MANAGING NUTRIENTS IN BEEF FEEDLOT MANURE – LESSONS FROM A 45-YEAR FIELD STUDY

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ABSTRACT

The original objective of a long-term field experiment established in 1973 was to determine the safe loading capacity of soil with beef cattle feedlot manure. Manure was applied annually at 0, 30, 60, and 90 Mg ha^{-1} (wet weight) under rainfed and 0, 60, 120, and 180 Mg ha^{-1} under irrigated conditions. The long-term manure applications increased organic matter, nitrogen (N), phosphorus (P) and potassium (K) content and salinity in the soil, and barley forage yield at all manure rates but reduced barley grain yields at higher application rates. The N and P content in barley forage and grain also increased with the rate of manure application. Manure improved soil biological quality by increasing soil microbial biomass and enzyme activities. Active carbon (C) (permanganate-oxidizable C) was sensitive to both water and manure management, while appearing to be the soil health indicator most closely related to the enzymes involved in C, N, P and S cycling, representing meaningful, high throughput, and thus emerged as a cost-effective soil health indicator for manured soils of the Great Plains. When 30 years of manure application at 60 Mg ha^{-1} was followed by a decade or so without manure, there were limited legacy effects on GHG fluxes and most soil health indicators. The high nutrient levels in manured soil increases the potential for nutrient losses and surface and groundwater contamination. The soil nutrient enrichments were long-lasting and could pose environmental threats long after application has stopped.

INTRODUCTION

Manure is a valuable resource when used judiciously as a soil amendment, but can become an environmental polluter when mismanaged. While traditional farm crop and livestock production complemented each other locally with minimal nutrient export, this local linkage has now been broken in the specialized modern farm. Various subsidies and cheap inorganic fertilizers have also contributed to livestock/crop production decoupling. Nutrient export/import has increased, and nutrients now flow over great distances compared to the prior practice of nutrient recycling within a farm. For example, the beef cattle industry in southern Alberta imports corn feed from the U.S. mid-west and exports timothy grass to Japan and Korea as a source of fiber for dairy cows and horses. The decoupling of animal and crop production has led to manure over-supply near the source (large confined feeding operations), which often have insufficient surrounding land base to accommodate the volume of manure produced. Since the N/P ratio in animal manure is generally lower than crops need, repeated applications of manure based on crop N needs leads to excess P accumulation in soil.

The research objectives were to determine: (1) the optimum loading rates of feedlot manure; and (2) the legacy effects of repeated annual applications of beef feedlot manure on soil properties, barley production, and groundwater quality; and (3) legacy effects on greenhouse gas emission, soil carbon storage and soil health.

MATERIALS AND METHODS

The long-term manure (LTM) experiment was established in Lethbridge, Alberta in autumn 1973 on a Dark Brown Chernozemic (Typic Haploborolls) clay loam soil. Two adjacent fields were used, one was rainfed and the other irrigated with about 15-cm water/year. The beef feedlot manure application rates were 0, 30, 60, and 90 Mg ha^{-1}, wet mass, for the rainfed field (Treatments Mr0, Mr30, Mr60, and Mr90) and 0, 60, 120, and 180 Mg ha^{-1} for the irrigated field (Treatments Mi0, Mi60, Mi120, and Mi180). The application rates corresponded to one, two and three times the 1973 recommended rates for rainfed and irrigated crop production for the soil type. To compare methods of incorporating manure into the soil, three tillage treatments (plow, rototill, and cultivator plus disc) were used. All treatments were replicated three times. Since tillage system had no effect on most soil properties investigated, since 1987 manure was incorporated with a cultivator for all plots. Manure applications for the previously rototilled strip were ceased after 14 annual applications. Then in 2003, manure application ceased for the previously plowed strip after 30 annual applications (Table 1).

