

2005-02-17

Soil microorganisms and crop yields after cattle manure, hog manure, or fertilizer application

Lupwayi, N.Z.

<http://hdl.handle.net/10388/9485>

Downloaded from HARVEST, University of Saskatchewan's Repository for Research

Soil Microorganisms And Crop Yields After Cattle Manure, Hog Manure Or Fertilizer Application

N.Z. Lupwayi¹, T. Lea², J.L. Beaudoin² and G.W. Clayton³

¹Agriculture and Agri-Food Canada, Box 29, Beaverlodge, Alberta, Canada T0H 0C0

²Smoky Applied Research & Demonstration Association (SARDA), Box 90, Falher, AB, T0H 1M0

³Agriculture and Agri-Food Canada, 6000 C & E Trail, Lacombe, Alberta, Canada T4L 1W1

Keywords: Functional diversity, Gray Luvisol, manure quality, NPK fertilizers, soil microbial communities.

Abstract

Soil biological properties can be significantly impacted by land management. Cattle manure, hog manure or inorganic fertilizers were applied annually or triennially to a Gray Wooded soil at Falher, Alberta, over three years. A control treatment without manure or fertilizer was also included. Canola (*Brassica napus*) was grown in Year 1, hulless barley (*Hordeum vulgare*) in Year 2, and wheat (*Triticum aestivum*) in Year 3. Where effects were significant, cattle manure increased soil microbial biomass C (MBC) by 26-86%, hog manure by 31%, and inorganic fertilizers reduced MBC by 20%. Similar effects, except the reduction by inorganic fertilizers, were observed for functional diversity of soil bacteria (Shannon index, H'). Crop N uptake from hog manure was higher than that in other treatments in Year 1, when hog manure increased grain yields by 75%, cattle manure by 49%, and inorganic fertilizers had no significant effect. However, cattle manure out-yielded other treatments in Years 2 and 3 (25-50% increase over the control) even though N uptake from inorganic fertilizers was the highest in Year 2. This implies that factors other than nutrient uptake also influenced crop yields. Frequency of application usually had no effects on MBC or H', but the triennial application rate of inorganic fertilizers reduced crop yields relative to annual applications in Year 1.

Introduction

Land management practices have a significant impact on soil biological and biochemical properties, usually through increase or depletion of soil organic matter. Application of manure to farm land increases soil organic matter, which increases nutrient availability (Stevenson et al. 1998; Hao and Chang 2002; Mooleki et al. 2002) and improves soil physical properties like structure, aeration, drainage and water holding capacity (Whalen and Chang 2002; Miller et al. 2002; Reynolds et al. 2003). Mineralization of biodegradable C contained in applied manure also alters soil ecology. Rochette and Gregorich (1998) reported 2- to 3-fold increases in soil respiration and MBC after three years of manure application. Lalande et al. (2003) reported that application of 11.5 t ha⁻¹ of co-composted papermill sludge and hog manure increased soil enzyme activity by 30% and MBC by 55%. Peacock et al. (2001) observed that Gram-negative bacteria increased by 15-27% with dairy manure treatments, but decreased by 15% with ammonium nitrate treatments, compared with control treatments. Marschner et al. (2003) and

Parham, et al. (2003) found that manure promoted bacterial growth more than fungal growth in soils. It has been hypothesized that the effect of manure on soil microbial communities is similar to the rhizosphere effect due to high levels of soluble organic C which support high levels of microbial activity in both cases (Peacock et al. 2001).

