SOIL CONDITIONS AND EARLY CROP GROWTH AFTER REPEATED MANURE APPLICATIONS

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ABSTRACT

Development of the swine and cattle industries has led to an increase of manure application to agricultural lands in Saskatchewan. Studies have been conducted to determine the nutrient benefits of swine manure application. However, a need was also identified for information on the effects of manure application on soil physical and chemical properties. The objective of this study was to examine the effect of repeated applications of manure on soil physical and chemical properties and to relate those effects to early plant growth and development.

Four experimental sites were used, representing the Dark Brown (Plenty), Brown (Riverhurst – irrigated), Black (Dixon) and Gray (Melfort) Soil Zones of Saskatchewan, where liquid swine manure had been applied for four to seven years. At each site, treatments were 1) a control treatment, 2) a nitrogen based agronomic rate of manure application, 3) a high rate of manure application (2-4x the agronomic rate) and 4) a urea fertilizer treatment. At the Dixon site, the same two manure treatments with cattle manure were also examined.

Soil strength, as determined by penetration resistance measurements and barley (*Hordeum vulgare*) emergence were measured at two experimental sites (swine and cattle manure trials at Dixon, SK) in a field study. Penetration resistance was measured at 5, 10, 15 and 20 cm depths, 20, 39 and 123 days after seeding using a recording cone penetrograph. Twenty days after seeding, there were no significant differences among treatments at the 10, 15 and 20 cm depths. But, at the 5 cm depth, the control treatment had soil strength 0.11 MPa lower than the two manure rates. The manure treatments were not significantly different from the urea treatment. Thirty-nine days after seeding, the soil strength of the low rate manure treatment was 1.1 MPa greater than the control at the 10 cm depth, but not significantly different from the urea treatment. One hundred and twenty three days after seeding, the control treatment had greater soil strength than the high rate of manure at 5 and 10 cm depths by 0.28 and 0.71 MPa respectively. At the 20 cm depth, the high rate of manure had the greatest soil strength. Barley emergence on the two manured treatments did not differ significantly from the control. Aggregate size was

measured in field samples collected from all sites. Aggregate size for the manured treatments did not differ from the control at any site.

Soil crust strength, flax emergence, infiltration rate, salinity, sodicity, coefficient of linear extensibility (COLE) and modulus of rupture were measured under controlled conditions in intact cores of soil removed from all five experimental sites. All soils were treated with a simulated rainfall from a Guelph Rainfall Simulator II. Following the simulated rainfall, crust strength was measured with a hand-held penetrometer. Soil crust strength was measured daily for 10 days as the cores dried. Repeated applications of liquid swine manure at either low or high rates decreased soil strength in the Plenty, Riverhurst and Melfort soils, and increased soil strength in the Dixon soil. Repeated applications of liquid swine manure at low rates caused flax emergence to decrease for the Riverhurst soil compared to its control and had no significant effect at the other sites. There were no notable differences in infiltration rates among treatments. Repeated applications of liquid swine manure caused salinity (EC) to increase slightly for the Plenty and Riverhurst soils, and sodicity (ESP) to increase slightly for the Melfort and Dixon soils relative to their control. The COLE and modulus of rupture measurements indicated no significant effects and were inconclusive due to difficulties in measurement.

None of the properties measured in any of the treatments exceeded threshold values for soil productivity, or where plant injury might be considered an issue. It is concluded that repeated (four to seven) annual applications of liquid swine or cattle manure would not cause any large alterations in soil strength, aggregation, infiltration, salinity, or sodicity that would affect early plant growth and development. This was supported by field and lab measurements of emergence that showed limited effect.

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Finally, I must thank my family, who may have thought from time to time that what I chose to study was a little strange, but understood all the same.

DEDICATION

I dedicate this thesis to my wife Leah, who has helped me in many ways to get this thesis completed.

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LIST OF ABBREVIATIONS

BD	Bulk density
CEC	Cation exchange capacity
COLE	Coefficient of linear extensibility
DAS	Days after seeding
DEDL	Diffuse electrical double layer
DSD	Drop size distribution
DVD	Drop velocity distribution
EC	Electrical conductivity
ESP	Exchangeable sodium percentage
GRSII	Guelph rainfall simulator II
LSD	Least significant difference
MWD	Mean weight diameter
PAMI	Prairie Agriculture Machinery Institute
PVC	Polyvinyl chloride
SAR	Sodium adsorption ratio
SOC	Soil organic carbon
SOM	Soil organic matter

CHAPTER 1

GENERAL INTRODUCTION

The physical and chemical nature of the soil at the surface of the profile greatly influences plant emergence and early growth, especially of the root system. The soil surface is easily influenced by human activity, especially in annual cropping systems common to Saskatchewan. Tillage practises, compaction by equipment or animal traffic, fertilizer addition, and irrigation are all ways agriculture can influence the soil surface. The addition of organic amendments like livestock manure to the soil is another management practice that can influence soil characteristics. The effect of repeated manure additions on soil physical and chemical properties important to crop emergence and early crop development has not been well documented in prairie soils for some manure types. This thesis attempts to address this gap.

The soil physical and chemical properties as influenced by long-term cattle manure applications to prairie soils has been well documented, based on research out of Lethbridge, AB (Sommerfeldt and Chang, 1985; Hao and Chang, 2002; Miller et al., 2002a; Miller et al., 2002b; Hao and Chang, 2003; Hao et al., 2003; Miller et al., 2004; Miller et al., 2005). Cattle manure, based on aforementioned research consistently improves the overall soil quality. Liquid swine manure, conversely, has not been researched as intensively for prairie soils. Early swine manure research focused primarily on the yield response and nutrient levels in the soil (Mooleki et al., 2000; Qian and Schoenau, 2000; Mooleki et al., 2001; Qian and Schoenau, 2001; Qian et al., 2003; Mooleki et al., 2004; Qian et al., 2004; Qian et al., 2005).

The limited research that has been completed on how swine manure influences soil physical and chemical properties has yielded some inconsistent results. More often than not, there were no measurable effects from the liquid swine manure on the properties investigated (Assefa, 2002; Zeleke, 2003). However, compared with the cattle manure research out of Lethbridge, these findings are based on relatively short-term histories of application.

In addition, while past research has addressed soil physical and chemical properties, there has been little research on the impact of any soil changes on emergence and early plant growth. Charles (1999) found yield to decrease as manure rates increased above agronomic rates. Effects on early plant growth, especially emergence, may have been the reason. Further, these effects may vary with soil type and climatic conditions. This thesis will attempt to address known gaps in liquid swine manure research and reaffirm cattle manure research from Alberta, under Saskatchewan soil conditions.

The objectives of the research described in this thesis are as follows:

1) Quantify soil strength (penetrability) and crop emergence under field conditions as affected by repeated additions of liquid swine manure and solid cattle manure in four contrasting soils;

2) Determine the effect in the laboratory on crusting, emergence, aggregation, surface seal, infiltration, sodicity and salinity resulting from repeated applications of liquid swine manure and solid cattle manure in four contrasting soils.

1.1 References

Assefa, B. 2002. Single and repeated applications of hog and cattle manure and their effects on soil conditions and plant growth in gray luvisolic and black chernozemic soils. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 131 p.

Charles, J.J. 1999. Soil and crop response to hog and cattle manure additions in east central Saskatchewan. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 151 p.

Hao, X., and C. Chang. **2002.** Effect of 25 annual cattle manure applications on soluble and exchangeable cations in soil. Soil Sci. **167**:126-134.

Hao, X., and C. Chang. **2003.** Does long-term heavy cattle manure application increase salinity of a clay loam soil in semi-arid southern Alberta? Agric. Ecosyst. Environ. **94**:89-103.

Hao, X., C. Chang, G.R. Travis, and F. Zhang. **2003.** Soil carbon and nitrogen response to 25 annual cattle manure applications. J. Plant Nutr. Soil Sci. **166**:239-245.

