

Phosphorus and trace metal distribution under confined cattle feeding operations in Southern Alberta

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Abstract

Intensive beef cattle production in confined cattle feeding operations (CCFO) are characterized by accumulating layers of solid manure that cover the underlying mineral soil all year round. The extent to which nutrients and trace elements accumulate in the underlying soils is unknown but these present a potential risk to water sources as a result of surface run-off and leaching. Therefore, concentrations and depth distributions of phosphorus (P) and trace elements as typical marker compounds of manure affected environments were investigated in soil profiles of a research CCFO and compared to an unaffected grassland soil in the semi arid area of southern Alberta, Canada. Mean total P concentrations (TP) in the soil profiles were 384 mg kg⁻¹ for the CCFO and 409 mg kg⁻¹ for the grassland with only few significant differences between the soil profiles within each location and between the two locations. These differences could be explained by slight changes in the parent material. A sequential P fractionation revealed that most P occurred in the HCl fraction (> 51 % of TP), demonstrating strong binding of P to calcium and thus low mobility in these calcareous Dark Brown Chernozemic clay loam soils. There were no uniform enrichments and changes in the P fractions determined after nine years of CCFO operation. Similarly, there was no accumulation of the trace elements Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn in the soil profiles under the CCFO. In conclusion, under current feeding and management practices, there is a low risk of groundwater pollution through leaching from CCFOs under these semi-arid climate conditions.

Keywords: Phosphorus fractionation, phosphorus and metal accumulation

Zusammenfassung

Verteilung von Phosphor und Schwermetallen in Böden unterhalb intensiver Rinderhaltung im südlichen Alberta, Kanada

In Kanada ist intensive Rinderhaltung in offenen Masttieranlagen (Feedlots) eine gängige Produktionspraxis. In Feedlots verbleibt der anfallende Rindermist fast ganzjährig auf dem anstehenden verdichteten Mineralboden. Unklar ist inwieweit Nährstoffe und Schwermetalle wie Cd, Cr, Cu, Fe, Mn, Ni, Pb und Zn, in den darunterliegenden Böden akkumulieren und natürliche Wasserressourcen durch Austrag mit Oberflächenabfluss oder Sickerwasser gefährden. In dieser Studie wurden Konzentrationen und Verteilungen von Phosphor und Schwermetallen in Bodenprofilen unter einem experimentellen Feedlot und einem langjährig genutzten Graslandstandort ohne Beweidung untersucht. Die mittlere Konzentration an P-Total (TP) in Böden des Feedlots lag bei 384 mg kg⁻¹ und bei 409 mg kg⁻¹ unterhalb des Graslandes. Unterschiede in TP waren nur vereinzelt signifikant, sowohl beim Vergleich zwischen den Tiefenstufen innerhalb eines Bodenprofils, wie auch zwischen gleichen Tiefenstufen der Feedlot- und Graslandböden. Die wenigen signifikanten Unterschiede wurden mit Unterschieden im Ausgangsmaterial erklärt. Mittels sequentieller P Fraktionierung wurde der überwiegende P Anteil in der HCl-Fraktion nachgewiesen (> 51 % von TP), was die feste Bindung von P an Calcium und damit die geringe Mobilität in diesen tonigen Tschernosem-Braunerden hervorhebt. Es wurden keine gerichteten Anreicherungen und Veränderungen in den verschiedenen P Fraktionen wie auch den Schwermetallgehalten infolge neunjähriger Nutzung als Feedlot nachgewiesen. So ist zu schlussfolgern, dass in dieser semi-ariden Region und unter dem derzeitigen Futter- und Betriebsmanagement des Feedlots keine Auswaschung von Phosphor und Schwermetallen ins Grundwasser zu erwarten ist.

Schlüsselworte: Phosphor Fraktionen, Phosphor- und Schwermetallanreicherung

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Introduction

Confined cattle feeding operations (CCFOs) are a common practice for beef production in Canada with the highest density occurring in southern Alberta. The construction and management of these CCFOs is regulated by the Alberta Agricultural Operation Practices Act guidelines. Modern operations are sited and managed according to these guidelines aiming to protect the environment by minimizing adverse impacts on the surrounding landscapes and watersheds (Olsen et al., 2005). The typical CCFOs structure includes the natural subsoil as the base, from which the topsoil was removed in the construction phase. During operation the subsoil is mostly covered by a black layer of mixed organic and mineral soil that forms in pens through cattle activity. This black layer is covered by manure which reaches up to 60 cm (Dantzman et al., 1983). The manure layer can be an important source of nutrient leaching and runoff (Miller et al., 2006; Olsen et al., 2005). In addition its physical properties influence nutrient transport by absorbing up to 25 mm of any precipitation before runoff occurs (Miller et al., 2008).

Previous studies focusing on the transport of nutrients, especially nitrate (NO_3^-) and phosphorus (P) (Schuman and McCalla, 1975), to the groundwater under such operations revealed contradicting results. Although increased concentrations of NO_3^- and salts in the soil profiles beneath CCFOs were found (Coote and Hore, 1979; Mielke et al., 1974), the risk of elevated P concentrations in the soils was low (Campbell and Racz, 1975; Coote and Hore, 1979). Studies investigating the nutrient enrichment under CCFOs built on loam soils tended to reveal only minimal leaching of NO_3^- from CCFOs operating for less than 40 years and no leaching of P operating for up to 100 years (Vaillant et al., 2009; Zhu et al., 2004). By contrast, studies examining groundwater usually detected some nutrient enrichment under CCFOs (Miller et al., 2004). A study of five 25- to 35-year old CCFOs in central Saskatchewan focusing on nutrient concentration groundwater showed that 50 to 67 % of the groundwater samples had elevated solute concentrations due to the accumulation of manure (Maulé and Fonstad, 2000, 2002).

