co	Cd	Cr	Cu
	Prob > F[a]							
T	NS	NS	NS	NS	NS	NS	NS	NS
B	NS	*	NS	NS	*	***	NS	***
R	***	***	***	***	***	**	***	***
T × B	NS	NS	NS	NS	NS	NS	NS	NS
T × R	*	*	NS	NS	NS	NS	*	NS
B × R	NS	*	NS	NS	NS	*	NS	NS
T × B × R	NS	NS	*	NS	NS	NS	NS	NS
Bedding (B) effect[b]								
ST	—	—	—	—	6.5 ± 0.1a	—	—	24.5 ± 0.9a
WD	—	—	—	—	6.3 ± 0.1b	—	—	22.1 ± 0.8b
Rate (R) effect[b]								
13	—	—	—	471 ± 9.4a	6.9 ± 0.1a	—	—	19.0 ± 0.4c
39	—	—	—	449 ± 10.7a	6.4 ± 0.1b	—	—	23.5 ± 0.5b
77	—	—	—	404 ± 6.7b	5.9 ± 0.1c	—	—	27.5 ± 0.9a

Note: Means within a column not sharing a lowercase letter differ significantly at the $P < 0.05$ level. T, manure type (stockpiled vs composted feedlot manure); B, bedding material (straw vs wood-chips); R, application rate (13, 39, and 77 Mg ha^{-1} dry basis).

[a]*F* values are significant at the 0.05 (*), 0.01 (**), and 0.001 (***) probability level. NS, not significant ($P \ge 0.05$).

[b]Data are in mg kg^{-1}. Values are mean ± standard error. Within a column, means not sharing a lowercase letter differ significantly at the $P < 0.05$ level. —, indicates a significant interaction effect and main effect means are not reported.

Table 5. Treatment effects on strong-acid extractable concentrations of trace elements in soil (0–15 cm depth) after 16 yr (2014) applications of feedlot amendments.

Treatment	Li	Mn	Ni	Pb	Sr	Ti	V	Zn
	Prob >F^a							
T	NS	NS	NS	NS	NS	NS	NS	NS
B	*	NS	NS	NS	NS	NS	NS	NS
R	***	NS	***	NS	***	***	***	***
T × B	NS	NS	NS	NS	NS	NS	NS	NS
T × R	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
Bedding (B) effect[b]								
ST	9.8 ± 0.2a	—	—	—	—	—	—	—
WD	9.5 ± 0.1b	—	—	—	—	—	—	—
Rate (R) effect[b]								
13	10.2 ± 0.2a	—	19.2 ± 0.3a	—	39.4 ± 1.2c	—	—	80.5 ± 1.0c
39	9.7 ± 0.1b	—	17.5 ± 0.2b	—	44.5 ± 0.9b	—	—	103 ± 2.5b
77	9.0 ± 0.1c	—	16.0 ± 0.2c	—	49.9 ± 1.0a	—	—	124 ± 4.2a

Note: Means within a column not sharing a lowercase letter differ significantly at the $P < 0.05$ level. T, manure type (stockpiled vs composted feedlot manure); B, bedding material (straw vs wood-chips); R, application rate (13, 39, and 77 Mg ha^{-1} dry basis).

[a] F values are significant at the 0.05 (*), 0.01 (**), and 0.001 (***) probability level. NS, not significant ($P \geq 0.05$).

[b] Data are in mg kg^{-1}. Values are mean ± standard error. Within a column, means not sharing a lowercase letter differ significantly at the $P < 0.05$ level. —, indicates a significant interaction effect and main effect means are not reported.

In contrast, significant negative correlations were found between Al, As, Ba, Co, Cr, Fe, Li, Ni, Ti, and V with total C. A significant positive correlation occurred between Fe and pH, and a significant negative correlation was found between Mn and pH as well as Cd and pH.