Miller, J.J., N.J. Sweetland, and C. Chang. **2002a.** Hydrological properties of a clay loam soil after long term cattle manure application. J. Environ. Qual. **31**:989-996.

Miller, J.J., N.J. Sweetland, and C. Chang. **2002b.** Soil physical properties of a Chernozemic clay loam after 24 years of beef cattle manure application. Can. J. Soil Sci. **82**:287-296.

Miller, J.J., B.W. Beasley, F.J. Larney, and B.M. Olson. **2005.** Soil salinity and sodicity after application of fresh and composted manure with straw or wood-chips. Can. J. Soil Sci. **85**:427-438.

Miller, J.J., B.P. Handerek, B.W. Beasley, E.C.S. Olson, L.J. Yanke, F.J. Larney, T.A. McAllister, B.M. Olson, L.B. Selinger, D.S. Chanasyk, and P. Hasselback. **2004.** Quantity and quality of runoff from a beef cattle feedlot in Southern Alberta. J. Environ. Qual. **33**:1088-1097.

Mooleki, P., J.J. Schoenau, J. Charles, and G. Wen. **2004.** Effect of rate, frequency and incorporation of feedlot cattle manure on soil nitrogen availability, crop performance and nitrogen use efficiency in east-central Saskatchewan. Can. J. Soil Sci. **84**:199-210.

Mooleki, S.P., J.J. Schoenau, and G. Hultgreen. 2000. Hulless barley performance in the third year of hog and cattle manure application in east-central Saskatchewan. p.286-292. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen, and J.L. Charles. 2001. Crop response to liquid swine effluent and solid cattle manure over four years in east-central Saskatchewan. p.291-297. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 22-23 Feb 2001.

Qian, P., and J.J. Schoenau. 2000. Effect of hog manure on soil phosphorus forms. p.274-285. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

Qian, P., and J.J. Schoenau. 2001. Evaluation of nitrogen availability from different manure amendments with different C:N ratios. p.477-487. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 22-23 Feb 2001.

Qian, P., J.J. Schoenau, T. Wu, and S.P. Mooleki. **2003.** Copper and zinc amounts and distribution in soil as influenced by application of animal manure in east-central Saskatchewan. Can. J. Soil Sci. **83**:197-202.

Qian, P., J.J. Schoenau, T. Wu, and P. Mooleki. **2004.** Phosphorus amounts and distribution in a Saskatchewan soil after five years of swine and cattle manure application. Can. J. Soil Sci. **84**:275-281.

Qian, P., J.J. Schoenau, T. King, and M. Japp. **2005.** Effect of repeated manure application on potassium, calcium and magnesium in soil and cereal crops in Saskatchewan. Can. J. Soil Sci. **85**:397-403.

Sommerfeldt, T.G., and C. Chang. **1985.** Changes in soil properties under annual applications of feedlot manure and different tillage practices. Soil Sci. Soc. Am. J. **49**:983-987.

Zeleke, T.B. 2003. Surface soil physical properties after crop residue incorporation and injection of liquid swine effluent. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 104 p.

CHAPTER 2

LITERATURE REVIEW

2.1 Manure as a Soil Amendment

Manure is a form of fertilizer applied to soil to improve crop production. The intensification of the livestock industry in recent years has resulted in large quantities of manure applied to a relatively small land base. Odour, nutrient loading, fecal coliforms and soil degradation are all concerns that arise when animal manure from intensive livestock operations is considered. Manure management is a public, agronomic and environmental issue.

Most of the manure that originates from somewhere other than a pasture is applied to agricultural land (Assefa, 2002). Although manure is widely considered to be a low-cost nutrient option, in large volumes it can pose a significant environmental hazard. Land managers must be aware of the dangers, and take precautionary steps to avoid catastrophe. Consideration must be taken in handling, storage and application. This review will cover the impact of manure addition on soil properties pertinent to soil quality and crop growth, with an emphasis on environmentally and agronomically sound manure application practices for agricultural land.

2.1.1 Manure as a Chemical Amendment

Animal manure is a natural form of fertilizer available for crop production. Although manure is animal waste, to the agricultural industry it is a valuable commodity. Agricultural producers use manure as a nutrient source because it is inexpensive and provides a complete nutrient package (Table 2.1). The macro- and micro-nutrients in manure, when applied to the soil, provide the crop with a competitive advantage over no fertilizer (Mooleki et al., 2002; Mooleki et al., 2004). Additionally, some of the nutrients in manure are in the organic and some in the inorganic forms (Qian and Schoenau, 2000;

Schoenau et al., 2000; Prairie Province's Committee, 2003). Inorganic forms are readily taken up by the crop, but organic forms mineralize slowly providing nutrients throughout the growing season (Schoenau et al., 2000; Prairie Province's Committee, 2003; Wen et al., 2003).

However, there are two problems associated with looking at manure as simply a source of fertilizer. One, is that manure rarely contains the relative balance of nutrients required by a crop (Qian and Schoenau, 2000). The other problem is that some of the potential for damage from other constituents in manure, like salts, are ignored (Weiterman et al., 2000; Assefa, 2002).

Table 2.1 Nutrient concentration ranges of liquid swine and solid beef manure (adapted from Prairie Province's Committee, 2003).

	Manure Nutrient Concentrations					
	Liquid Swine†			Solid Beef‡		
Nutrient	Avg	Min	Max	Avg	Min	Max
	--------------------%--------------------					
Total N	0.31	0.04	0.68	0.60	0.14	2.02
Total P	0.10	0.00	0.51	0.14	0.03	0.64
Total K	0.14	0.03	0.37	0.59	0.16	2.54
	--------------------ppm--------------------					
NH_4^+-N	1946	230	5150	564	11	2656
S	*271.3*§	*42.8*	*1220*	2458	679	6042
B	*1.98*	*0.32*	*11.20*	6.9	1.7	16.5
Cu	*37.2*	*1.6*	*177.0*	22.6	0.84	49.9
Zn	*53.98*	*1.18*	*239.0*	152	21.6	589

† n = 133
‡ n = 45
§ Numbers in italics are based only on swine feeder operations. n = 92

Manure applied infrequently and at low rates is unlikely to cause concern (Assefa, 2002; Mooleki et al., 2002; Zeleke, 2003). However, because of economies of scale, the animals are often concentrated into large barns or feedlot operations. The result of large barns and feedlot operations, and poor economics of transport, is that large volumes of manure are generally applied to a small agricultural land base. When paying for transport and application costs only, the producer can realize more economic benefit using manure instead of inorganic fertilizers as a nutrient source, provided the manure does not have to be transported more than a few kilometers away from the source (Nagy et al., 1999). In Saskatchewan, there are over 3.2 million cattle (Saskatchewan Agriculture, 2003a) and

1.25 million swine (Saskatchewan Agriculture, 2003b) that produce 66 800 tonnes and 6 400 tonnes of manure respectively per day (Bennett and Olson, 1996). Manure management varies, depending upon where the manure is. Manure in a feedlot or barn is managed differently than manure in a pasture. Most of the manure from intensive livestock operations is applied to agricultural land (Assefa, 2002).

In addition to fertility, manure also has the potential to affect soil physical and chemical properties. Manure contains many salts, including sodium salts. Sodium can influence both chemical and physical soil properties. Weiterman et al. (2000) raised the question of the potential for soil quality degradation in Saskatchewan. The reasons for concern are well founded. Sodium can cause deflocculation of soil particles. In particular, clay particles disperse, decreasing overall soil quality (USA, 1954; Henry, 2003). Salinity, caused by salts, disturbs the osmotic pressure gradient, making it difficult for plants to obtain water from the soil (USA, 1954).