Solute transport from the manure was attributed to both matrix flow and preferential flow and contaminated shallow groundwater 20 m outside the CCFO (Miller et al., 2004). Also, in a three year operated CCFO the P concentrations in pen wells increased, whereas soil analyses indicated available P accumulations only down to 0.15 m soil depth, which may simply be a result of mechanical mixing by cattle (Olson et al., 2005). These discrepancies between the soil and groundwater data may be the result of possible preferential flow in the soil (Olson et al., 2005).

For predicting the mobility, bioavailability and potential of P transfer knowledge of the P distribution and availabil-

ity in soils beneath manure with high P concentration is essential. A sequential fractionation allows a classification of the P in the soil in pools with varying availability for plants, leaching and the resulting environmental consequences (Thiessen and Moir, 1993; Negassa and Leinweber, 2009). This procedure separates P into plant-available (H_2O - and NaHCO_3 -extractable; soil test P (STP)), Al- and Fe-hydroxide and oxide-associated (NaOH-extractable) and Ca-bound (HCl-extractable) forms (Hedley et al., 1982). Research has shown that high application rates of cattle manure on surrounding fields can cause an accumulation and change of P distribution in soil (Hao et al., 2008) and may increase concentrations of P in surface runoff and groundwater. This raises the question whether CCFOs with year round manure accumulation leads to changes in P fractions in the soil.

Besides organic matter, manure also contains major plant nutrients and trace elements, such as cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn). With the exception of Pb, Cd and Cr, trace elements may be added as animal feed supplements to the cattle diet, in order to promote physiological processes and maintain animal health (Nicholson et al., 1999). Consequently, long-term application of such enriched manure to agriculture land increased the concentration of these metals in the soil (Benke et al., 2008; Thiele and Leinweber, 2001). This may also be the case for soils below CCFOs themselves as these are in contact with trace elements-enriched manure for long time periods. Depending mainly on the elements solubility, soil pH and binding capacity (Hesterberg, 1998) metals may be transported by leaching (Li and Shuman, 1997) or runoff (Moore et al., 1998) to water resources. Leaching of trace metals mostly occurred in acidic and coarse textured soils (McBride, 1995), under neutral to alkaline soil conditions leaching is related to metal complexation with dissolved organic matter and preferential flow (Maeda and Bergstrom, 2000; McBride et al., 1997). Whereas the transport of nutrients may result in visible signs of eutrophication of water resources, the accumulation and transport of trace elements from soils beneath CCFOs and their possible enrichment in the food chain is relatively unknown and therefore should be taken into consideration when assessing the impact of CCFOs on the environment.

Therefore, in this study we determined the P and trace element concentration and the P distribution in manure and a soil of a Canadian research feeding operation and as a control in the subsoil of a natural grassland. We tested the hypothesis that after nine years of operation P and trace metals were translocated and accumulate in the soil underneath the manure and that this resulted in a change of P forms and therefore P availability even in deeper soil layers.

Material and Methods

Site description

This study was carried out at two research sites: (1) the research CCFO of the Agriculture and Agri-Food of Canada Lethbridge Research Centre in Lethbridge, AB, Canada (49° 43' N, 112° 48' W) and (2) a nearby grassland control. Both locations are of the same pedogenesis and soils classified as Dark Brown Chernozemic clay loam soils (Aridic Haplustolls – US Soil Taxonomy, Hao et al., 2003). The site of the CCFO consisted of lacustrine material with about 1 m thickness over an oxidized till deposit (Olson et al., 2005).

The CCFO was constructed in 1995 to 1996 (Olson et al., 2005). During the construction phase the topsoil was, according to Alberta Agricultural Operation Practices Act guidelines, removed from the area, therefore all presented results will refer to the original subsoil. Clay material was used to construct the surface topography with an overall slope from south to north for drainage (Miller et al., 2003, 2004). The operation included 32 pens, each 14 m × 19.5 m. Each pen held 15 beef cattle (*Bos taurus*). All pens were bedded with barley straw and typically cleaned out by the end of August. During operation the cattle activity will create a typical black layer, a mixture of organic matter and clay. The grassland control was located approx. 1 km north of the CCFO. The site was reseeded to grass in 1930 and maintained without any fertilizer application or human activities until sampling. General soil characteristics can be found in Table 1. As stated by Aust et al. (2008) there were no significant differences in texture between the two sample sites.

The climate in this area is semiarid with an annual mean temperature of 6.4 °C between 1995 and 2005. The mean annual precipitation during this time was 409 mm, with a range from a maximum of 625 mm in 2005 to a minimum of 149 mm in 2001. Whereas in July 2005 only 13 mm precipitation was measured, in June 2005 the highest monthly precipitation of 269 mm occurred. In this month six rainfall events with > 22 mm per day and a maximum daily precipitation of 67 mm were recorded. All weather data were obtained from the meteorological station at the Lethbridge Research Centre at a distance of 0.7 km from the CCFO.