The alteration of the composition and activities of soil microbial communities by manure is important for crop nutrition and health. Manure supplies both macro- and micro-nutrients (Stevenson et al. 1998; Hao and Chang 2002). Most of the N and P contained in manures is in organic forms, which are not available to plants. Soil microorganisms mineralize these nutrients into inorganic forms that plants can utilize. However, manure application rates based on crop N requirements can result in soil accumulation and runoff of P because manure N/P ratio is usually smaller than crop N/P uptake ratio (Eghball and Power 1999). With regard to crop health, crops grown on soils with high organic matter and active soil microorganisms tend to be less infested with weeds (Kremer and Li 2003), diseases (Bailey and Lazarovits 2003) and insect pests (Altieri and Nicholls 2003). Contrary to the belief that animal manures increase the incidence of common scab disease of potatoes (Bailey and Lazarovits 2003), Conn and Lazarovits (1999) found reduced incidences of wilt, common scab and a number of plant-parasitic nematodes for three years after a single manure application. The mechanisms of disease control by N-rich organic manures include release of allelochemicals generated during manure storage or subsequent decomposition, and stimulation of microorganisms with bio-control properties (Lazarovits 2001; Bailey and Lazarovits 2003).

The objective of this work was to investigate changes in soil MBC, functional diversity of bacteria, and crop yields after application of cattle manure, hog manure and inorganic fertilizers in Gray Luvisolic soils of northern Alberta.

Methodology

In field experiments conducted at a low inorganic-N site at Falher, Alberta, cattle (*Bos taurus*) manure (solid), hog (*Sus domesticus*) manure (liquid) or inorganic fertilizers were applied to meet crop N requirements according to soil test recommendations. A control treatment without organic manure or inorganic fertilizer treatment was also included. The nutrient sources were applied either annually or triennially, i.e., as a one-time application (in Year 1) of a projected 3-year N requirement. The two factors (nutrient source and application frequency) were arranged factorially in a randomized complete block design (RCBD) with four replications. The trial was conducted from 2000 to 2002. The soil was Gray Luvisolic with the following characteristics (0-15 cm depth) before treatments were established: pH (1:1 soil:water) 6.8, 15.5 g organic C, 17.3 mg NO₃-N, 8.0 mg PO₄-P and 17.0 mg SO₄-S per kg soil. Soil PO₄-P was extracted with CH₃COOH + NH₄F and the available P was considered as low. Sulphate-S was extracted with CaCl₂ and the soil had adequate S.

The nutrient contents of the manures at the time of application are listed in Table 1. The bedding for cattle manure was wheat straw. The triennial application rate for cattle manure in Year 1 was 111 t/ha, and annual applications were 17, 37 and 30 t/ha. The corresponding rates for liquid hog manure were 157 m³/ha triennial rate, and annual applications were 45, 56 and 26 m³/ha in Years 1 to 3. Manures were broadcast on the soil surface and disced into soil at 15 cm depth within 24 h. The N from inorganic fertilizer was side-banded as urea (46-0-0 N-P₂O₅-K₂O) to supply 263 kg N/ha triennially, and annual applications were 39, 90 and 62 kg N/ha in

Years 1, 2 and 3, respectively. In the fertilizer treatments, phosphorus and potassium were applied (seed-placed) as a blend of ammonium phosphate (12-51-0) and potassium chloride (0-0-60) according to soil test recommendations, and the N in ammonium phosphate was accounted for when applying urea. These P and K fertilizers were applied only at annual rates, only in fertilizer treatments. Triennial application rates were greater than the sum of the corresponding three annual rates because triennial rates were based on Year 1 soil analysis, but subsequent annual rates were adjusted according to soil analysis results in each year.

Table 1. Characteristics (on wet weight basis) of cattle and hog manures applied.

Manure property	Year 1		Year 2		Year 3	
	Cattle ^e	Hog	Cattle	Hog	Cattle	Hog
DM (g/kg or L) ^z	316.5	37.2	n.d. ^y	n.d.	n.d.	n.d.
Total N ^x (g/kg or L)	7.4	4.6	10.7	2.6	8.5	2.7
Organic N (g/kg or L)	7.4	1.3	n.d.	n.d.	n.d.	n.d.
NH ₄ -N ^w (g/kg or L)	0.067	3.3	n.d.	1.3	n.d.	1.5
NO ₃ -N ^w (g/kg or L)	0.007	0.007	n.d.	n.d.	n.d.	n.d.
Total P ^x (g/kg or L)	1.5	1.0	1.4	0.2	1.3	0.1
Total K ^x (g /g or L)	7.8	2.0	5.8	0.1	5.4	1.2

^zg/kg for solid cattle manure and g/L for liquid hog manure.