Discussion

Our finding of significantly greater SAE concentrations of Cu, Sr, and Zn for MAN than unamended soils after 16 applications (estimate comparisons) was consistent with other long-term manure studies on total or extractable Cu and Zn after 5–7 yr (Kingery et al. 1994; van der Watt et al. 1994; Brock et al. 2006; Lipoth and Schoenau 2007; Benke et al. 2008). Chang et al. (1991) found significantly greater extractable Zn in surface (0–15 cm) soil after 11 annual applications at rates up to 180 Mg ha^{-1}, but found no evidence of Cu enrichment. Qian et al. (2003) reported no enrichment of total Cu and Zn in surface (0–15 cm) soils after 5 yr of annual applications of swine or beef manure, but there was an increase of the moderately labile fractions. Sheppard and Sanipelli (2012) reported significantly greater total Zn concentrations in surface (0–15 cm) soil at seven of nine sites, greater Cu at two of nine sites, and no evidence of Sr enrichment where cropland had a history of heavy applications of beef and swine manure. Copper and Zn are routinely used as mineral supplements in feedlots, but not Sr (National Research Council 2000). Therefore, we speculate that the higher Sr in amended soils was likely derived from the barley grain or silage that was fed to cattle, or possibly from soil incorporated into the manure during pen cleaning.

Similar SAE concentrations of Fe and measured trace elements for the IN treatment and unamended CON (estimate comparisons) suggested that long-term IN application (NH_4NO_3, TSP) did not significantly increase these elements in the soil. The only exception was Al, where it was significantly lower for IN treatment than unamended CON. Our finding that 16 yr of annual applications of IN did not enrich the surface soil in Al, Fe, and trace elements compared with unamended soil was consistent with other studies (Mortvedt 1996; Jones et al. 2002; Franklin et al. 2005; Jia et al. 2010; Richards et al. 2011; Ajayi et al. 2012). In contrast, other studies reported enrichment of certain trace elements in surface soils after long-term fertilizer use (Atafar et al. 2010; Czarnecki and Düring 2015). Ammonium nitrate, which was applied to our plots, generally contains low or nondetectable concentrations of Ba, Cd, Co, Cr, Li, Ni, Sr, and V; and concentrations are highest for Cu (12.0 mg kg^{-1}) and Zn (5.0 mg kg^{-1}) (McBride and Spiers 2001). In contrast, TSP which was applied to our plots generally has higher and measureable concentrations of trace elements than NH_4NO_3 (McBride and Spiers 2001). Most of the trace elements measured in our study were detectable in TSP, and the ones in the P fertilizer with highest concentration of most concern are Cd, Cr, Sr, V, and Zn (McBride and Spiers 2001). Cadmium accumulation in the amended soils did not exceed the CCME guideline likely because P fertilizer was applied at agronomic rates. Application of

Fig. 1. Manure type × application rate effects on concentrations (strong-acid extractable) of Al, Cr, and Ti in surface soil (0–15 cm) after 16 yr of amendments. The vertical bars are means plus one standard error. Different lowercase letters indicate significant ($P \leq 0.05$) manure type effects between stockpiled manure (SM) and composted manure (CM) at each application rate.