Soil and manure sampling

First, for comparison of P enrichment in the soil, samples from the CCFO and grassland were taken in July 2005 using a hydraulically powered truck mounted core tube (diameter 5 cm). From the grassland two sets of samples were taken to a depth of 110 cm in 10 cm increments. For comparison of the subsoil profiles, the topsoil samples from this location were excluded from further analysis; therefore, all results relate to subsoil depths. Samples were composited in increments of 0-10, 10-30, 30-60 and 60-90 cm. In the CCFO manure and soil samples were taken from locations with high manure density close to the feedbunk. Sampling ditches were created by removing the mixture of bedding and manure from the soil surface with a pitchfork on a square of approx. 30 cm × 30 cm. Three manure samples were taken above the mineral soil surface. Soil samples were taken in five different pens, in each pen three soil cores were obtained and samples were segmented in the depths 0-10, 10-30, 30-60 and 60-90 cm. As we tested the hypotheses that the nine year

Table 1:

Soil physical and chemical properties of the confined cattle feeding operation and the grassland in 2005

| Depth cm | Sand % | Clay % | pH | | TC | OC g kg ⁻¹ | TN |
|-----------------------------------|-----------|-----------|-------------|---|--------------|--------------------------|---------------|
| Confined cattle feeding operation | | | | | | | |
| 0-10 | 29 | 31 | 7.94 ± 0.03 | A | 18.32 ± 3.53 | 11.99 ± 1.27 | 1.43 ± 0.14 |
| 10-30 | 30 | 29 | 7.81 ± 0.07 | A | 14.16 ± 3.35 | 6.70 ± 0.96 | B 0.79 ± 0.13 |
| 30-60 | 37 | 30 | 7.97 ± 0.01 | A | 16.78 ± 2.61 | B 4.83 ± 0.84 | B 0.49 ± 0.09 |
| 60-90 | 33 | 29 | 8.02 ± 0.03 | | 13.88 ± 2.45 | B 3.62 ± 0.03 | B 0.35 ± 0.01 |
| Grassland | | | | | | | |
| 0-10 | 47 | 22 | 7.26 ± 0.09 | B | 15.99 ± 0.16 | 15.64 ± 0.20 | 1.64 ± 0.03 |
| 10-30 | 34 | 27 | 7.44 ± 0.06 | B | 19.52 ± 0.04 | 19.27 ± 0.03 | A 1.99 ± 0.00 |
| 30-60 | 30 | 27 | 7.74 ± 0.09 | B | 37.04 ± 1.26 | A 14.22 ± 1.36 | A 1.48 ± 0.05 |
| 60-90 | 36 | 25 | 7.95 ± 0.07 | | 29.64 ± 0.27 | A 6.00 ± 0.32 | A 0.73 ± 0.01 |

For each soil depth, values in a column followed by different uppercase letters indicate significant ($P < 0.05$) location effects. Only significant differences are stated. TC total carbon, OC organic carbon, TN total nitrogen

CCFO resulted in P enrichment in the subsoil through constant manure storage, total P and available P was determined in all pens. Since there was no difference between the pens, we focused further on the distribution of various P pools under such conditions. Therefore, as a second aspect, the changes over time caused by management were investigated. Therefore, samples from one pen, sampled in 1996, 1999 and 2005 were tested. The detailed sampling for the years 1996 and 1999 is described by Olsen et al. (2005). Briefly, soil samples were collected during the construction in March 1996 phase and during operation in August 1999. On the second sampling date the pens were empty of cattle and in the process of being cleaned of manure. Composite samples were prepared from three cores samples in depth increments of 0-15, 15-30, 30-60 and 60-90 cm. Since the annual cleaning resulted in a removal of the first cm of the original subsoil, it seems more suitable to only compare the first 10 cm in 2005 with the first 15 cm in the years 1996 and 1999. All samples taken in 1996, 1999 and 2005 were air dried, ground (< 2mm), and stored before analysis.

Soil and manure analysis

Available P and pH was measured in air dried and sieved < 2 mm soil and manure samples. The pH was measured in 0.01 M CaCl₂ at a solid to liquid ratio of 1:2.5 for soil and 1:10 for manure. Available P was determined with sodium bicarbonate (Olsen-P) according to (Olsen et al., 1954). Phosphorus concentrations in the extracting solutions were determined using a Technicon autoanalyzer (Technicon Industrial Systems, Tarrytown, NY). Soil texture was determined using the sieve-pipette-method according to DIN ISO 11277 (2002).

Soil and manure samples were further finely ground to < 0.150 mm for total carbon (TC) and total nitrogen (TN) analysis, determined by using dry combustion techniques with an automated elemental analyzer (Carlo Erba, Milan, Italy). Inorganic C was measured after acid treatment with a gas chromatograph using a modified method of Amundson et al., (1988) and organic C was calculated as the difference between total and inorganic C content (Table 1). Total P (TP) was measured by two methods. First, using the wet digestion method of Parkinson and Allen (1975). Briefly, 0.25 g of the soil sample was weighed into a digestion tube and digested at 360 °C for 1.5 h with concentrated H₂SO₄, Li₂SO₄, Se powder, and hydrogen peroxide. Phosphorus in digests was analyzed colorimetrically by the ammonium molybdate–ascorbic acid method (Murphy and Riley, 1962) using a Technicon AutoAnalyzer (Technicon Industrial Systems).

Secondly, TP was calculated as the sum of various P fractions; the P fractionation followed the method of Sui et al.

(1999). Briefly, 1.5 g soil or 0.25 g manure (< 2 mm) were sequentially extracted as replicates with 30 mL of H₂O, 0.5M NaHCO₃, 0.1M NaOH and 1M HCl after 16 hours of shaking, centrifuge at 15,000 rpm and supernatant solution decanted. Afterwards the residues were digested with 18M H₂SO₄ (+ H₂O₂ and Li₂SO₄ + Se powder for digesting). The inorganic P (P_i) concentration in the extracts was directly analyzed colorimetrically by the ammonium molybdate-ascorbic acid method (Murphy and Riley, 1962) and the total P (P_t) concentration was measured after digestion with ammonium persulfate + 0.9M H₂SO₄ using a Technicon Autoanalyzer (Technicon Industrial Systems, Tarrytown, NY). The organic P (P_o) in the extract was calculated as the difference between P_t and P_i. Summarization of all P_i concentrations in extracts (H₂O, NaHCO₃, NaOH and HCl) and in the digested residual was the total P (TP) in the soil or manure. The sum of P_i in H₂O, NaHCO₃, NaOH and HCl is classified as total P_i, whereas the corresponding organic fractions are classified as P_o. The P_t H₂SO₄ is referred to as residual P (P_{res}).