^yn.d. = not determined.

^xDigested with H₂SO₄ + H₂O₂ (Thomas et al. 1967).

^wWater-extractable.

Canola was grown in Year 1, hulless barley in Year 2, and wheat in Year 3, all under zero tillage except for the discing-in of manures. The crops were seeded about a week after manure application, but fertilizers were applied at seeding time. Glyphosate was applied as a pre-seeding burn-off, and in-crop herbicides were applied according to weed spectra.

At flowering stage of canola, and flag-leaf stage of barley and wheat, soil samples were collected between crop rows to 7.5 cm depth from four different locations per plot. This soil is here-in called bulk soil. In 2002, rhizosphere soil was also sampled by excavating plants from 0.5 m row length at four different locations in a plot, shaking off loose soil, and carefully collecting (by brushing) soil adhering to plant roots. The soil was sieved through a 2 mm sieve and stored at 4 °C until required for analysis, typically within a month.

Soil MBC was measured using the substrate-induced respiration (SIR) method (Horwath and Paul 1994; Lupwayi et al. 1999). Functional bacterial diversity was evaluated by the Biolog™ method (Zak et al. 1994), which tests the ability of a microbial community to utilize different C substrates contained in a microplate. The procedure was adapted by colorimetrically standardizing inoculum densities in 1 g field-moist soil samples to about 10³ cells/mL (Lupwayi et al. 2001a). On the basis of the patterns of utilization of the substrates by the bacteria from

each soil, Shannon index (H') of functional diversity was calculated as follows (Magurran 1988; Zak et al. 1994), using PC-ORD software (McCune and Mefford 1997):-

$$H' = -\sum p_i (\ln p_i)$$

where p_i = Ratio of activity (i.e., optical density reading) on the i th substrate to the sum of activities on all substrates.

At the same time that soil samples were collected for microbiological analysis, shoots of five plants were collected from each plot to measure N uptake after wet digestion with $H_2SO_4 + H_2O_2$ (Thomas et al. 1967).

At harvest, grain yields were determined from a 1.5 m x 15.2 m area.

Results

Microbial biomass C

In Year 1, cattle manure increased MBC in bulk soil by 26% (to 634 mg/kg soil), but inorganic fertilizers reduced MBC by 20% (to 402 mg/kg soil), compared with the control (503 mg/kg soil) (Table 2). Although hog manure did not increase MBC relative to the control, it increased MBC compared with inorganic fertilizers. Frequency of application (annual or triennial) had no effects on MBC and there were no interactions between nutrient source and frequency of application. In Year 2, no factor affected MBC, but a similar pattern to that observed in Year 1 was evident with respect to nutrient source effects. In Year 3 in bulk soil, cattle manure increased MBC by 86% (to 1383 mg/kg soil), and hog manure increased MBC by 31% compared with the control (742 mg/kg soil). Annual applications increased MBC by 17% relative to triennial application (891 mg/kg soil). In wheat rhizosphere, cattle manure increased MBC by 70% relative to the control (566 mg/kg soil), and frequency of application had no effects. As in Years 1 and 2, there were no interactions between nutrient source and frequency of application in Year 3.

Functional diversity

In Years 1 and 2, H' was not affected by treatment (Table 2, Year 2 data not shown). In Year 3 in bulk soil, all soil amendments (manures and inorganic fertilizers) increased H' . Frequency of application had no effects on functional bacterial diversity in bulk soil or rhizosphere. There were no interactions between nutrient source and frequency of application.