Irrigation with poor quality water has resulted in salinization and/or sodification of soil (Curtin et al., 1995; Buckland et al., 2002). Similarly, livestock manure application has resulted in some small changes in salinity, pH (Assefa, 2002; Zeleke, 2003; Assefa et al., 2004) and sodium adsorption ratio (SAR) (Zeleke, 2003), but not beyond critical limits (Table 2.2). Similarly, Qian et al. (2005) found an increase in exchangeable sodium percentage (ESP) at one of three sites. Liquid swine manure tends to decrease pH and increase SAR. It is more difficult to draw a conclusion about salinity as determined by electrical conductivity (EC), as some study sites have resulted in increases, others in decreases and some with no significant changes. No large changes have occurred in soil organic carbon (SOC) with short to medium (three to six) annual applications of liquid swine manure (Table 2.2) (Assefa, 2002; Zeleke, 2003; King, 2007). Land receiving applications of liquid swine manure needs to be monitored for soil chemical changes, but past research indicates that agronomic rates of swine manure application were generally beneficial to crop production and did not have adverse effects on soil and environmental quality.

Table 2.2 Summary of past research on soil physical and chemical properties after liquid swine manure application in Saskatchewan and Alberta (adapted from Assefa, 2002; Zeleke, 2003).

Measurement	(Zeleke, 2003)		(Assefa, 2002)			
	Plenty, SK†	Riverhurst, SK†	Fahler, AB‡	Fairview, AB‡	Burr, SK§	Dixon, SK§
Chemical						
pH	-0.3¶	0	0	0	-0.4	0
EC ($dS \cdot m^{-1}$)	+1.9	0	+0.11	-0.18	0	0
SAR	+0.14	0	--	--	+0.89	0
SOC (%)	--	--	--	--	0	0
Physical						
B.D. ($Mg \cdot m^{-3}$)	0	0	--	--	-0.11	0
Aggregate Size (%)	-35	0	+53	0	-41	0
Aggregate Stability	--	--	0	+0.1	0	0
Crust Strength (kPa)	--	--	0	0	0	0
Soil Penetration (kPa)	0	0	--	--	--	--
Shear Resistance (kPa)	0	0	--	--	--	--
Macro-porosity ($m^3 \cdot m^{-3}$)	-0.02	0	--	--	--	--

† Manure applied at 126 $m^3 \cdot ha^{-1}$ each year for three to four years.
‡ Manure applied to treatments at 39.8, 42.1, 48.9, 87.6, 145.6, 176.3 $kL \cdot ha^{-1}$ for one year.
§ Manure applied to treatments at 37.5, 75.1, 150.2 $kL \cdot ha^{-1}$ each year for four years.
¶ Differences are the maximum recorded significant change by the author(s). A zero (0) is used to indicate no significant change and two dashes (--) to indicate that that particular measurement was not taken for that site. Plus (+) and minus (-) indicate the direction of the change.

Compared with liquid swine manure, solid beef cattle manure contains relatively large amounts of organic matter and has relatively high P levels, and therefore different concerns arise. Phosphorus loss from beef cattle manure has been extensively researched in the past, concluding that N based manure application rates result in P loading and a potential environmental hazard from P loss, particularly concerning the eutrophication of water bodies. Cattle manure application results in a decrease in pH, increased EC and SAR (Assefa, 2002; Hao and Chang, 2002) and increased SOC in the long term (Assefa, 2002; Hao et al., 2003) (Table 2.3). Similar to swine manure, the research indicates that application rates based on overall nutrient demand are best. However, continued application of solid beef cattle manure does require monitoring of soil chemical and physical properties.

Table 2.3 Summary of past research on soil physical and chemical properties as affected by solid beef feedlot manure application in Saskatchewan and Alberta (adapted from Assefa, 2002; Hao and Chang, 2002; Miller et al., 2002b; Whalen and Chang, 2002; Hao et al., 2003).

Measurement	(Assefa, 2002)				Various sources from Lethbridge, AB†‡§¶	
	Fahler, AB#	Fairview, AB††	Burr, SK‡‡	Dixon, SK‡‡	Dryland§§	Irrigated¶¶
Chemical						
pH	0##	0	0	0	-0.23†	-0.51†
EC ($dS \cdot m^{-1}$)	0	-0.17	0	+1.3	+1.47†	+1.42†
SAR	--	--	+0.99	+1.17	+1.67†	+1.96†
O.C. ($g\ kg^{-1}$)	--	--	0	0	+26.7‡	+57.1‡
Physical						
B.D. ($Mg \cdot m^{-3}$)	--	--	-0.12	0	-0.23§	-0.49§
Aggregate Size (%)	0	+56%	-30%	0	-¶	-¶
Aggregate Stability	0	0	+0.09	0		
Crust Strength (kPa)	-430	0	0	0		
Soil Penetration (MPa)	--	--	--	--	0§	-1.31§

† (Hao and Chang, 2002)
‡ (Hao et al., 2003)
§ (Miller et al., 2002b)
¶ The researchers did not report their results in the same way (MWD) as Assefa (2002). Instead they reported on specific size fractions. I include here the general trend from their results (Whalen and Chang, 2002).
\# Manure applied at 16, 32, 66, 103 $Mg \cdot ha^{-1}$ for one year. Manure was approximately 5 years old and well composted, leading to relatively high nutrient concentration and lower application rates.
†† Manure applied at 36, 34, 91, 185 $Mg \cdot ha^{-1}$ for one year. Manure was approximately 1 year old.
‡‡ Manure applied at 7.6, 15.2, 30.4 $Mg \cdot ha^{-1}$ each year for four years.
§§ Manure applied at 30, 60, 90 $Mg \cdot ha^{-1}$ each year for 25 years, except (Miller et al., 2002b) which was after 24 years.
¶¶ Manure applied at 60, 120, 180 Mg·ha-1 each year for 25 years, except (Miller et al., 2002b) which was after 24 years.
\## Differences are the maximum recorded significant change by the author(s). A zero (0) is used to indicate no significant change and two dashes (--) to indicate that that particular measurement was not taken for that site. Plus (+) and minus (-) indicate the direction of the change.

2.1.2 Manure as an Organic Amendment

Organic matter, however, can improve soil quality. When organic material is present in the soil, or added to the soil, it can favourably affect pH, nutrient content, water holding capacity, cation exchange capacity (CEC), bulk density, aggregate formation and more (Hornick, 1988; Dormaar and Carefoot, 1996; Bulluck et al., 2002).

Livestock manures vary considerably in organic matter content. Liquid swine manure, on average, has a dry matter content between 1 and 10% and a corresponding low organic matter content. Solid cattle manure, on average, has a dry matter content between 20 and 40% and a relatively high organic matter content (Prairie Province's Committee, 2003). Cattle manure is recognized as directly causing an increase in soil organic matter (Hao et al., 2003; King, 2007). Swine manure adds little organic carbon directly to the soil. Instead it influences SOC through its effects on plant growth and residue addition. Research has shown that the addition of liquid swine manure can increase or decrease the total light fraction organic carbon (King, 2002; King, 2007).

2.1.3 Manure as a Physical Amendment

In addition to direct and indirect effects on SOC, manure can also influence soil bulk density (Assefa, 2002; Miller et al., 2002b; Zeleke, 2003), aggregate size (Assefa, 2002; Whalen and Chang, 2002; Zeleke, 2003), aggregate stability and crust strength (Assefa, 2002), infiltration and macro-porosity (Zeleke, 2003) and soil penetration (Miller et al., 2002b; Zeleke, 2003) (Table 2.2 and Table 2.3).

Similar to chemical properties, due to variability, it is difficult to determine consistent significant impacts of liquid swine manure on soil physical properties (Table 2.2). In any measurement where a significant increase or decrease occurred, it was typically small. Except, in the case of aggregate size (measured in millimetres), where decreases in size of 35 and 41% were recorded at two of six sites, while another site showed an increase of 53%. There were no significant changes in either direction at three other sites (Assefa, 2002; Zeleke, 2003). Zeleke (2003) found overall that liquid swine manure did not have any significant effect on soil water retention characteristics. Liquid swine manure application over the short term (three to five years) does not appear to have any substantial effect on soil physical properties, based on past results in Saskatchewan and Alberta.