Table 1. The LTM treatment description

Field	Treatment	Description
Rainfed	Mr0	No fertilizer or manure input since 1973
	Mrf	Fertilizer at 50 kg N ha^{-1} yr^{-1} since 1990
	Mr30	Manure at 30 Mg ha^{-1} yr^{-1} since 1973
	Mr60	Manure at 60 Mg ha^{-1} yr^{-1} since 1973
	Mr90	Manure at 90 Mg ha^{-1} yr^{-1} since 1973
	Dr30	Manure at 30 Mg ha^{-1} yr^{-1} from 1973 to 1986 (14 annual applications); application ceased in 1987
	Dr60	Manure at 60 Mg ha^{-1} yr^{-1} from 1973 to 1986 (14 annual applications); application ceased in 1987
	Dr90	Manure at 90 Mg ha^{-1} yr^{-1} from 1973 to 1986 (14 annual applications); application ceased in 1987
	DDr30	Manure at 30 Mg ha^{-1} yr^{-1} from 1973 to 2002 (30 annual applications); application ceased in 2003
	DDr60	Manure at 60 Mg ha^{-1} yr^{-1} from 1973 to 2002 (30 annual applications); application ceased in 2003
	DDr90	Manure at 90 Mg ha^{-1} yr^{-1} from 1973 to 2002 (30 annual applications); application ceased in 2003
Irrigated	Mi0	No fertilizer or manure input since 1973
	Mif	Fertilizer at 100 kg N ha^{-1} yr^{-1} since 1990
	Mi60	Manure at 60 Mg ha^{-1} yr^{-1} since 1973
	Mi120	Manure at 120 Mg ha^{-1} yr^{-1} since 1973
	Mi180	Manure at 180 Mg ha^{-1} yr^{-1} since 1973

	Di60	Manure at 60 Mg ha^{-1} yr^{-1} from 1973 to 1986 (after 14 annual applications); application ceased in 1987
	Di120	Manure at 120 Mg ha^{-1} yr^{-1} from 1973 to 1986 (after 14 annual applications); application ceased in 1987
	Di180	Manure at 180 Mg ha^{-1} yr^{-1} from 1973 to 1986 (after 14 annual applications); application ceased in 1987
	DDi60	Manure at 60 Mg ha^{-1} yr^{-1} from 1973 to 2002 (after 30 annual applications); application ceased in 2003
	DDi120	Manure at 120 Mg ha^{-1} yr^{-1} from 1973 to 2002 (after 30 annual applications); application ceased in 2003
	DDi180	Manure at 180 Mg ha^{-1} yr^{-1} from 1973 to 2002 (after 30 annual applications); application ceased in 2003

RESULTS AND DISCUSSION

Soil Chemistry and Salinity

Soil organic C, N, P, K, Zn and Cu contents in soil increased with the manure rates. The increase was mainly due to applying nutrients via manure at greater rates than crop removal.

After 25 annual applications, soil electrical conductivity, soluble sodium (Na), K, magnesium (Mg), bi-carbonate, sulfate and chloride concentrations increased with the manure rates, reflecting the soluble ions composition of the manure applied. The increases in K were greatest, changing the soil solution from initially calcium (Ca)-dominant to K-dominant in the manured soil. The increases were greater under rainfed than irrigated conditions. The greater increases in soil salinity under rainfed conditions largely reflect the semi-arid climate whereby the annual evaporation potential far exceeded precipitation. Under irrigation, soluble ions may be leached beyond the 1.5 m sampling depth used in our study.

The potential salinity problems due to long-term manure applications on arable land in southern Alberta are probably greater from potassium than from sodium because of the high potassium content in cattle manure and the low mobility of K in Chernozemic soil. Although soil salinization due to cattle manure was lower with irrigation, leaching of salt to groundwater may compromise groundwater quality over time. In either case, repeated applications of high manure rates are not sustainable under dry semi-arid conditions.

Soil Microbiology

Soil phospholipid fatty acid analysis showed that after 37 years of annual manure applications at 60 Mg ha^{-1}, soil microbial biomass was 3.2 times that of the control, but 20 years of fertilizer N applied at 100 kg N ha^{-1} had no effect. β-glucosidase activities with manure were 1.9 to 2.4 times the control, but fertilizer N had no effect. Increasing the manure rate to 180 Mg ha^{-1} increased soil microbial biomass linearly, but quadratic increases were observed for β-glucosidase activity. The soil microbial biomass and enzyme activities were positively correlated with soil organic C, total N, and available P. MiSeq sequencing revealed that 43 years of annual manure applications increased the relative abundances of soil *Firmicutes*, γ-*Proteobacteria*, and *Gemmatimonadetes*, but decreased the relative abundance of *Acidobacteria*. Discontinuation of manure application for up to 29 years showed that manure legacy effects on the activities of the soil enzymes involved in C, N, P and S cycling decreased with the number of years without manure, following quadratic patterns, and the legacy effects on enzymes lasted longer than the microbial biomass.