Crop N uptake

In Year 1, plants that had received hog manure absorbed more N than the control (Table 3). In Year 2, plants that had received inorganic fertilizers absorbed more N than the control. In Year 1, more N was absorbed with triennial application than annual applications, but the reverse was observed in Year 2. In Year 3, there were no effects of nutrient source or application frequency on N uptake. There were no interactions between nutrient source and frequency of application.

Crop yields

Canola grain yields in Year 1 increased by 75% with hog manure (to 1.94 t/ha) and 49% with cattle manure, relative to the control (1.11 t/ha) (Table 3). The effect of application frequency depended on nutrient source: grain yields were reduced when inorganic fertilizers were applied triennially compared with annual applications, but triennial application of organic manures increased yields slightly (interaction data not shown). In Year 2, only cattle manure increased barley grain yields (by 25% to 3.50 t/ha), regardless of frequency of application, compared with

the control (2.81 t/ha). In Year 3, cattle manure increased wheat grain yields by 50% (to 3.07 t/ha), inorganic fertilizers by 33% and hog manure by 32%, compared with the control (2.04 t/ha).

Table 2. Microbial biomass C (MBC) and bacterial diversity (H') in bulk soil and rhizosphere (rhizo.). Rhizosphere MBC and diversity were measured in Year 3.

Treatment	MBC (mg/kg soil)				Shannon index (H')		
	Year1	Year 2	Year 3		Year 1	Year 3	
			Bulk soil	Rhizo.		Bulk soil	Rhizo.
<i>Nutrient source (n=8)</i>							
Cattle manure	634a	458	1383a	960a	2.86	2.75a	2.62
Hog manure	514b	261	969b	740b	2.67	2.62a	2.49
Inorg. fert.	402c	219	775bc	495c	2.85	2.62a	2.44
Control	503b	285	742c	566bc	2.98	2.23b	2.34
SEM ^z (21 df ^y)	30	86NS ^x	68	65	0.10NS	0.09	0.13NS
<i>Application frequency (n=16)</i>							
Annual	498	336	1043a	753	2.78	2.57	2.53
Triennial	529	276	891b	627	2.89	2.54	2.41
SEM (21 df)	21NS	61NS	48	46NS	0.07NS	0.07NS	0.09NS
Interaction	NS	NS	NS	NS	NS	NS	NS

^zSEM = standard error of the mean.

^ydf = degrees of freedom for error.

^xNS = not significantly different at 5% significance level.

a-c Means followed by the same letter in a column (within a treatment category) are not significantly different at 5% significance level according to the Least Significant Difference (LSD) test.

Correlations

H' in bulk soil was negatively correlated with crop N uptake ($r = -0.996^{**}$) in Year 1, and positively correlated with crop grain yields ($r = 0.990^{**}$) in Year 3.

Discussion

Cattle manure usually increased MBC more than hog manure. One possible reason is that hog manure contained insufficient C substrate (as reflected in low DM contents relative to cattle manure, Table 1) for microbial cell biosynthesis and energy. The soil had low organic C content (16 g/kg). The increase in MBC and functional diversity with organic manure application is important because soil microorganisms mineralize nutrients from organic soil amendments. Langmeier et al. (2002) reported that a greater proportion of N applied as cattle manure was mineralized in a long-term organically managed soil, characterized by higher soil microbial activity, than in a conventionally managed soil that had received only inorganic fertilizers.

Table 3. Crop N uptake in above-ground plant material, sampled at cereal flagleaf stage or canola flowering stage, and grain yields at maturity.