Cattle manure addition (Table 2.3), on the other hand, shows a trend toward decreased soil bulk density. Hao et al (2003) found that cattle manure application resulted in higher soil organic matter. Other reported effects include decreasing the bulk density (Assefa, 2002; Miller et al., 2002b) and decreasing soil aggregate size (Assefa, 2002; Whalen and Chang, 2002). This is contradictory to the findings of Sommerfeldt and Chang (1985), who reported that following seven years of feedlot manure application, amounts of aggregates greater than 1 mm increased. In addition to other indirect changes in the soil, cattle manure has been reported to decrease sand content in the field, as a result of removing soil from the feedlot during cleaning. The soil at the feedlot was of lower sand content than the site the manure was applied to, thereby decreasing the relative sand content (Miller et al., 2002b). Miller et al. (2002a) found cattle manure application increased soil water retention by 5-48%, increased field soil water content by 10-22%, increased ponded infiltration by 200%, increased saturated hydraulic conductivity by 76-128%, but had no significant effect on unsaturated hydraulic conductivity.

2.1.4 Different Manure Sources

Manure varies considerably in composition, both between species and within the species that produced it. Although the physiology of an animal has a large influence, feed and water sources, and the animal's environment also play roles, as summarized by Assefa (2002). Breed can be a factor as well, as University of Guelph researchers have bred a pig (Enviropig™) that retains more P than its counterparts by digesting normally indigestible phytate (other swine barns either add the enzyme phytase or supplemental phosphate to pig rations). The Enviropig™ has reduced P in the manure by up to 60% compared with other pigs (Forsberg and Phillips). The resulting product can be applied to the soil at higher rates without overapplying P; a common problem in manure application.

Manure handling can also affect the end product. Swine manure and dairy cattle manure tend to be liquid, whereas beef cattle manure remains solid. Beef cattle manure may be composted, increasing the nutrient concentration (Assefa, 2002). Swine lagoons may be aerated or agitated which will influence the manure composition. Agitation, as the manure is being pumped out and applied, more evenly distributes the solids, which contains most of the P and some microbes (Prairie Province's Committee, 2003).

Beef cattle manure is usually handled in the solid form, with bedding (straw). It tends to be high in P, relative to inorganic N (Prairie Province's Committee, 2003). Application is usually with a broadcast spreader followed by incorporation through tillage. Swine manure is in the liquid form. It has, at most, 2-3% organic matter and tends to be higher in sodium than cattle manure – 67 g Na versus 30 g Na released per 1000 kg live animal mass per day (ASAE, 1999 *In* Assefa, 2002). As a liquid, the method of application can vary. These methods include irrigation, broadcast and injection. The latter is most agronomically and environmentally sound as nutrient losses and odour are minimized.

2.2 Assessing Soil Chemical Properties

2.2.1 Salinity

The application of livestock manure adds substantial quantities of salt to the soil, raising the concern of soil salinization. Salts are strong electrolytes that, in water, dissociate into ions. In water, the ionized electrolytes become hydrated, lowering the potential energy of the soil water (Chang, 1998). Plants require an osmotic gradient of high potential energy in the soil water to lower potential energy in the plant, thus allowing water and nutrients to flow into the plant. In addition to the effects on the osmotic gradient, soil moisture tension increases (USA, 1954), increasing the cohesion between water and soil, which further limits the ability of the plant to obtain water from the soil when salts are present.

Soils with a high concentration of soluble salts are defined as saline soils (Table 2.4) (USA, 1954; Holm and Henry, 1982; Henry, 2003). "Salinity is determined by measuring the electrical conductivity (EC) of a water extract of a soil." p.80 (Henry, 2003). A saturated paste extract is the preferred method, as the result is independent of soil texture, but a 1:1 suspension is easier and therefore more common. Fortunately, there are equations with high correlations to make the conversion from suspension determined EC to the standard extract determined EC (Hogg and Henry, 1984).

2.2.2 Sodicity

The application of livestock manure adds substantial quantities of sodium to the soil, raising the concern of soil sodification. Sodic soils, by definition, have a high concentration of readily exchangeable sodium, a low concentration of soluble salts, and when the soil has a high pH, it is alkali (Table 2.4) (USA, 1954; Henry et al., 1992; Henry, 2003).

Although sodicity is of a chemical nature, the effects will compound into physical problems. Soil properties affected by sodicity include: instability of soil structure, surface crust formation, reduced hydraulic conductivity, reduced rate of water infiltration, and poor seed germination and establishment (So and Aylmore, 1993). In addition, permeability, bulk density, pore-size distribution, and aggregation may all be adversely affected (USA, 1954).

A sodic soil is defined as one in which more than 15 per cent of the clay's negative charge is balanced by sodium ions (Table 2.4) (USA, 1954; Henry et al., 1992; Henry, 2003). However, So and Aylmore (1993) suggest the threshold is between seven and 20%, depending on the soil. Sodium is a monovalent cation with a large hydrated radius. Whether clay particles disperse or flocculate depends on the thickness of the diffuse electrical double layer (DEDL) between clay surfaces and the surrounding soil solution. The DEDL is created by the electrical attraction of a cation to the negative charge on clay and the “pull” of the concentration gradient back into solution. The thinner the DEDL, the more soils tend to flocculate and form aggregates. As the DEDL thickens, the tendency is for clay particles to disperse because of electrostatic repulsion. Two factors influence the thickness of DEDL, the valency of cations on the exchange and solute concentration. When divalent cations such as Ca^{2+} and Mg^{2+} dominate, the DEDL is thinner than when monovalent cations like Na^{+} are present. And, the more dilute the soil solution is, the thicker the DEDL becomes (Craig, 1997; Clark et al., 2000; Australian Academy of Science, 2006). This process is how increased salinity can prevent some of the more severe soil physical changes, such as soil crusting, from occurring in a sodic soil.

Sodicity is measured by either the sodium adsorption ratio (SAR) or by the exchangeable sodium percentage (ESP), which are measures of the amount of sodium available to be exchanged (Equation 2.1 and Equation 2.2). The SAR and ESP are linked to each other (Equation 2.3).

Equation 2.1 (Henry et al., 1992)

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{++} + Mg^{++})/2}}$$

, where SAR is Sodium Adsorption Ratio and concentration is in millimoles (+), or milliequivalents per litre of extract.

Equation 2.2 (Henry et al., 1992)

$$ESP = \frac{Exchangeable Na}{CEC} \times 100$$

, where ESP is Exchangeable Sodium Percentage and concentration is in centimoles (+) per kg or milliequivalents per 100g

Equation 2.3 (Henry et al., 1992)

$$ESP = \frac{100\left[(-0.0126 + 0.01475)SAR\right]}{1 + \left[(-0.0126 + 0.01475)SAR\right]}$$

, where ESP is Exchangeable Sodium Percentage and SAR is Sodium Adsorption Ratio

Table 2.4 Classification of three types of salt-affected soils (adapted from USA, 1954; Henry et al., 1992)

Type	Electrical Conductivity (EC)	Exchangeable Sodium Percentage (ESP)	Sodium Adsorption Ratio (SAR)
	$dS \cdot m^{-1}$	%	
Saline	>4	<15	<13
Saline-Sodic	>4	>15	>13
Sodic	<4	>15	>13

Although salinity is harmful in itself, it can limit the effects of sodicity. In saline-sodic soils, when the soluble salt content is relatively high, the soil may be in better physical condition than a sodic soil with the same sodium content and lower soluble salt content (Holm and Henry, 1982; Clark et al., 2000). These findings are consistent with the findings of Shainberg et al. (1980), who measured dispersivity and found it occurred at a lower ESP using distilled water, compared with a 3.0 meq/litre salt solution. Similarly, Curtin et al. (1995) found that salinity prevents the dispersion of clays in sodic soils because the soil particles remain flocculated, despite the presence of sodium in relatively high concentration (USA, 1954).

In addition, the ratio of calcium to magnesium on the exchange can influence how sodium reacts with the soil. Emerson and Bakker (1973) found that soil dispersion occurs at a lower ESP (less than 6) when sodium and magnesium dominate the exchange than when sodium and calcium dominate. The authors hypothesized that the reason for this was that the number of Mg ions in the DEDL increased faster than the number of Ca ions, allowing swelling and dispersion.