Total concentrations of the elements Cd, Cr, Cu, Ni, Pb, Zn, Fe and Mn were determined after combustion of fresh soil at 950°C (Zeien and Brümmer, 1989). Briefly, 100 to 200 mg of combusted fine ground soil (< 0.125 mm) was weighed into 50 mL teflon tubes and 3 mL HNO₃ and 1 mL H₂O₂ were added. Fivefold samples were digested for 6 h at 170°C, filtered and diluted to 50 mL with double distilled water. The concentrations of trace metals in the resulting solution were determined using a Varian AA 240 DUO AAS (Varian, Germany).

Data handling and statistical analysis

Soil P fractions were statistically analyzed separately for the experimental research CCFO at three different sampling dates (1996, 1999 and 2005) and in the year 2005 at the two locations (CCFO and the grassland control). Trace elements in 2005 were also statistically analyzed for the two locations. The replicates were nested in location and year, so that the analysis was performed using a completely randomized design with PROC MIXED (SAS Institute Inc., 2005) with location, year and sampling depth, and their interaction treated as fixed effects. Tests of significant difference between the mean values were made using Fisher's protected LSD test and were considered significant only at $P < 0.05$.

Results and Discussion

Soil organic carbon and total nitrogen

While the TC contents were relatively constant in the CCFO profile, they showed a steep increase at 30-60 cm

in the grassland profile (Table 1). However, OC was enriched only in the upper 10 cm of the CCFO. Below this depth OC varied in the range of 4 to 7 g kg⁻¹. This range of concentrations was observed in the grassland control profiles at 60-90 cm depth. Similar to OC the TN contents were smaller in the CCFO than in the grassland profile. The OC:TN ratio as indicators of organic matter changes in the profiles ranged from 8 to 10 (CCFO) and 10 to 8 (grassland) and indicated animal dung-derived N enrichments in the first 30 cm of the CCFO profile. If we compare the largest TN content under CCFO (1.43 g kg⁻¹) with the TN contents in the upper part of the grassland profile, than it is obvious that the dung accumulation in the CCFO did not result in any organic N enrichment. This can be explained by two processes: (i) arable soil management prior to the CCFO construction had reduced the native organic N content, and (ii) more excrement derived N was lost to the atmosphere in gaseous form than caused enrichments in soils. Reductions in TN contents of 0.6 g kg⁻¹ following cultivation of the prairies were observed in a pair of native and cultivated soils from the Lethbridge region, and of 1.5 to 1.9 g kg⁻¹ in soils from Saskatchewan (Leinweber et al., 2009). The above difference of 0.6 g kg⁻¹ is comparable to the difference in TN between the grassland and the CCFO at 0-30 cm soil depth. Atmospheric N losses from the ex-

crement can originate from NH₃ volatilization and denitrification. Major factors conducive to denitrification such as high organic matter, limited oxygen, due to compaction and alkaline pH (Tisdale et al., 1985) are combined in the CCFO (Table 1). Therefore, it is not surprising that no particular enrichment in TN was found in the CCFO soil profile

Total phosphorus in manure and soil

The TP concentration in the manure was 3097 mg kg⁻¹ (Table 2), which is in the range of other studies on cattle manure (Turner and Leytem, 2004). The TP concentrations in the first 10 cm of the mineral soil beneath the manure were 384 in the CCFO and 391 mg kg⁻¹ in the subsoil of the grassland. These values are typical for subsoils in this dark brown Chernozemic clay loam soils. In the CCFO profile the TP concentration varied between 356 and 409 mg kg⁻¹, with the highest concentration at a soil depth of 30-60 cm (Table 3). The TP distribution in the grassland soil was similar, but slightly higher values were observed (391 to 507 mg kg⁻¹). For both locations the pattern in the soil profile could be explained by the parent material with a change in soil texture and accumulation as calcium phosphate. Whereas in other areas high rainfall causes P leaching through the subsoil resulting in non-uniform dis-

Table 2:

Mean concentration (mg kg⁻¹) of various total P forms (P_t) and total P (TP) in the manure of the confined cattle feeding operation including the percentage of each fraction of TP (in parentheses) and the ratio of P_t/P_o per fraction (in parentheses)

| H ₂ O P _t | NaHCO ₃ P _t | NaOH P _t | HCl P _t | H ₂ SO ₄ P _t | TP |
|---------------------------------|-----------------------------------|---------------------|--------------------|---|--------|
| 788.6 (25.5) | 694.4 (22.4) | 615.5 (19.9) | 826.1 (26.7) | 172.5 (5.6) | 3097.1 |
| (78/22) | (80/20) | (28/72) | (41/59) | | |

Table 3:

Mean concentration (mg kg⁻¹) of various total P forms (P_t) and total P (TP) in the confined cattle feeding operation and the grassland control in 2005

| Depth cm | mg kg ⁻¹ | | | | | | | | | | TP | |
|-----------------------------------|---------------------------------|----|-----------------------------------|----|---------------------|-----|--------------------|-----|---|-----|-------|----|
| | H ₂ O P _t | | NaHCO ₃ P _t | | NaOH P _t | | HCl P _t | | H ₂ SO ₄ P _t | | | |
| Confined cattle feeding operation | | | | | | | | | | | | |
| 0-10 | 5.6 | a | 15.2 | a | 32.1 | Ba | 216.5 | c | 69.9 | a | 349.3 | |
| 10-30 | 5.4 | ab | 3.7 | Bb | 7.0 | Bb | 282.1 | Abc | 59.5 | Bb | 356.4 | B |
| 30-60 | 4.9 | b | 4.6 | Bb | 6.0 | Bbc | 349.9 | a | 43.3 | Bc | 408.7 | |
| 60-90 | 5.0 | ab | 4.2 | b | 4.5 | Bc | 318.7 | Bab | 42.0 | Bc | 374.4 | B |
| Grassland | | | | | | | | | | | | |
| 0-10 | 5.4 | | 10.4 | | 88.1 | Ab | 213.8 | c | 73.5 | b | 391.1 | c |
| 10-30 | 5.4 | | 10.7 | A | 100.2 | Aa | 208.1 | Bc | 81.0 | Aab | 405.4 | Ac |
| 30-60 | 5.0 | | 8.2 | A | 40.1 | Ac | 364.3 | a | 89.2 | Aa | 506.8 | a |
| 60-90 | 4.7 | | 12.9 | | 8.5 | Ad | 401.8 | Aab | 47.9 | Ac | 475.8 | Ab |

For each soil depth, P concentration in a column followed by different uppercase letters indicate significant ($P < 0.05$) location effects. For each location, P concentration in a column followed by different lowercase letters indicate significant ($P < 0.05$) soil depth effects. Only significant differences are stated.

Table 4:

Mean concentration (mg kg⁻¹) of various total P forms (P_t) and total P (TP) in the confined cattle feeding operation in the years 2005, 1999 and 1996

| Depth cm | H ₂ O P _t | | NaHCO ₃ P _t | | NaOH P _t | | HCl P _t | | H ₂ SO ₄ P _t | | TP | |
|--|---------------------------------|-----|-----------------------------------|----|---------------------|----|--------------------|-----|---|----|-------|----|
| mg kg ⁻¹ | | | | | | | | | | | | |
| Confined cattle feeding operation 2005 | | | | | | | | | | | | |
| 0-10 | 5.6 | ABa | 15.2 | Ba | 32.1 | Ba | 216.5 | Ac | 69.9 | a | 349.3 | |
| 10-30 | 5.4 | ab | 3.7 | Bb | 7.0 | Cb | 282.1 | bc | 59.5 | b | 356.4 | |
| 30-60 | 4.9 | b | 4.6 | Ab | 6.0 | bc | 349.9 | Aa | 43.3 | Cc | 408.7 | |
| 60-90 | 5.0 | ab | 4.2 | b | 4.5 | c | 318.7 | ab | 42.0 | c | 374.4 | |
| Confined cattle feeding operation 1999 | | | | | | | | | | | | |
| 0-10 | 6.5 | Ba | 27.0 | Aa | 62.2 | Aa | 249.4 | Ab | 65.3 | a | 410.4 | a |
| 10-30 | 5.6 | b | 4.6 | Bb | 20.3 | Bb | 255.7 | b | 57.5 | b | 343.7 | b |
| 30-60 | 5.5 | b | 3.4 | Bb | 7.9 | c | 247.7 | Bb | 68.5 | Aa | 333.0 | b |
| 60-90 | 5.5 | b | 3.7 | b | 4.0 | c | 313.9 | a | 44.8 | c | 371.9 | ab |
| Confined cattle feeding operation 1996 | | | | | | | | | | | | |
| 0-10 | 4.9 | A | 9.4 | Ca | 31.7 | Ba | 221.3 | Bc | 68.6 | a | 336.0 | b |
| 10-30 | 5.2 | | 6.7 | Ab | 24.7 | Ab | 261.0 | bc | 65.0 | ab | 362.6 | ab |
| 30-60 | 6.4 | | 4.5 | Ac | 8.3 | c | 302.9 | ABb | 53.4 | Bb | 375.5 | ab |
| 60-90 | 5.2 | | 4.3 | c | 5.5 | c | 351.2 | a | 37.4 | c | 403.7 | a |

For each soil depth, P concentration in a column followed by different uppercase letters indicate significant ($P < 0.05$) effects over years. For each location, P concentration in a column followed by different lowercase letters indicate significant ($P < 0.05$) soil depth effects. Only significant differences are stated.

tribution (Godlinski et al., 2004), this process is negligible in this semiarid area. Also, whereas TP concentrations in subsoils of cultivated soils increased after long-term heavy manure application (Eghball et al., 1996; James et al., 1996; Whalen and Chang, 2001), the uniform distribution of TP in the soil below the CCFO did not indicate a recent influence by tillage or uptake by plants. For the grassland, the long-term growth of perennial grass might have caused the partly significant differences in the soil profile as a result of microbial activity in the root zone.

During the period 1996 to 2005 no significant change in the TP concentration in the soil profile of the CCFO was observed (Table 4). Slightly different patterns in the profile were attributed to the mixing activity of the cattle, the cleaning process, the replacing of the clay layer and different sampling locations within the pen. Our results are in contrast to increases in P concentrations in CCFO soil profiles after 10 yrs on a fine sand loamy soil in Florida (Dantzmman et al., 1983), which may be explained by the coarser soil texture and the up to 3 times higher annual rainfall in Florida compared to the site of the present study.