Treatment	N uptake (mg/plant)			Grain yield (t/ha)		
	Year 1 (Canola)	Year 2 (Barley)	Year 3 (Wheat)	Year 1 (Canola)	Year 2 (Barley)	Year 3 (Wheat)
<i>Nutrient source (n=8)</i>						
Cattle manure	137b	80b	38	1.65b	3.50a	3.07a
Hog manure	238a	91b	43	1.94a	2.99b	2.69b
Inorganic fertilizers	140b	120a	37	1.33c	2.98b	2.71b
Control	88b	68b	35	1.11c	2.81b	2.04c
SEM ² (21 df ³)	18	8	5NS ^x	0.09	0.14	0.11
<i>Application frequency (n=16)</i>						
Annual	129b	100a	41	1.55	3.12	2.73
Triennial	172a	80b	35	1.47	3.02	2.52
SEM (21 df)	13	6	3NS	0.06NS	0.10NS	0.08NS
Interaction	NS	NS	NS	**	NS	NS

²SEM = standard error of the mean.

³df = degrees of freedom for error.

^xNS = not significantly different at 5% significance level.

a-c Means followed by the same letter in a column (within a treatment category) are not significantly different at 5% significance level according to the Least Significant Difference (LSD) test.

Inorganic fertilizers reduced MBC in Year 1, and had no effect on MBC in subsequent years. Similar negative effects of inorganic fertilizers on soil microorganisms have been reported before (Gupta et al. 1988; Lupwayi et al. 2001b; Peacock et al. 2001). Such effects are due to factors like soil acidity and osmotic pressure (Gupta et al. 1988). However, fertilizers can have positive indirect effects by producing healthy crops, whose root exudates would increase microbial growth and activity (Lynch and Whipps 1990). For example, Lupwayi et al. (2001b) observed that sulphur fertilizers decreased soil microbial diversity in bulk soil, but increased diversity in wheat and canola rhizosphere. In addition, fertilizers increase yields of crop grain and residues which, when incorporated into the soil, will stimulate microbial growth (Doran and Linn 1994; Lupwayi et al. 2004).

In Year 1, crop yields were in the order: hog manure > cattle manure > inorganic fertilizers > control, but cattle manure out-yielded other treatments subsequently. The reason is probably because most (72%) of the N in hog manure was in inorganic (ammonium) form, whereas virtually all the N in cattle manure was in organic form (Table 1). Inorganic N is immediately available to crops, but organic N has to be converted to inorganic forms by soil microorganisms before crop roots can absorb it. During this conversion, some of the N gets immobilized into microbial tissue if the manure contains insufficient N (wide C/N ratio) for microbial requirements, but this N is released back into the soil when microorganisms die and decompose. Therefore, hog manure seems to have more immediate nutrient value to crops than cattle manure, as trends in crop N uptake in Year 1 indicated, but cattle manure probably has more residual nutrient value than hog manure.

In Year 2, crop N uptake was greater where inorganic fertilizers had been applied, but crop yields were greater where cattle manure had been applied. In addition, uptake of N was greater with annual applications than triennial application, but crop yields were not affected by application frequency. This means that differences in crop yields were not entirely due to nutrient uptake. In other cases, where H' was positively correlated with crop yields, it was not correlated with nutrient uptake; and where H' was negatively correlated with nutrient uptake, it was not correlated with crop yields. Therefore, other microbiological interactions probably affected crop yields, and biological pest control is a possibility. In field trials and farmers' fields, Conn and Lazarovits (1999) found that as populations of soil bacteria increased by up to 1000-fold with application of N-rich organic amendments, including hog manure, populations of plant pathogens were reduced. Bulluck et al. (2002) found similar results in field trials comparing organic manures with inorganic fertilizers.

Conclusions

Cattle manure usually increased soil MBC, hog manure sometimes increased MBC, and inorganic fertilizers sometimes reduced MBC. All nutrient sources usually increased the functional diversity of soil bacteria. Hog manure increased N uptake and crop grain yields more than other amendments in Year 1, but cattle manure produced the highest grain yields in subsequent years even when N uptake was greatest with inorganic fertilizers. The effects of soil organic or inorganic amendments on soil microbiological properties were usually the same with annual or triennial applications. Whereas N uptake was greater with triennial application than with annual application in Year 1, the reverse was true in Year 2, and there were no differences in Year 3. In Year 1, there were instances of reduced grain yields with triennial applications of inorganic

fertilizer or hog manure. Therefore, judicious application of organic manures in the low-C Gray Luvisolic soils should be encouraged to increase crop productivity on a sustained basis due to improved soil biological quality.