Crop Yield and Quality

After 16 consecutive annual applications, rainfed grain barley yield decreased by 10 and 16% for the 60 and 90 Mg ha^{-1} manure rates, respectively, when moisture conditions were below normal. However, barley grain yield increased when manure was applied under irrigation, with the 60 Mg ha^{-1} rate producing a 20% higher average yield than the control. After 18 annual applications, barley yield decreased for both rainfed and irrigated conditions. Regardless of irrigation, N, P, K, Mg, Na, Cu and Zn contents in barley forage (harvested at the growth stage for making silage) were higher, but Ca content was lower in manure plots than the control. All elemental contents, except Ca, increased with increasing manure application rates. The Ca content was negatively related to manure rate. The reduction in Ca content and uptake observed in barley may be due to increased salinity caused by repeated manure applications. In some years the Ca/P and K/(Ca+Mg) ratios fell outside the optimum range for barley forage used as cattle feed, while high nitrate levels (> 2 g kg^{-1}) were also observed during the drought years.

Rate of Soil Recovery after Manure Application Ceased

Using an exponential decay function and data from 14 annual manure applications (1973-1986) followed by no application (1987-1998), the estimated recovery time for soil to return to the pre-manure N, P and salinity levels increased with the previous manure application rate and was shorter under irrigation than rainfed conditions. For soil total N and P, and soil test P, estimated recovery time ranged from 17 to 99 years for surface soil and 0 to 157 years for the 15-30 cm depth, while soil nitrate-N and salinity in the soil profile (0-150 cm) could require 182 to 297 years under rainfed and 24 to 52 years under irrigation. Thus, long lasting nutrient enrichment from excessive long-term cattle manure applications poses important challenges with respect to sustainable manure management, not to mention the environmental consequences, long after manure applications have ceased.

Greenhouse Gas Emission

Greenhouse gas (GHG) fluxes were measured for two years following manure application in November 2015 until late October 2017. Continuous manure application at 60 Mg ha^{-1} yr^{-1} led to greater cumulative CO_2 and N_2O emissions than non-amended, synthetically fertilized, and discontinued manured soils under rainfed and irrigated conditions ($p < 0.05$). With continuous manure, irrigated soils emitted more CO_2 and N_2O than rainfed soils. However, irrigation did not alter soil CO_2 and N_2O fluxes from unamended soil. Legacy effects of manure application on soil GHG fluxes were negligible in the long-term; residual, bioavailable C/N fractions were likely depleted 17 (2003) and 33 (1987) years after manure application stopped as the GHG fluxes returned to baseline rates for the manure application rate monitored.

Soil Health Assessment

The suitability of the Comprehensive Assessment of Soil Health was assessed for manured fields using soil samplings collected in spring and fall 2016. Our results showed that three indicators (soil pH, wet aggregate stability and active C) were sensitive to both the effects of water and manure management over more than four decades. Soil pH decreased with irrigation and continuous manure application, suggesting that both irrigation water and manure had neutralizing effects on this calcareous soil. Both wet aggregate stability and active C were significantly greater with irrigation and continuous manure. This provides further evidence that wet aggregate stability and active C are sensitive to a variety of management practices in different climates. Active C was positively correlated to the potential enzyme activity of NAGase, Acid phosphomonoesterase, and Arylsulfatase ($r = 0.49$ to 0.71; $p < 0.05$). When 30 years of manure application was followed by a decade or so without manure, there were limited legacy effects on most soil health indicators, but soil organic C, active C and cation exchange capacity remained higher than the non-amended control soil. Overall, the soil health indicator mean values were near or within the range recently reported for fine-textured soils from the Mid-Atlantic, Midwest, and Northeast regions of the USA. Published values of soil health indicators that include the complete suite of physical, chemical and biological properties from the Midwest US, north through the Northern Great Plains are limited, and thus there is a need to get data published or conduct further studies in this vast region.

Current Ongoing Research

The focus of the current 3-year project (April 2018 – March 2021) is to investigate the stability of manure C after application to soil. This was achieved by employing a density and particle-size fractionation approach. By comparing the amount and forms of soil C associated with light, sand, silt or clay fractions in soil for treatment with various time periods of manure applications and legacies (the time since manure application stopped), we hope to be able to gain some insight into the effectiveness of livestock manure application on soil C sequestration, storage and stability.