Phosphorus fractions in manure and soil

The manure was characterized by an almost even distribution between the P fractions with 20 to 27 % of total P, except the H₂SO₄ (≤ 6 %) fraction (Table 2). Because nearly 50 % of the P is readily soluble (H₂O and NaHCO₃), there is a

high potential for leaching or surface runoff after high rainfall events and pollution of water resources. In contrast to our findings, other researchers reported much greater proportions of available P, with P distributions of 67, 13, 5, and 5 % P from dairy (Dou et al., 2000) or 11, 43, 19 and 6 % P from cattle manures (Turner and Leytem, 2004) extracted by H₂O, NaHCO₃, NaOH, and HCl. Varying P concentration in bedding material, supplemented Ca to the animal feed to benefit reproductive health (Cooperband and Good, 2002), and different storage times are responsible for the wide range of P concentrations and distribution of P forms in manure. This is especially relevant in the HCl fraction.

In both of the calcareous dark brown chernozemic clay loam soils most of the P was determined in the HCl fraction (≤ 86 %), followed by the NaOH (≤ 24 %) > H₂SO₄ (≤ 20 %) > NaHCO₃ (≤ 4 %) > H₂O (≤ 2 %) fractions (Table 5). This distribution varied slightly between the two locations (Table 5) and over the years (Table 6), but in most cases this variation was not significant.

Whereas the proportion of the available P fractions (H₂O and NaHCO₃) and moderately labile fraction (NaOH) of TP decreased with soil depth, the proportion of the HCl fraction increased. This high proportion of Ca-bound P can be explained by the high calcium carbonate concentration in this glacial formed area (Table 1). While in the first 10 cm of the CCFO only 34.5 % are carbonate, it is > 52.7 % in the deeper layers. Similar results for high proportion of Ca-bound P were reported for soil profiles with pH > 7 from

Table 5:

Ratio of inorganic to organic P in each fraction and percentage of each fraction of total P (TP) for the confined cattle feeding operation and the grassland control in 2005

| Depth cm | H ₂ O P | | NaHCO ₃ P | | NaOH P | | HCl P | | H ₂ SO ₄ P |
|-----------------------------------|--------------------------------|---------|--------------------------------|---------|--------------------------------|---------|--------------------------------|---------|----------------------------------|
| | P _i /P _o | % of TP | P _i /P _o | % of TP | P _i /P _o | % of TP | P _i /P _o | % of TP | % of TP |
| Confined cattle feeding operation | | | | | | | | | |
| 0-10 | 10/90 | 1 | 61/39 | 4 | 23/77 | 8 | 95/5 | 68 | 18 |
| 10-30 | 8/92 | 2 | 100/0 | 1 | 20/80 | 2 | 97/3 | 79 | 17 |
| 30-60 | 9/91 | 1 | 100/0 | 1 | 43/57 | 1 | 89/11 | 86 | 11 |
| 60-90 | 16/84 | 1 | 100/0 | 1 | 60/40 | 1 | 92/8 | 85 | 11 |
| Grassland | | | | | | | | | |
| 0-10 | 26/74 | 1 | 82/18 | 3 | 14/86 | 23 | 94/6 | 55 | 19 |
| 10-30 | 12/88 | 1 | 88/12 | 3 | 10/90 | 24 | 93/7 | 52 | 20 |
| 30-60 | 16/84 | 1 | 93/7 | 2 | 7/93 | 8 | 95/5 | 72 | 18 |
| 60-90 | 40/60 | 1 | 33/67 | 3 | 14/86 | 2 | 100/0 | 84 | 10 |

Table 6:

Ratio of inorganic to organic P in each fraction and percentage of each fraction of total P (TP) for the confined cattle feeding operation in the years 2005, 1999 and 1996

| Depth cm | H ₂ O P | | NaHCO ₃ P | | NaOH P | | HCl P | | H ₂ SO ₄ P |
|--|--------------------------------|---------|--------------------------------|---------|--------------------------------|---------|--------------------------------|---------|----------------------------------|
| | P _i /P _o | % of TP | P _i /P _o | % of TP | P _i /P _o | % of TP | P _i /P _o | % of TP | % of TP |
| Confined cattle feeding operation 2005 | | | | | | | | | |
| 0-10 | 10/90 | 1 | 61/39 | 4 | 23/77 | 8 | 95/5 | 68 | 18 |
| 10-30 | 8/92 | 2 | 100/0 | 1 | 20/80 | 2 | 97/3 | 79 | 17 |
| 30-60 | 9/91 | 1 | 100/0 | 1 | 43/57 | 1 | 89/11 | 86 | 11 |
| 60-90 | 16/84 | 1 | 100/0 | 1 | 60/40 | 1 | 92/8 | 85 | 11 |
| Confined cattle feeding operation 1999 | | | | | | | | | |
| 0-10 | 12/88 | 2 | 100/0 | 7 | 28/72 | 15 | 95/5 | 61 | 16 |
| 10-30 | 13/87 | 2 | 57/43 | 1 | 14/86 | 6 | 96/4 | 74 | 17 |
| 30-60 | 12/88 | 2 | 96/4 | 1 | 15/85 | 2 | 100/0 | 74 | 21 |
| 60-90 | 28/72 | 1 | 100/0 | 1 | 25/75 | 1 | 94/6 | 84 | 12 |
| Confined cattle feeding operation 1996 | | | | | | | | | |
| 0-10 | 14/86 | 1 | 72/28 | 3 | 24/76 | 9 | 96/4 | 66 | 20 |
| 10-30 | 14/86 | 1 | 69/31 | 2 | 13/87 | 7 | 88/12 | 72 | 18 |
| 30-60 | 15/86 | 2 | 87/13 | 1 | 15/85 | 2 | 92/8 | 81 | 14 |
| 60-90 | 27/73 | 1 | 78/22 | 1 | 39/61 | 1 | 91/9 | 87 | 9 |

dairies in south Florida (Nair et al., 1995) and calcareous soils in Manitoba (Kashem et al., 2004).