2.2.3 Water Source Considerations for Manure

The salt and sodium content of manure, like irrigation water, are two major concerns related to land application. They have been the subject of many studies with mixed findings (Shainberg et al., 1980; Curtin et al., 1995; Weiterman et al., 2000; Assefa, 2002; Buckland et al., 2002; Hao and Chang, 2002; Hao and Chang, 2003; Zeleke, 2003). The above studies have shown that in some cases there is an increase in salinity and/or sodicity, while in others there is no change. Swine barn and feedlot managers need to consider the water source for the animals (J.L. Henry, personal communication, 2003).

The Judith River formation is a bedrock aquifer which underlies much of Saskatchewan's grainbelt. Many rural areas in Saskatchewan depend on it as a water source. As a bedrock aquifer, it has a lower hardness relative to EC when compared to glacial aquifers. The result is soft water. "Soft water makes land hard. Hard water makes land soft." p.100 (Henry, 2003). Wells drawing from this aquifer produce water with an EC between 2000 and 2500 μS/cm, hardness of 3 grains per gallon, and bicarbonate contents of 500-1000 ppm (Henry, 2003). The effluent from animals drinking from this water source will have a greater potential to cause salinity or sodicity than other water sources (J.L. Henry, personal communication, 2003).

2.3 Assessing Soil Physical Properties

The combined effect of soil physical properties is often termed the 'tilth' of a soil. A soil with good tilth has high infiltration rates, is well aggregated, has a low modulus of rupture and resists surface sealing.

2.3.1 The Soil Surface

The soil surface is an important layer that is the direct interaction between the soil and the external environment. When rain falls, it impacts the surface first; and the interaction between the rain and the soil surface determines the amount of infiltration, whether or not overland flow occurs, to what extent it occurs, and the severity of erosion. In addition, the soil surface is the zone through which an emerging seedling must finally make its way in order to begin photosynthesis and obtain energy from the sun rather than seed reserves.

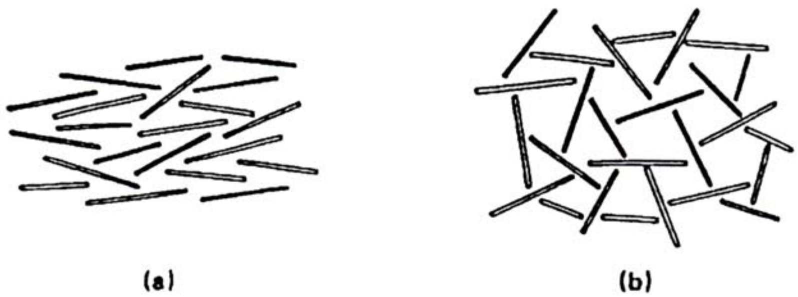
Soil crusts are the result of the breakdown of aggregates at the soil surface. This breakdown results in a 'continuous massive layer' of soil particles at the surface. It is defined as being less than 2 mm thick and, denser, with greater shear strength, smaller pores and decreased permeability compared with the soil it overlies (McIntyre, 1958; McInnis, 2001). McIntyre (1958) described the first 0.1 mm as a 'skin seal', with the remaining thickness up to 2 mm as a 'washed in layer'. The author found that the permeability of the underlying soil was 200x greater than the washed in region and 2 000x greater than that of the skin seal. The author also found that in soils with good structure the washed in region was either absent or did not have the same reduction in permeability as in poorly structured soils.

A soil's crust, in addition to influencing erosion, can play an important role in crop emergence. Studies have shown that emergence can be hindered or slowed by soils with severe crusting (Arndt, 1965; McInnis, 2001). Arndt (1965) measured the force to break a dry crust and found that it would take 630 to 940 kPa for a seedling to emerge through it. However, it would only take 63 kPa for a crack to form, which the seedling may emerge through.

2.3.1.1 Formation of crusts.

Although all textures, except coarse sand, can form crusts (Lutz, 1952 *In* Bradford and Huang, 1992), formation is dependent upon the clay particle (Wace and Hignett, 1991) for two reasons. The first is the shape of the clay particle; it is thin and plate-like. When clay particles are arranged parallel to one another and dispersed, as depicted in Figure 2.1

the surface seals and crusts form. Second, is the inherent negative charge of the clay particle. The repulsion of clay particles causes dispersion, leading to crusts.



a) Dispersed structure, b) flocculent structure.

Figure 2.1 Dispersed and flocculated clay structures. Adapted from Craig (1997).

Soil crusts can be formed either physically or chemically. Physically, crusts are formed when aggregates are pulverized by falling rain. The aggregates disperse, and with the flowing water, individual particles flow into soil pores – plugging them. During a rainfall event, loose particles migrate with rainwater into the pores at or near the surface of the soil, resulting in a surface seal formation. The surface seal then leads to overland flow and erosion. Upon drying, the surface seal will become a layer of soil known as the crust.

Chemical dispersion causes deflocculation and the dispersed clay particles will migrate into soil pores. Sodium, bound to clay and organic colloids, causes the aggregates to disperse because of the ion's influence on the DEDL. In soils with a high concentration of Na relative to Ca and Mg on the exchange sites, aggregation is poor and the overall soil structure is unstable. Upon wetting a sodic soil, water is drawn in between the clay and colloids causing the soil to swell. When the soil dries, the clay colloids, dispersed by the moisture, form a dense layer. At the soil surface, this is a crust. For further explanation of chemical dispersion caused by Na, refer to section 2.2.2 Sodicity.

After repeated manure applications, the concern is that the abundance of monovalent cations such as sodium may become concentrated in the surface layers resulting in crusting and overall reduced soil quality.

2.3.1.2 Prevention of soil crusts.

Soil crust formation is dependent upon many factors. Heil et al. (1997) summarized them as follows: soil type, climate, rainfall intensity and duration, initial water content and drying time. Aggregate stability, affected by aggregation and texture, organic matter content, inorganic cements, salt contents, and types of ions saturating clays, is also important.

All the above factors can be divided into those that are manageable and those that are not. Climate, topography, texture, and inorganic cements are not manageable features of the soil. However, organic matter content can be managed and thereby influence water content and aggregation, as organic matter acts as a cementing agent, binding soil particles and colloids and preventing dispersion. Salt content and the types of ions can also be managed by additions to the soil such as fertilizer, irrigation water and manure.

2.3.1.3 Rainfall simulators.

A rainfall simulator is commonly used to measure run-off rates and erosion, and to induce soil crust development. The Guelph Rainfall Simulator (GRS) was designed for this purpose (Pall et al., 1983). The operator is able to control rain droplet size, drop height and drop rate.

Saskatchewan has many minor showers, but they do not contribute much to the overall precipitation total. Most precipitation comes in large, intense rainfall events. According to Cutforth et al. (2001), 64.9% of Canadian Prairie rainfall events are less than 5 mm, which only account for 20.0% of the rainfall received. A rainfall simulator should be able to simulate these conditions.

Intensity and uniformity of the simulated rainfall are dependent on aperture angle, nozzle pressure, disk angular velocity, and the interaction between nozzle pressure and angular velocity (Pall et al., 1983). Pall et al. (1983) summarize many of the characteristics past researchers have found to be required in a rainfall simulator. The following paraphrased parameters should be as close as possible to natural rainfall:

- Drop size distribution
- Drop impact velocity
- Rainfall intensity
- Uniform rainfall
- Total energy
- Angle of impact (nearly vertical)
- Uniformity of intensity

The dripping type simulators have some material that holds the water. The water releases from the material by breaking adhesion with the material. Large droplets form, but low volumes are ensured. Energy is gravitational; therefore, the drop height must be sufficient to have a substantial impact on the soil surface. These characteristics make this type of simulator best for infiltration and erosion research (Pall et al., 1983).