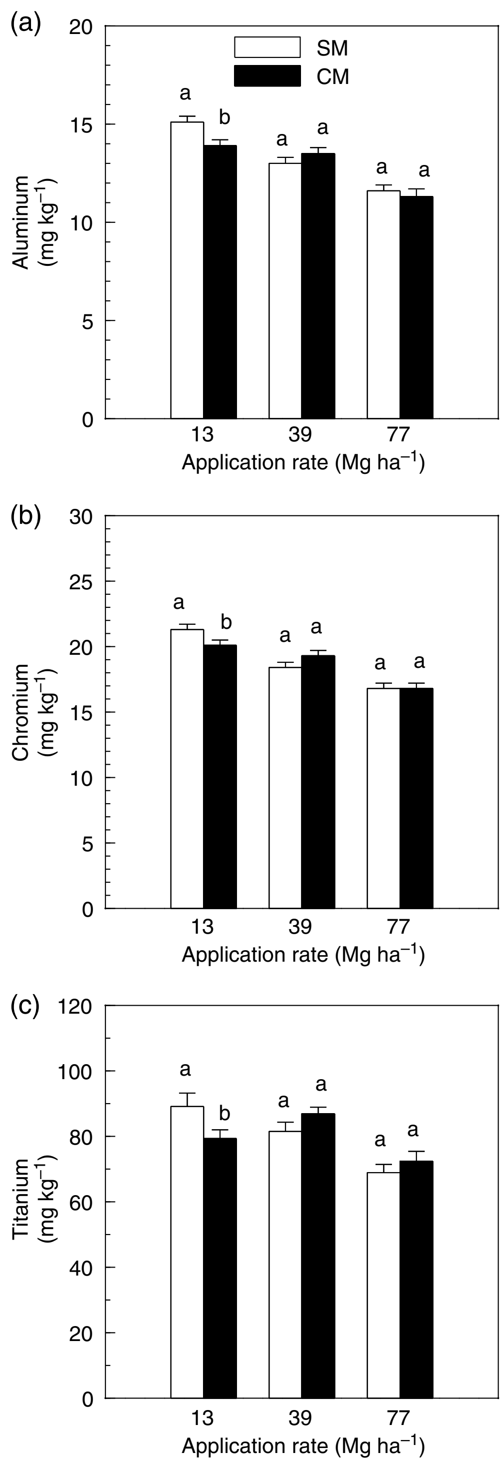
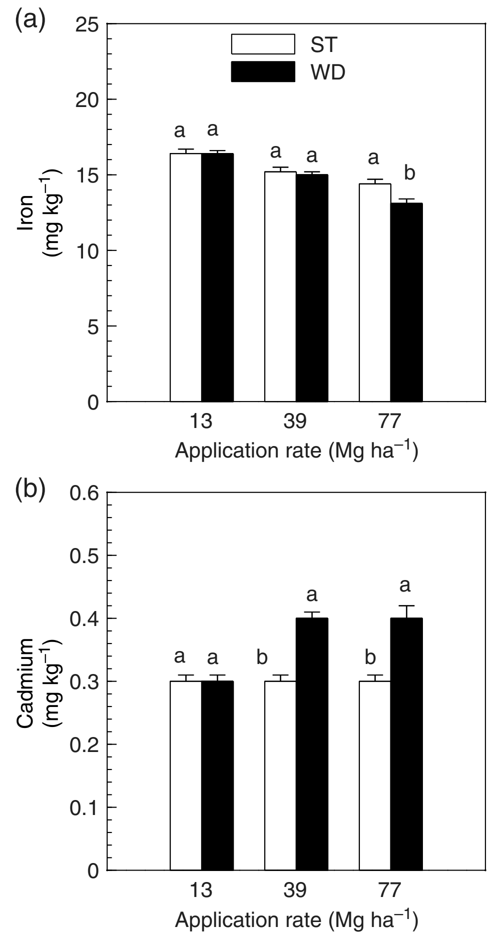


Fig. 2. Bedding × application rate effects on concentrations (strong-acid extractable) of Fe and Cd in surface soil (0–15 cm) after 16 yr of amendments. The vertical bars are means plus one standard error. Different lowercase letters indicate significant ($P \leq 0.05$) bedding effects between straw (ST) and wood-chips (WD) at each application rate.



high-P fertilizers at excessive rates may lead to Cd accumulation in crops (Grant and Sheppard 2008). Our finding of no enrichment of metals and trace elements in surface soil after 16 yr of fertilizer application was likely related to the low contents of these chemicals in NH_4NO_3 and TSP, as well as moderate rates of application. Although our application rates were higher than agronomic rates but lower than some other studies, they were still consistent with actual rates used by commercial feedlots. McBride and Spiers (2001) concluded that it would take decades to enrich soils in trace elements because of low concentrations in INs applied at agronomic rates.

Significantly greater SAE concentrations of Al, As, Co, Cr, Fe, Li, Ni, and V for the IN treatment compared with MAN treatments (estimate comparisons) suggested greater enrichment of these elements in the soil for IN than feedlot manure amendments. This was also consistent with the significant negative correlation between these eight elements and total C in the soil, and volumetric dilution of these elements in the amended soil by manure. This may have occurred for these elements whose concentrations are generally greater in background soil than the amendment. In

Fig. 3. Manure type × bedding × application effects on concentrations (strong-acid extractable) of As and V in surface soil (0–15 cm) after 16 yr of amendments. The vertical bars are means plus one standard error. Different lowercase letters indicate significant ($P \leq 0.05$) manure type-bedding effects at each application rate. The manure types were stockpiled (SM) and composted (CM) manure. The bedding materials are straw (ST) and wood-chips (WD).