The distribution of total P_i, P_o and P_{res} in the manure measured in 2005 was 54.2, 40.2 and 5.6 %, respectively, compared to the grassland soil with 57.1, 24.1 and 18.8 % and the CCFO soil with 69.3, 12.5 and 18.2 %. Higher proportion of P_o in the grassland than in the CCFO demonstrates a higher microbial activity, associated with biomass accumulation. This result agrees with data from a 13 yr-old feedlot on an alkaline sandy soil in Canada pub-

lished by Campbell and Racz (1975), where the percentage of P_o and P_{res} decreased with depth, whereas P_i increased. This indicated that either P_i was more mobile than P_o and P_{res} or less P was incorporated into microbial biomass in the deeper soil horizons. Lower P_o concentrations under CCFOs were also reported by Campbell and Racz (1975), which were caused by a greater mineralization and depletion of organic P under anaerobic conditions.

The ratio of P_i and P_o suggested P_i dominance in manure for the H₂O and NaHCO₃ extracts, whereas P_o was domi-

nant in the NaOH and HCl fraction (Table 2). These results revealed that, especially in the manure, significant concentrations of P_o can be found in the HCl fraction, which is in agreement with results for cattle manure and soil from He et al. (2006) as well as for swine and broiler samples (He et al., 2003; Dou et al., 2003). However, Turner and Leytem (2004), using ^{31}P NMR, determined only P_i in the HCl fraction of cattle manure. These discrepancies could be explained by the type and amount of bedding material and the Ca and Mg concentration in it. In comparison to the manure, the soil samples were classified by higher P_i than P_o ratios in the NaHCO_3 and HCl fraction, but higher P_o in the H_2O and NaOH fraction (Table 5 and 6). Values were similar for both locations, all soil depths and for all years for the CCFO. This indicates that neither P_o nor P_i of one of the mobile fractions was particularly leached and accumulated in deeper soil layers.

Our findings demonstrate that even though approximately 50 % of the P in the manure was determined in readily available form or in soluble fractions, the nine year management of the CCFO did not result in a significant P accumulation in the soil profile. This confirms results from long term CCFO's in southern Alberta (Sommerfeldt et al., 1973) and southern Minnesota (Zhu et al., 2004). Possible reasons are the compaction of the pen surface by cattle and machinery, which increased the bulk density from 1.70 to 2.18 g cm^{-3} within the first three years of usage (Olson et al., 2005), and scraping and removal of the enriched black mixed manure-soil layer which probably contained most P. Also, the semi-arid climate with mean annual precipitation around 400 mm reduces the P transport and transformation in the soil. Most precipitation will be absorbed in the manure or results in surface runoff after high rainfall events (Aust et al., 2008; Miller et al., 2008). Since the environmental pollution from this CCFO can be classified the application of this manure to surrounding agricultural land poses a risk of P enrichment in soil and groundwater due to leaching of labile fractions and wind erosion.

Trace metal concentrations within soil profiles

The total mean Cd concentrations at both locations (CCFO: 0.22 mg kg^{-1} and grassland: 0.36 mg kg^{-1}) were in the range 0.07 to 0.87 mg Cd kg^{-1} , reported for agriculturally used subsoils in Saskatchewan (Mermut et al., 1996; Krishnamurti et al., 1997). These authors reported that most of the Cd in the subsoil was precipitated as CdCO_3 . Therefore, it is assumed that in the carbonaceous substrates with $\text{pH} > 7$ investigated in this study, Cd was also bound in carbonate form, making it less available for leaching. Other findings from a long-term manure experiment in the same Lethbridge area demonstrated higher

values in the range 0.45 to 0.60 mg kg^{-1} (Benke et al., 2008), which is attributed to the long-term manure application (25 years), different origin of the manure and increased leaching through the soil because of irrigation.

The total Cr concentrations (mean 0.10 mg kg^{-1}) beneath the CCFO were lower than from the grassland and much lower than values published for subsoils in Saskatchewan ($\leq 103 \text{ mg kg}^{-1}$; Mermut et al., 1996) and geochemical background concentration in soils across Canada (average 78 mg kg^{-1} ; Rencz et al., 2006).

Mean Cu values $\leq 14 \text{ mg kg}^{-1}$ were in the lower range of values across Canada with 5 to 50 mg kg^{-1} (McKeague and Wolynetz, 1980; Rencz et al., 2006) or in subsoils of heavily manured plots (Benke et al., 2008). Because of the basic soil pH (7-8) Cu occurs mostly in CuCO_3 form or adsorbed to Mn oxides, whereas the low Fe concentration in these soils plays a minor part for Cu sorption (Kabata-Pendias and Pendias, 2000).

The mean total Ni concentration in the soil profile of the CCFO (27.70 mg kg^{-1}) was slightly higher than in the grassland (24.86 mg kg^{-1}). However, both concentrations were in the range of soil and till values across Canada with a mean of 26.8 mg kg^{-1} (Rencz et al., 2006). The mobility of Ni in the soil is reduced by strong association to Mn as well as to organic matter. Although complexing ligands such as sulfate and organic acids reduce the sorption of Ni (Kabata-Pendias and Pendias, 2000), reduced leaching under these semi arid conditions prevents downward transport.