While drip type simulators have a uniform drop size, nozzle simulators have a drop size distribution closer to that of actual rainfall. Pall et al. (1983) cited several examples of rainfall simulators that quite closely represent the drop characteristics of natural rainfall in terms of rain intensity, drop energy and drop size distribution.

A portable rainfall simulator was developed in Guelph for their erosion research program (Pall et al., 1983). A second simulator was later developed (GRSII), which offered improvements over the original model (Tossell et al., 1987). This rainfall simulator addressed many of rainfall parameters summarized in Pall et al. (1983). The apparatus is capable of producing a wide array of storm intensities (17.5 to 200 mm h^{-1}), and can vary raindrop velocity (by varying height). It can be adapted to suit most needs because many different nozzle sizes were tested for three different pressures (48.3, 69, 96.5 kPa). The results from testing this simulator indicated that it had among the best uniformity of rainfall intensity in the literature (Tossell et al., 1987). The researchers stated that it would be best to choose a larger nozzle if possible, as this will provide a raindrop size distribution more appropriate to that of natural rainfall. Tossell et al. (1990b) found that the GRSII produced rainfall with mean drop diameter concentration of up to 405% greater than that of natural rainfall (in the 0.95mm size class). However, the researchers found that the GRSII produced a raindrop concentration more and more similar to natural rainfall as size class increased. When compared with natural rainfall, the GRSII produced from 178 to 284% more water volume in the smallest drop diameter class (0.92

– 0.95mm) than natural rainfall, as rainfall intensity increased from 36 to 432 mm h^{-1}. Nozzle type simulators will produce smaller droplets than drip type or natural rainfall. The conclusion of these findings is that natural rainfall will tend to be more erosive than simulated rainfall due to greater concentration of drops in the larger size classes, at a given intensity (Tossell et al., 1990b).

The drop velocity distribution (DVD) of rainfall is related to the nozzle type, nozzle height and pressure. The greater proportion of small droplets in simulated rainfall is susceptible to air pressures. At higher nozzle heights, the velocity of these droplets can be lower than lower nozzle heights. The nozzle ejects the water at high velocity and the droplets slow down. However, even at heights of 2 m, larger droplets may not reach terminal velocity before impact. Natural rainfall is considered to reach terminal velocity (Tossell et al., 1990b). The kinetic energy of a raindrop at impact is another factor which has often been related to soil detachment (Tossell et al., 1990a; Tossell et al., 1990b). However, increased water content of the soil prior to rainfall decreases soil detachment (Truman et al., 1990; Wace and Hignett, 1991). Kinetic energy is a product of mass and velocity. The GRSII produced kinetic energy flux densities (EFD) from 31% to 67% of natural rainfall, increasing with intensity. The reason for the low proportions was the lower DVD, the degree to which DVD was important in the EFD equation and drop size distribution (DSD) (Tossell et al., 1990b).

Pall et al. (1983) categorizes rainfall simulators into two categories: dripping rainfall simulators and nozzle rainfall simulators. They cite one of the major problems with the latter is the large volumes of water released. Many researchers who build rainfall simulators have attempted various methods to reduce the amount of water hitting the surface of the ground, but nonetheless, this type of rainfall simulator is also limited in simulating rainfall. I prefer to think of them as rainfall emulators, where the attempt is made to create an event like rainfall, but not necessarily succeeding in doing so. Simulate seems to imply that a good job is done in creating that event.

The rate of infiltration into a soil and development of a surface seal is indicative of how much erosion can be expected in a rainfall event. A soil with good surface characteristics will be able to maintain a good infiltration rate without sealing over for some time. In one study, percolation stability decreased as the ratio of saturated hydraulic conductivity in an uncrusted soil to that of a crusted soil increased (Mbagwu and Auerswald, 1999). However, this depends upon the intensity of the rainfall event. A severe rainfall will cause plugging of pores more quickly. Intense raindrops are more effective at pulverizing the aggregates at the soil surface. As the clays begin to deflocculate, they plug the pores at the surface of the soil and overland flow begins. Not surprisingly, as ponding neared, infiltration rate dropped rapidly. Infiltration rate decreased with increasing rainfall energy (Wace and Hignett, 1991). According to Mazurak et al. (1975), soil detachment due to simulated rainfall increased after manure application.

2.3.2 Soil Strength

Soil penetrometers measure the resistance to penetration in a soil, which is used as a measure of soil strength (Lowrery and Morrison, 2002). Soil strength is a function of water content, contact area of the root to soil, and distance between individual soil particles. The latter is dependent on texture, total porosity or bulk density, pore size distribution, and SOM (Bennie, 1996). The likelihood of a root penetrating through soil is dependent upon soil strength (Taylor et al., 1966). Root growth is commonly considered to be severely inhibited at 2 MPa. However, research indicates that this depends on plant species (Bennie, 1996). Soil resistance is dependent upon water content, bulk density, soil compressibility, soil strength parameters, soil structure, and texture (Lowrery and Morrison, 2002). After three applications of cattle manure incorporated to 10 cm, crust strength decreased from 3.5 MPa (36 $kg \cdot cm^{-2}$) to 0.4 MPa (4.4 $kg \cdot cm^{-2}$). However, when incorporated to 30 cm, the decrease was reduced, but the trend was the same (Mazurak et al., 1975).

2.3.3 Aggregation

Aggregate mean weight diameter (MWD) is the weighted average of the aggregate size classes. It is the sum of the products of the mean of each diameter size class and the proportion of total sample weight in that size class. Soil aggregation is the binding of primary soil particles to make larger soil units (Diaz-Zorita et al., 2002). These units are part of the soil structure and strength. An increase in aggregate MWD is considered an improvement to the soil quality (Arshad et al., 1999). Dispersed aggregates are undesirable in soil, as they lead to surface seals and crusting.

McConkey et al. (2000) found that no-till cropping rotations increased aggregate size and stability compared with minimum till and conventional till. The increase in SOM under no-till provided a favourable environment for aggregate formation. A Nebraskan study found that cattle manure application increased the proportion of aggregates in large size classes (Mazurak et al., 1975).

2.4 Agronomic Implications

Yield has long been the agronomic indicator of manure performance. Past research has shown that rates of manure in excess of agronomic requirements can decrease yield (Charles, 1999). This begs the question: why? Possible reasons may include alterations of soil physical and chemical properties previously reviewed that may impact emergence, stand density and early crop development. Adverse effects on emergence and root development can ultimately have a detrimental effect on yield.

2.5 References

Australian Academy of Science, 2006. Sodicity - a dirty word in Australia [Online] www.science.org.au/nova/035/035print.html (posted April 2006; verified 14 October, 2006).

Arndt, W. 1965. The nature of the mechanical impedance to seedlings by soil surface seals. Aust. J. Soil Res. **3**:45-54.

Arshad, M.A., A.J. Franzluebbers, and R.H. Azooz. **1999.** Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Tillage Res. **53**:41-47.

ASAE, American Society of Agricultural Engineers. 1999. ASAE Standards: Engineering practices data. 46th ed. pp.655-734

Assefa, B. 2002. Single and repeated applications of hog and cattle manure and their effects on soil conditions and plant growth in gray luvisolic and black chernozemic soils. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 131 p.

Assefa, B.A., J.J. Schoenau, and M.C.J. Grevers. 2004. Effects of four annual applications of manure on Black Chernozemic soils. Canadian Biosystems Engineering 46:6.39-6.46.

Bennett, D.R., and B.M. Olson. **1996**. Environmentally responsible manure management. Irrigation and Resource Management Division, Alberta Agriculture, Food and Rural Development, Agriculture Centre, Lethbridge, Alberta.

Bennie, A.T.P. 1996. Growth and mechanical impedance. p. 453-470. *In* Y. Waisel, et al. (eds.) Plant roots: The hidden half, 2nd ed. Marcel Dekker, New York.

Bradford, J.M., and C. Huang. **1992**. Mechanisms of crust formation: physical components. p. 55-71. *In* M.E. Sumner and B.A. Stewart (eds.) Advances in soil science: Soil crusting chemical and physical processes. Lewis Publishers, Boca Raton, Florida.