Acknowledgments

We are grateful to Shawna Schwerdt, Vance Yaremko, Andrew Tye and several summer staff for technical support in the field, and to Andrea Eastman, Mandy Collins and Wendy Walter for microbiological analyses. We also acknowledge the contribution of Tom Staples in setting up the trial, and the financial contributions of Alberta Environmentally Sustainable Agriculture (AESAs) Agreement and Alberta Agricultural Research Institute (AARI) On Farm Demonstration Funding Program.

References

- Altieri, M. A. and Nicholls, C. I. 2003.** Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems. *Soil Till. Res.* **72**: 203-211.
- Bailey, K. L. and Lazarovits, G. 2003.** Suppressing soil-borne diseases with residue management and organic amendments. *Soil Till. Res.* **72**: 169-180.
- Bulluck, L. R. III, Brosius, M., Evanylo, G. K. and Ristaino, J. B. 2002.** Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Appl. Soil Ecol.* **19**: 147-160.
- Conn, K. L. and Lazarovits, G. 1999.** Impact of animal manures on verticillium wilt, potato scab, and soil microbial populations. *Can. J. Plant Pathol.* **21**: 81-92.
- Doran, J. W. and Linn, D. M. 1994.** Microbial ecology of conservation management systems. Pages 1-27 in J. L. Hatfield and B.A. Stewart, eds, *Soil biology: effects on soil quality*. CRC Press, Boca Raton, FL, USA.
- Eghball, B. and Power, J. F. 1999.** Phosphorus- and nitrogen-based manure and compost applications: corn production and soil phosphorus. *Soil Sci. Soc. Am. J.* **63**: 895-901.
- Gupta, V. S. S. R., Lawrence, J. R. and Germida, J. J. 1988.** Impact of elemental sulfur fertilization on agricultural soils. I. Effects on microbial biomass and enzyme activities. *Can. J. Soil Sci.* **68**: 463-473.
- Hao, X. and Chang, C. 2002.** Effect of 25 annual cattle manure applications on soluble and exchangeable cations in soil. *Soil Sci.* **167**: 126-134.
- Horwath, W. R. and Paul, E. A. 1994.** Microbial biomass. Pages 753-773 in R. W. Weaver, S. Angle, P. Bottomly, D. Bezdicsek, S. Smith, A. Tabatabai and A. Wollum, eds. *Methods of soil analysis. Part 2. Microbiological and biochemical properties*. Soil Science Society of America, Madison, Wisconsin.
- Kremer, R. J. and Li, J. 2003.** Developing weed-suppressive soils through improved soil quality management. *Soil Till. Res.* **72**: 193-202.
- Lalande, R., Gagnon, B. and Simard, R. R. 2003.** Papermill biosolid and hog manure compost affect short-term biological activity and crop yield of a sandy soil. *Can. J. Soil Sci.* **83**: 353-362.
- Langmeier, M., Frossard, E., Kreuzer, M. P., Dubois, D. and Oberson, A. 2002.** Nitrogen fertilizer value of cattle manure applied in soils originating from organic and conventional farming systems. *Agronomie* **22**: 789-800.