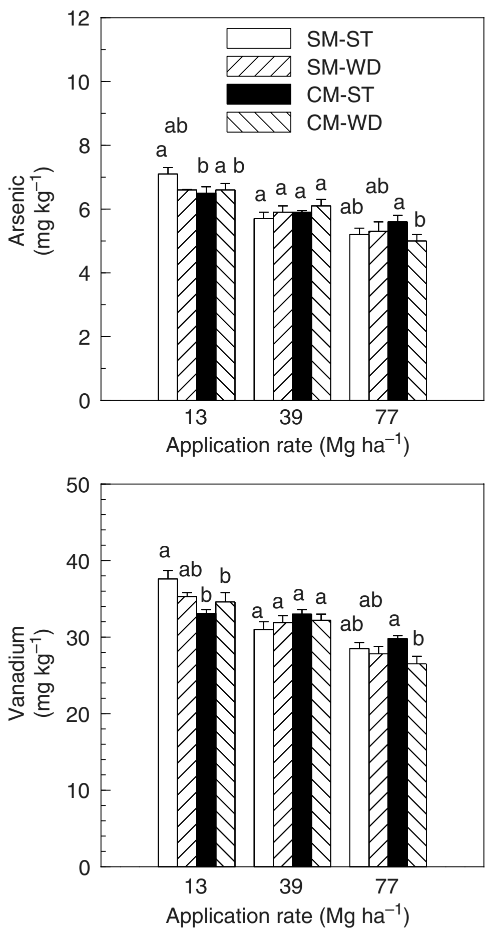


Table 6. Pearson's correlation coefficients between metal and strong-acid extractable concentrations of trace elements and total C (2015), and pH (2013) in soil (0–15 cm depth).

	Correlation coefficient (r)[a]	
Chemical	Total C	pH[b]
Al	−0.77***	0.16
As	−0.76***	0.12
Ba	−0.60***	−0.04
Cd	0.28*	−0.41**
Co	−0.75***	0.12
Cu	0.70***	0.02
Cr	−0.76***	0.06
Fe	−0.81***	0.28*
Li	−0.74***	0.24
Mn	0.03	−0.34**
Ni	−0.74***	0.10
Pb	0.35**	0.08
Sr	0.64***	0.02
Ti	−0.41**	−0.05
V	−0.80***	0.16
Zn	0.73***	−0.05

[a]Correlations are significant at 0.05 (*), 0.01 (**), and 0.001 (***) levels.
[b]The pH was done on a saturation paste extract.

contrast, concentrations of Cu, Sr, and Zn were greater for manured than IN treatments. This trend was also consistent with significant positive correlations between these three elements and total C in the soil. This suggested an influx of Cu, Sr, and Zn to amended soil from amendments for these elements whose concentrations are generally greater in amendment than soil. Concentrations of Ba, Mn, Pb, and Ti were similar for IN and MAN treatments.

Wei et al. (2006) reported that total concentrations of Cu, Fe, Mn, and Zn in surface soils after 18 yr for continuous maize or winter wheat were generally greater for co-application of IN and beef manure treatment compared with only IN treatment. Sheppard et al. (2009*b*) used modelling to predict inputs of trace elements to agricultural soils in Canada for 100 yr into the future. They found greater inputs of As to soils from INs compared with livestock manure, but the reverse trend for Cu and Zn, which was consistent with our findings. Luo et al. (2009) estimated the inputs of trace elements to soils in China and found that loadings of As, Cr, Cu, Ni, Pb, and Zn were greater for livestock manures compared with IN. Although IN and manure treatments were at different sites, Richards et al. (2011) found that long-term application of beef manure increased extractable concentrations of Cu, Fe, Mn, and Zn in the soil considerably more than IN when compared with CON. Contrasting findings are likely related to the different concentrations of metals and trace elements in IN and livestock wastes, and the application rates used.

The SAE concentrations of As, Ba, Co, Cr, Cu, Ni, Pb, V, and Zn in amended soils after 16 applications were well below the maximum recommended guidelines (total concentrations) for agricultural land use (CCME 1999). This was likely because we measured SAE instead of total concentrations. Benke et al. (2008) found that maximum total concentrations of Cu (34 mg kg^{-1}) and Zn (188 mg kg^{-1}) in amended soils after 25 applications at rates up to 180 Mg ha^{-1} were well below the CCME guideline for Cu, but were very close (94%) to the maximum allowable limit for Zn. There are currently no agricultural land use guidelines for total Al, Fe, Li, Mn, Sr, and Ti in soils of Canada.