Summary

The 45-year LTM field experiment demonstrated that annual manure applications increased soil organic matter, N, P, soluble salts and trace element contents and crop straw yield at all manure rates, but reduced grain yields and negatively affected crop quality at higher manure rates. Increased soil nutrient levels also increase the potential for nutrient losses and surface and groundwater contamination. Manure improved the biological quality of the soil by increasing soil microbial biomass and the activities of enzymes involved in C, N, P and S cycling. Active C was sensitive to both water and manure management, while appearing to be the soil health indicator most closely related to the enzymes involved in C, N, P and S cycling, representing a meaningful, high throughput, and cost-effective soil health indicator for manured soils of the Great Plains. When 30 years of manure application was followed by a decade or so without manure, there were limited legacy effects on GHG fluxes and most soil health indicators.

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SELECTED REFERENCES

Benke, M.B., Indraratne, S.P., Hao, X., Chang, C. & Goh, T.B. 2008. Trace Metals and boron changes in soil after long-term cattle manure applications. J. Environ. Qual. 37:798-807.

Chang, C. & Entz, T. 1996. Nitrate leaching losses under repeated cattle feedlot manure applications in southern Alberta. J. Environ. Qual. 25:145–153.
Chang, C. & Janzen, H. 1996. Long-term fate of nitrogen from annual feedlot manure applications. J. Environ. Qual. 25:785-790.
Chang, C., Janzen, H. & Entz, T. 1994. Long-term manure application effects on nutrient uptake by barley. Can. J. Plant Sci.74:327-330.
Chang, C., Sommerfeldt, T.G. & Entz, T. 1990. Rates of soil chemical changes with eleven annual applications of cattle feedlot manure. Can. J. Soil Sci.70:673-681.
Chang, C., Sommerfeldt, T.G. & Entz, T. 1993. Barley performance under heavy applications of cattle feedlot manure. Agron. J. 855. 1013-1018.
Chang, C., T. Sommerfeldt & Entz, T. 1991. Soil chemistry after eleven annual applications of cattle feedlot manure. J. Environ. Qual. 20:475–480.
Fine, A.K., van Es, H.M. & Schindelbeck, R.R. 2017. Statistics, scoring functions, and regional analysis of a comprehensive soil health database. Soil Sci. Soc. Am. J. 81:589–601.
Hao, X. & Chang, C. 2002. Effect of 25 annual cattle manure applications on soluble and exchangeable cations in soil. Soil Sci. 167:126-134.
Hao, X. & Chang, C. 2003. Does long-term heavy cattle manure application increase salinity of a clay loam soil in semi-arid southern Alberta? Agric. Ecosyst. and Environ. 94:89-103.
Hao, X., Chang, C., Travis, G.R. & Zhang, F. 2003. Soil carbon and nitrogen response to 25 annual cattle manure application. J. Plant Nutri. Soil Sci. 166:239-245.
Indraratne, S.P., Hao, X., and Chang, C., & Godlinski, F. 2009. Rate of soil recovery following the termination of long-term cattle manure application. Geoderma. 150:415-423.
Lupwayi, N.Z., Kanashiro, D.A., Eastman, A.H. and Hao, X. 2018. Soil phospholipid fatty acid biomarkers and β-glucosidase activities after long-term manure and fertilizer N applications. *Soil Science Society of America Journal* 82:342-353.
Lupwayi, N.Z., Zhang, Y., Hao, X., Thomas, B.W., Eastman, A.H. and Schwinghamer, T.D. 2019. Linking soil microbial biomass and enzyme activities to long-term manure applications and their nonlinear legacy. *Pedobiologia* 74:34-42.
Sommerfeldt, T.G. & Chang, C. 1985. Changes of soil properties under annual applications of feedlot manure and different tillage practices. Soil Sci. Soc. Am. J. 49:983-987.
Sommerfeldt, T.G. & Chang, C. 1987. Soil-water properties affected by twelve annual applications of cattle manure. Soil Sci. Soc. Am. J. 511:7-9.
Sommerfeldt, T.G., Chang, C. & Entz, T. 1988. Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. Soil Sci. Soc. Am. J. 52:1668-1672.
Whalen, J.K. & Chang, C. 2001. Phosphorus accumulation in cultivated soils from long-term annual applications of cattle feedlot manure. J. Environ. Qual. 30:229–237.
Zhang, Y., Hao, X., Alexander, T.W., Thomas, B.W., Shi, X. and Lupwayi, N.Z. 2018. Long-term and legacy effects of manure application on soil microbial community composition. *Biology and Fertility of Soils* 54:269-283.