Buckland, G.D., D.R. Bennett, D.E. Mikalson, E. de Jong, and C. Chang. **2002.** Soil salinization and sodication from alternate irrigations with saline-sodic water and simulated rain. Can. J. Soil Sci. **82**:297-309.

Bulluck, L.R., M. Brosius, G.K. Evanylo, and J.B. Ristaino. **2002.** Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Applied Soil Ecology **19**:147-160.

Chang, R. 1998. Chemistry. 6th ed. McGraw-Hill Companies. pp.995

Charles, J.J. 1999. Soil and crop response to hog and cattle manure additions in east central Saskatchewan. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 151 p.

Clark, D.R., C.J. Green, and J.A. Gordon. **2000.** Laboratory exercises to demonstrate effects of salts on plants and soils. J. Nat. Res. Life Sci. Educ. **29**:41-45.

Craig, R.F. 1997. Soil Mechanics. 6th ed. E and FN Spon, Great Britain. pp.485

Curtin, D., H. Steppuhn, A.R. Mermut, and F. Selles. **1995.** Sodicity in irrigated soils in Saskatchewan: Chemistry and structural stability. Can. J. Soil Sci. **75**:177-185.

Cutforth, H.W., O.O. Akinremi, and S.M. McGinn. 2001. Precipitation trends on the Canadian Prairie. p.391-395. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 22-23 Feb 2001.

Diaz-Zorita, M., E. Perfect, and J.H. Grove. **2002.** Disruptive methods for assessing soil structure. Soil Tillage Res. **64**:3-22.

Dormaar, J.F., and J.M. Carefoot. **1996.** Implications of crop residue management and conservation tillage on soil organic matter. Can. J. Plant Sci. **76**:627-634.

Emerson, W.W., and A.C. Bakker. **1973.** The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. Aust. J. Soil Res. **11**:151-157.

Forsberg, C.W., and J.P. Phillips. Guelph transgenic pig research program [Online]. Available by University of Guelph http://www.uoguelph.ca/enviropig/ (verified November 27, 2005).

Hao, X., and C. Chang. **2002.** Effect of 25 annual cattle manure applications on soluble and exchangeable cations in soil. Soil Sci. **167**:126-134.

Hao, X., and C. Chang. **2003.** Does long-term heavy cattle manure application increase salinity of a clay loam soil in semi-arid southern Alberta? Agric. Ecosyst. Environ. **94**:89-103.

Hao, X., C. Chang, G.R. Travis, and F. Zhang. **2003.** Soil carbon and nitrogen response to 25 annual cattle manure applications. J. Plant Nutr. Soil Sci. **166**:239-245.

Heil, J.W., S.R. Anthony, and K.J. McInnes. **1997.** Soil properties influencing surface sealing of some sandy soils in the Sahel. Soil Sci. **162**:459-469.

Henry, L. 2003. Henry's handbook of soil and water Houghton Boston, Saskatoon, SK. pp.218

Henry, L., B. Harron, and D. Flaten. **1992**. The nature and management of salt-affected land in Saskatchewan. Saskatchewan Agriculture.

Hogg, T.J., and J.L. Henry. **1984.** Comparison of 1:1 and 1:2 suspensions and extracts with the saturation extract in estimating salinity in Saskatchewan soils. Can. J. Soil Sci. **64**:699-704.

Holm, H.M., and J.L. Henry. **1982**. Understanding salt-affected soils. Saskatchewan Agriculture.

Hornick, S.B. 1988. Use of organic amendments to increase the productivity of sand and gravel spoils: Effect on yield and composition of sweet corn. Am. J. Alternative Agric. **3**:156-162.

King, T. 2002. Liquid swine manure application to forage soil: Effect on soil carbon and economic returns. M.Ag. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 31 p.

King, T. 2007. Effect of repeated applications of manure on soil organic carbon and enzymes. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 112 p.

Lowrery, B., and J.E. Morrison, Jr. 2002. Soil penetrometers and penetrability. p. 363-388. *In* J. H. Dane and G. C. Topp (eds.) Methods of soil analysis. Part 4., 2nd ed. Soil Science Society of America, Madison, WI.

Lutz, J.F. 1952. Mechanical impedance and plant growth. p. 43-71. *In* B. T. Shawn (ed.) Soil physical conditions and plant growth. Academic Press, New York.

Mazurak, A.P., L. Chesnin, and A.E. Tiarks. **1975.** Detachment of soil aggregates by simulated rainfall from heavily manured soils in eastern Nebraska. Soil Sci. Soc. Am. Proc. **39**:732-736.

Mbagwu, J.S.C., and K. Auerswald. **1999.** Relationship of percolation stability of soil aggregates to land use, selected properties, structural indices and simulated rainfall erosion. Soil Tillage Res. **50**:197-206.

McConkey, B.G., B.C. Liang, C.A. Campbell, A. Moulin, S.A. Brandt, and G.P. Lafond. 2000. Long-term tillage and crop rotation effects on soil aggregation. p.626-641. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

McInnis, T.A. 2001. The effect of tillage and cropping frequency on soil crusting in the Brown Soil Zone of Saskatchewan. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 126 p.

McIntyre, D.S. 1958. Permeability measurements of soil crusts formed by raindrop soil impact. Soil Sci. **85**:185-189.

Miller, J.J., N.J. Sweetland, and C. Chang. **2002a.** Hydrological properties of a clay loam soil after long term cattle manure application. J. Environ. Qual. **31**:989-996.

Miller, J.J., N.J. Sweetland, and C. Chang. **2002b.** Soil physical properties of a Chernozemic clay loam after 24 years of beef cattle manure application. Can. J. Soil Sci. **82**:287-296.

Mooleki, P., J.J. Schoenau, J. Charles, and G. Wen. **2004.** Effect of rate, frequency and incorporation of feedlot cattle manure on soil nitrogen availability, crop performance and nitrogen use efficiency in east-central Saskatchewan. Can. J. Soil Sci. **84**:199-210.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen, and J.L. Charles. **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.

Nagy, C.N., J.J. Schoenau, and R.A. Schoeny. 1999. Economic returns and hauling distance of hog and cattle manure. p.18-27. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 25-26 Feb 1999.

Pall, R., W.T. Dickinson, D. Beals, and R. McGirr. **1983.** Development and calibration of a rainfall simulator. Can. Agric. Engin. **25**:181-187.

Prairie Province's Committee on Livestock Development and Manure Management. 2003. Tri-Provincial manure application and use guidelines.

Qian, P., and J.J. Schoenau. 2000. Effect of hog manure on soil phosphorus forms. p.274-285. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

Qian, P., J.J. Schoenau, T. King, and M. Japp. **2005.** Effect of repeated manure application on potassium, calcium and magnesium in soil and cereal crops in Saskatchewan. Can. J. Soil Sci. **85**:397-403.

Saskatchewan Agriculture, Food and Rural Revitalization. 2003a. July 1, 2003 Cattle on farms [Online] http://www.agr.gov.sk.ca/docs/statistics/livestock/cattleonfrms0307.pdf (posted 2003.08.19.)

Saskatchewan Agriculture, Food and Rural Revitalization. 2003b. July 1, 2003 Pigs on farms [Online] http://www.agr.gov.sk.ca/docs/statistics/livestock/pigsonfrm0307.pdf (posted 2003.08.19.)

Schoenau, J.J., P. Mooleki, P. Qian, G. Wen, and J. Charles. 2000. Nitrogen dynamics in manured Saskatchewan soils. p.265-273. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

Shainberg, I., J.D. Rhoades, and R.J. Prather. **1980.** Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. **45**:273-277.

So, H.B., and L.A.G. Aylmore. **1993.** How do sodic soils behave? The effects of sodicity on soil physical behaviour. Aust. J. Soil Res. **31**:761-777.

Sommerfeldt, T.G., and C. Chang. **1985.** Changes in soil properties under annual applications of feedlot manure and different tillage practices. Soil Sci. Soc. Am. J. **49**:983-987.