Manure type had no significant effect on SAE concentrations of any of the trace elements in our study. There was a significant type × rate effect for Al, Cr, and Ti, where mean concentrations were 6%–12% greater for SM than CM at the 13 Mg ha^{-1} rate. There was also a significant type × bedding × rate effect on As and V, where mean concentrations were 9% greater for SM than CM with ST at the 13 Mg ha^{-1} rate. Overall, greater concentrations of these elements for SM than CM did not support the hypothesis of greater concentrations for CM than SM. In addition, these findings for soil were not consistent with the concentrations in the applied amendments. However, we only analyzed one sample from each of the four amendments in 1 yr, and concentrations may have varied considerably within each amendment, and over the years the amendments were applied. Possible explanations were that the SAE concentrations in our SM and CM amendments were different than the total concentrations for the fresh, interim, and composted feedlot manure reported by Larney et al. (2008). In addition, the close similarity of CM and SM amendments, and masking of amendment effects after mixing with the soil (Miller et al. 2005), may have resulted in greater concentrations for SM than CM. We may have found more significant manure type effects if the amendments were FM versus composted manure instead of SM versus CM. Larney et al. (2006) found that total C in feedlot manure at the Lethbridge Research Center feedlot was highest for FM (294 kg Mg^{-1}), followed by SM (242 kg Mg^{-1}), and then CM (187 kg Mg^{-1}), and was due to C losses mostly as CO_2.

Significantly greater SAE concentrations of Co, Cu, and Li for ST than WD (averaged across all application rates), and greater Fe, As, and V for ST than WD at 77 Mg ha^{-1} rate supported the hypotheses of greater total concentrations with ST than WD. The finding of greater Co, Cu, Fe, Li, and V for ST than WD was consistent with the same trend for the applied amendments, but not for As which is similar in the two amendments. Zvomuya et al. (2005) found greater total contents of Co, Cu, Fe, and As in ST than WD composted manure from this same feedlot. They attributed greater trace elements in ST than WD composted manure to use of fertilizers, herbicides, and pesticides on the barley crop that was the source of ST bedding. Registered pesticides in Canada may contain trace levels of As, Cd, Cr, Pb, Ni, and Co (Pest Management Regulatory Agency-Health Canada, personal communication, November 2017). Fertilizer, herbicides, fungicides, and pesticides may all be used on barley in Alberta (Alberta Barley 2017). In contrast, none of these products were used on the lodgepole pine and white spruce trees that were the source of WD bedding (West Fraser Forest Products, personal communication, 2017).

In contrast, 33% greater SAE concentrations of Cd for WD than ST at 39 and 77 Mg ha^{-1} rates did support the hypotheses, and was the same trend found in the applied amendments. The Cd content of plants depends on the plant genetics and the concentration of extractable or bioavailable Cd in soil solution that is accessed by plants (Grant et al. 1999). Cadmium in soils is also generally greater in coarser textured soils with lower pH and cation exchange capacities (Grant et al. 1999; Alberta Agriculture and Forestry 2015). The soils in which lodgepole pine and white spruce were grown and used for WD were mainly Gray Luvisols (Lavkulich and Arocena 2011) and Eutric Brunisols (Smith et al. 2011). The soils in which barley was grown for ST bedding were mainly Dark Brown Chernozems (Pennock et al. 2011). Gray Luvisols in Canada were developed on fine- to medium-textured parent materials with high base status, and generally have acidic sola with the soil pH decreasing from Ae to a maximum in the Bt horizon (Lavkulich and Arocena 2011). Eutric Brunisols in Canada were developed on medium- to coarse-textured parent materials with a relatively high degree of base saturation, and the pH of the Bm horizon is ≥5.5 (Smith et al. 2011). Dark Brown Chernozemic soils in Canada were developed on a wide textural range of parent materials, have a high base status, and the pH is generally alkaline because of high $CaCO_3$ content (Pennock et al. 2011). In addition, both pedogenesis and the nature of the parent material may influence the concentration of Cd in surface horizons (Dudas and Pawluk 1977). Therefore, we speculate that the generally coarser texture, lower soil pH, lower base status (i.e., CEC), and different parent material of the forest than grassland soils may have resulted in greater soil availability and uptake of bioavailable Cd by lodgepole pine and white spruce compared with barley. Further research would be required to determine if the Cd content of WD bedding is actually greater than in ST bedding.