- Lazarovits, G. 2001.** Management of soil-borne plant pathogens with organic soil amendments: a disease control strategy salvaged from the past. *Can J. Plant Pathol.* **23**: 1-7.
- Lupwayi, N. Z., Arshad, M. A, Rice, W. A. and Clayton, G. W. 2001a.** Bacterial diversity in water-stable aggregates of soils under conventional and zero tillage management. *Appl. Soil Ecol.* **16**: 251-261.
- Lupwayi, N. Z., Clayton, G. W., O'Donovan, J. T., Harker, K. N., Turkington, T. K. and Rice, W. A. 2004.** Soil microbiological properties during decomposition of crop residues under conventional and zero tillage. *Can. J. Soil Sci.* (in print).
- Lupwayi, N. Z., Monreal, M., Clayton, G. W., Johnston, A. M., Grant, C. A. and Rice, W. A. 2001b.** Soil microbial biomass and diversity respond to tillage and sulphur fertilizers. *Can. J. Soil Sci.* **81**: 577-589.
- Lupwayi, N. Z., Rice, W. A. and Clayton, G. W. 1999.** Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation. *Can. J. Soil Sci.* **79**: 273-280.
- Lynch, J. M. and Whipps, J. M. 1990.** Substrate flow in the rhizosphere. *Plant Soil* **129**: 1-10.
- Magurran A. E. 1988.** Ecological diversity and its measurement. Princeton University Press, Princeton, New Jersey.
- Marschner, P., Kandeler, E. and Marschner, B. 2003.** Structure and function of soil microbial community in a long-term fertilizer experiment. *Soil Biol. Biochem.* **35**: 453-461.
- McCune, B. and Mefford, M. J. 1997.** PC-ORD. Multivariate analysis of ecological data, Version 3.0. MjM Software Design, Gleneden Beach, OR. 47 pp.
- Miller, J. J., Sweetland, N. J. and Chang, C. 2002.** Soil physical properties of a Chernozemic clay loam after 24 years of beef cattle manure application. *Can. J. Soil Sci.* **82**: 287-296.
- Mooleki, S. P., Schoenau, J. J., Hultgreen, G., Wen, G. and Charles, J. L. 2002.** Effect of rate, frequency and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. *Can J. Soil Sci.* **82**: 457-467.
- Parham, J. A., Deng, S. P., Da, H. N., Sun, H. Y. and Raun, W. R. 2003.** Long-term cattle manure application in soil. II. Effect on soil microbial populations and community structure. *Biol. Fertil. Soils* **38**: 209-215.
- Peacock, A. D., Mullen, M. D., Ringelberg, D. B., Tyler, D. D., Hedrick, D. B., Gale, P. M. and White, D. C. 2001.** Soil microbial community responses to dairy manure or ammonium nitrate applications. *Soil Biol. Biochem.* **33**: 1011-1019.
- Reynolds, W. D., Yang, X. M., Drury, C. F., Zhang, T. Q. and Tan, C. S. 2003.** Effects of selected conditioners and tillage on the physical quality of a clay loam soil. *Can J. Soil Sci.* **83**: 381-393.
- Rochette, P. and Gregorich, E. G. 1998.** Dynamics of soil microbial biomass C, soluble organic C and CO₂ evolution after three years of manure application. *Can. J. Soil Sci.* **62**: 283-290.
- Stevenson, F. C., Johnston, A. M., Beckie, H. J., Brandt, S. A. and Townley-Smith, L. 1998.** Cattle manure as a nutrient source for barley and oilseed crops in zero and conventional tillage systems. *Can. J. Plant Sci.* **78**: 409-416.
- Thomas, R. L., Sheard, R. W. and Moyer, J. R. 1967.** Comparison of conventional and automated procedures for nitrogen, phosphorus and potassium analysis of plant material using a single digestion. *Agron. J.* **59**:240-243.
- Whalen, J. and Chang, C. 2002.** Macroaggregate characteristics in cultivated soils after 25 annual manure applications. *Soil Sci. Soc. Amer. J.* **66**: 1637-1647.

Zak, J. C., Willig, M. R., Moorhead, D. L. and Wildman, H. G. 1994. Functional diversity of microbial communities: a quantitative approach. *Soil Biol. Biochem.* **26**: 1101-1108.