Both locations had similar Pb concentration with 7.30 mg kg^{-1} , which were lower than the average soil concentration (9.65 mg kg^{-1}) across Canada (Rencz et al., 2006) or $\leq 21 \text{ mg kg}^{-1}$ in subsoils in Saskatchewan (Mermut et al., 1996).

Total Zn concentrations in the soil of the CCFO were lower with a mean of 46.22 mg kg^{-1} than in the grassland (63.02 mg kg^{-1}). The concentrations at both locations were in the range of Canadian subsoils from a 25 year manure experiment or from native prairies (Benke et al., 2008, Mermut et al., 1996). The Zn downward transport in the soils was reduced because of the possible Zn precipitation with carbonate (Usman et al., 2004) and fixation with inorganic compounds (Clemente et al., 2006; Walker et al., 2003).

Similar to Ni, the concentrations of Fe and Mn were higher in the soil profile below the CCFO (42.47 and 319.66 mg kg^{-1}) compared to the grassland soil (29.42 and 259.80 mg kg^{-1}). These differences can be explained by the high natural soil variability in this area, but also by input with the cattle manure as a result of natural concentrations in the animal feed or as additional supplements for animal health. Also, the higher total Fe and Mn concentrations in the soil of the CCFO did not affect the P

distribution in the soil, especially the NaOH fraction. This leads to the conclusion that these two elements are not present in available form, which reduces their capability for P binding. The Fe concentrations in these soils correspond to < 16.5 % of the total Mn concentrations. Oxides and hydroxides of both elements are known for their high degree of association with trace elements (Kabata-Pendias and Pendias, 2000).

Overall, the trace element concentrations were not significantly different in the soil profile of the CCFO (Table 7). Even in the first 10 cm no accumulation occurred, because of removal of the black soil manure layer. Consequently, there was no potential for trace elements to move down the soil profile. Slightly higher mean concentrations, except for Fe, Mn and Ni, were measured in the soil profile of the grassland (Table 7) but also with no significant changes, except for Mn, Ni and Zn in the profile. Both lo-

Conclusions

The construction and management of the CCFO in the semi arid area of southern Alberta did not result in any undesired enrichment of organic matter or P in the soil profile. The annual cleaning process almost completely removed excrement, the black organic layer and the first cm of nutrient and trace metal enriched soil material and the high bulk density laid out during construction and enhanced through operation impeded leaching of solutes or colloidal matter into deeper parts of the soil profile. Low proportions of organic P as immobile Ca-bound P minimized P transport by matrix flow beneath the CCFO. Also the storage of manure in the pens did not significantly affect the metal concentrations in the underlying soil after nine years of intensive cattle use. In particular the high organic matter content of the manure probably favored

Table 7:

Total concentrations of trace elements in the confined cattle feeding operation and grassland in 2005

| Depth cm | Cd | Cr | Cu | Ni | Pb | Zn | Fe | Mn | | | | | | |
|-----------------------------------|------|-----|------|-------|-------|-------|------|-------|-------|-------|-------|-------|-------|----|
| mg kg ⁻¹ | | | | | | | | | | | | | | |
| Confined cattle feeding operation | | | | | | | | | | | | | | |
| 0-10 | 0.17 | b | 0.09 | 10.79 | 29.52 | 6.05 | b | 53.09 | 26.84 | 291.2 | | | | |
| 10-30 | 0.26 | a | 0.14 | 13.38 | 29.95 | 7.75 | a | 43.41 | 33.92 | 329.3 | | | | |
| 30-60 | 0.19 | Bab | 0.07 | B | 11.88 | 26.87 | 6.25 | Bb | 52.58 | 47.66 | 314.9 | | | |
| 60-90 | 0.21 | Bab | 0.10 | | 14.64 | 27.32 | A | 8.22 | a | 49.17 | 48.56 | 319.6 | A | |
| Grassland | | | | | | | | | | | | | | |
| 0-10 | 0.30 | | 0.17 | 11.59 | 27.15 | 6.13 | b | 70.52 | a | 25.40 | 282.5 | ab | | |
| 10-30 | 0.36 | | 0.20 | 13.46 | 25.30 | 7.65 | ab | 67.07 | ab | 32.91 | 314.3 | a | | |
| 30-60 | 0.39 | A | 0.20 | A | 15.23 | 26.68 | 7.93 | Aa | 60.55 | ab | 27.99 | 251.5 | ab | |
| 60-90 | 0.38 | A | 0.16 | | 15.66 | 20.31 | B | 7.53 | ab | 53.95 | b | 31.38 | 190.9 | Bb |

For each soil depth, means (n = 5) in a column followed by different uppercase letters indicate significant (P<0.05) location effects. For each location, means (n = 5) in a column followed by different lowercase letters indicate significant (P < 0.05) soil depth effects. Only significant differences are stated.

cations were mostly not significantly different in the trace element concentrations of each soil depth (Table 7).

Most trace elements are probably precipitated or in complex form with organic matter and/or P_o (Celi et al., 2000). This inhibits the mobility and therefore the availability for leaching in calcareous soils. Besides that, trace elements and phosphate in soils may influence the sorption of each other by competing for sorption sites or by influencing the surface charge (Thakur et al., 2006). Nevertheless, our results demonstrate a low risk for trace element transport under the CCFO.

the fixation within the first centimeters of the soil. Therefore, it can be concluded that the dry weather conditions and the alkaline pH in the underlying soils reduce transport of trace metals by leaching leading to a reduced risk of groundwater pollution. With correct implementation of the existing guidelines for CCFO the risk of groundwater pollution is relatively low under dry climate conditions, deep groundwater levels, compacted soils and soils with a high clay content. Consequently, the application of nutrient and trace metal enriched manure to surrounding fields needs to be regulated.

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