Significantly greater SAE concentrations of Cu, Sr, and Zn with increasing manure application rates supported the hypotheses that more manure would increase these elements. In contrast, significantly lower concentrations of Ba, Co, Li, and Ni occurred with greater manure application rates, suggesting a greater dilution effect of background soil elemental concentrations as manure rates increased. Concentrations also generally declined with greater rates for Al, Cr, and Ti with SM and CM (type × rate effect), with greater rates for Fe with ST or WD (bedding × rate effect), and with greater rates for As and V with the four manure types-bedding treatments (type × bedding × rate effect).

Chang et al. (1991) found that greater application rates (60, 120, and 180 Mg ha^{-1} wet weight) of beef feedlot manure over 11 yr significantly increased the concentration of extractable Zn in the surface soil, but not Cu. In a follow-up study after 25 annual applications, Benke et al. (2008) found that greater application rates significantly increased the concentration of total Cu and Zn, but had no effect on Co. Qian et al. (2003) reported no influence of application rate (100, 200, and 400 kg ha^{-1}) of solid cattle manure on total Cu and Zn in surface soils after 5 yr. Lipoth and Schoenau (2007) examined total Cu and Zn in soil after 5–7 yr of beef feedlot manure application (8, 15, and 30 Mg ha^{-1} dry weight). They found significantly greater total Cu for the 30 Mg ha^{-1} rate than two lower rates, but total Zn was unaffected by manure rate.

It should be pointed out that the current study only sampled the surface 0–15 cm of soil, and organic amendment effects are likely most amplified at this shallow depth. Deeper soil sampling below the ~20 cm depth of manure incorporation is less likely to show the impact of organic amendments, such as dilution effects on inherent soil elemental concentrations, although amendment-derived trace element leaching to depth cannot be ruled out.

It is possible that differences in crop yield and plant uptake of the trace elements may have influenced SAE concentrations of these elements. For example, if crop uptake was greater for a certain treatment, this may have lowered the concentration in the soil, and vice versa. Miller et al. (2015) reported treatment differences in dry matter yield of barley grown for silage, but yield differences were inconsistent across years. For example, mean yields after 8 yr (2005) were significantly greater for CM-ST than SM-WD, but CM-ST was similar to SM-ST and CM-WD when averaged over the three application rates. In contrast, yields after 12 yr (2009) were significantly lower for CM-WD compared with the other three treatments, and were greater for ST-13 and WD-77 compared with WD-13 treatment. Benke et al. (2013) reported that 37 yr of annual feedlot manure application resulted in significantly greater Zn uptake by barley silage.

Conclusions

Currently, most feedlots apply fresh or SM with ST bedding. If feedlot producers shift from SM to CM, our findings suggest that this will likely not result in any change in the total concentration of measured metals and trace elements after 16 yr or annual applications. In contrast, a shift from ST to WD bedding may decrease SAE concentrations of Co, Cu, and Li (averaged across all manure rates); as well as Fe, As, and V at the 77 Mg ha^{-1} rate; and this may be advantageous if the soils have excessive concentrations of these elements. However, WD bedding may increase Cd at the 39 and 77 Mg ha^{-1} rates, which may have a negative effect for agricultural land use, particularly human consumption of crops. Therefore, bedding material may be a possible option to manage these elements in MAN soils. If producers are applying feedlot manure at 13 Mg ha^{-1} rate and increase rates to 39 and 77 Mg ha^{-1}, this may cause an increase of Cu, Sr, and Zn in the soil, but not the other elements because these elements are derived from soil and were likely diluted by manure.

Long-term application of feedlot manure (Cu, Sr, and Zn) and fertilizer (Cd) to a clay loam soil caused an increase compared with unamended soils. Copper, Sr, and Zn were greater for manured than IN treatments, and the reverse trend occurred for Al, As, Co, Cr, Fe, Li, Ni, and V. None of the SAE concentrations after 16 annual applications of manure or fertilizer had increased to levels that exceeded the federal soil quality guidelines (total concentrations) for agricultural land use. However, this may have been due to SAE concentrations being lower than total concentrations.

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