Taylor, H.M., G.M. Roberson, and J.J. Parker, Jr. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. **102**:18-22.

Tossell, R.W., W.T. Dickinson, R.P. Rudra, and G.J. Wall. **1987.** A portable rainfall simulator. Can. Agric. Engin. **29**:155-162.

Tossell, R.W., G.J. Wall, W.T. Dickinson, R.P. Rudra, and P.H. Groenevelt. **1990a.** The Guelph rainfall simulator II: Part 1 - Simulated rainfall characteristics. Can. Agric. Engin. **32**:205-213.

Tossell, R.W., G.J. Wall, R.P. Rudra, W.T. Dickinson, and P.H. Groenevelt. **1990b.** The Guelph rainfall simulator II: Part 2 - A comparison of natural and simulated rainfall characteristics. Can. Agric. Engin. **32**:215-224.

Truman, C.C., J.M. Bradford, and J.E. Ferris. **1990.** Antecedent water content and rainfall energy influence on soil aggregate breakdown. Soil Sci. Soc. Am. J. **54**:1385-1392.

USA, Regional Salinity Laboratory. 1954. Diagnosis and improvement of saline and alkali soils U.S. Govt. Print. Off., Washington. pp.160

Wace, S.A., and C.T. Hignett. **1991.** The effect of rainfall energy on tilled soils of different dispersion characteristics. Soil Tillage Res. **20**:57-67.

Weiterman, G., L. Bohrson, H. Steppuhn, and W. Eilers. 2000. Can land utilization of swine effluent pose a soil sodicity hazard? p.669-673. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

Wen, G., J.J. Schoenau, J.L. Charles, and S. Inanaga. **2003.** Efficiency parameters of nitrogen in hog and cattle manure in the second year following application. J. Plant Nutr. Soil Sci. **166**:490-498.

Whalen, J.K., and C. Chang. **2002.** Macro-aggregate characteristics in cultivated soils after 25 annual manure applications. Soil Sci. Soc. Am. J. **66**:1637-1647.

Zeleke, T.B. 2003. Surface soil physical properties after crop residue incorporation and injection of liquid swine effluent. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 104 p.

CHAPTER 3

SOIL STRENGTH AND CROP EMERGENCE AFTER REPEATED MANURE APPLICATIONS – FIELD EXPERIMENT

3.1 Introduction

The land application of liquid swine manure from swine barns to a small land base is an activity that has become common in some areas of Saskatchewan. The effect on soil physical and chemical properties after long term cattle manure application is well-documented (Assefa, 2002; Hao and Chang, 2002; Miller et al., 2002; Whalen and Chang, 2002; Hao et al., 2003) and discussed in greater detail in Chapter 2. However, the effect on soil physical and chemical properties as a result of liquid swine manure application is less well documented and past research has documented effects after only three to four years (Assefa, 2002; Zeleke, 2003; Assefa et al., 2004). A thorough understanding of how manure interacts with and affects the physical condition of Saskatchewan soils is needed (Weiterman et al., 2000).

To address gaps in the research, soil strength was quantified on field plots at 5, 10, 15 and 20 cm depths in 2003. These depths were selected to reflect potential limitations to root growth (Lowrery and Morrison, 2002) in the zone of influence of the injected swine manure and incorporated cattle manure. Corresponding measurements of plant emergence were taken to address the concern of crusting. Aggregate size distribution was determined as well. Similar measurements were taken in the lab after a simulated rainfall on undisturbed cores (Chapter 4).

3.2 Materials and Methods

Five replicated experiments were carried out on soils from across the Brown, Dark Brown, Black and Grey Soil Zones of Saskatchewan. These soils represent a range of soil associations, textures and soil properties (Table 3.2 and Table 3.3). In accordance with recommendations from Prof. Les Henry, a small set of survey samples were also collected from southwest Saskatchewan where problems with soil structure are well documented and used for comparison to the five experimental sites (see Appendix C).

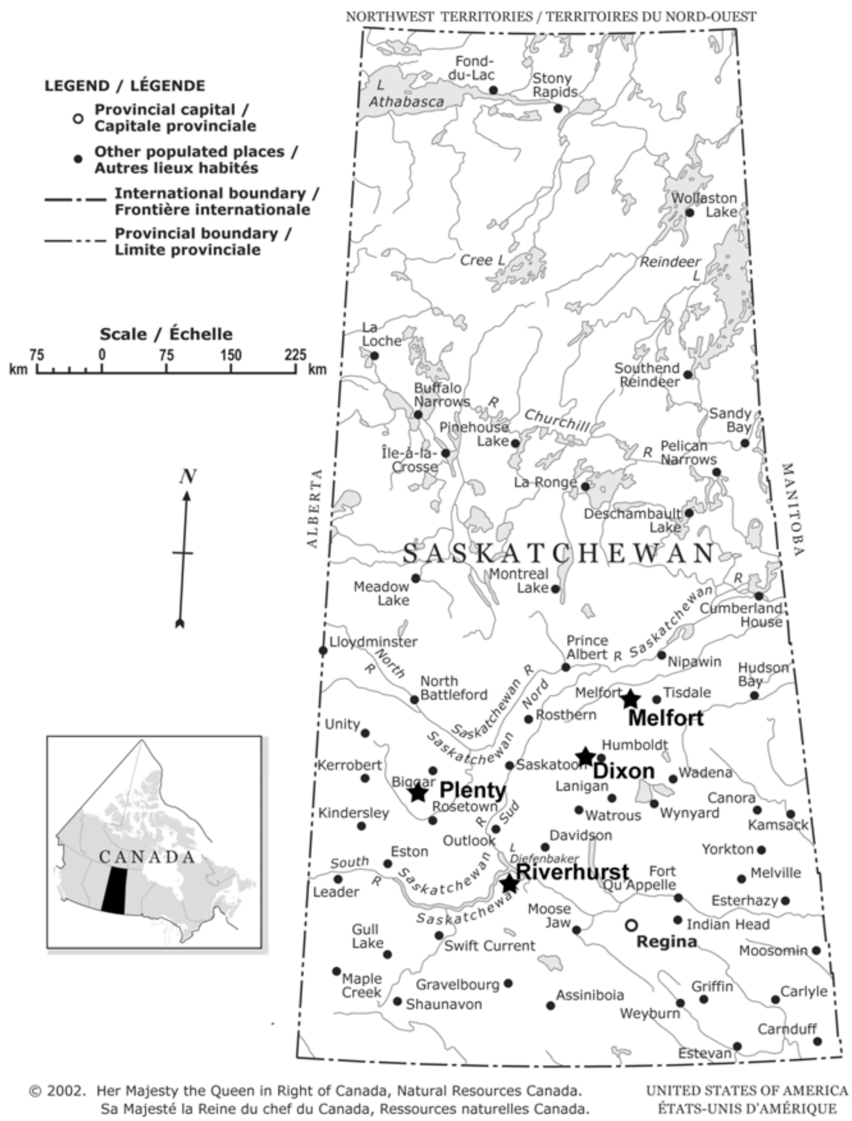


Figure 3.1 A map of Saskatchewan that shows the location of the four experimental sites (National Resources Canada).

3.2.1 Experimental Design

The experimental design at all five experimental sites was a Randomized Complete Block Design. In Dixon Swine, Dixon Cattle and Melfort sites, treatments were replicated four times, while at Plenty and Riverhurst sites, treatments were replicated three times.

3.2.1.1 Treatments

Manure rates were selected based on general agronomic N requirements for the region. The 1x rate is determined based on a desire to add approximately 100 kg N ha^{-1} with manure samples analyzed to determine the N content of the manure, from which the manure application rate is determined. That rate is then doubled (2x at Riverhurst and Plenty), tripled (3x at Melfort every third year) or quadrupled (4x at Dixon). Staff from the Prairie Agricultural Machinery Institute (PAMI) applied the liquid swine manure at approximately 10 cm depth, using a low-disturbance coulter injection system, mounted on the back of a tanker truck, with 30 cm band spacing. At the Dixon cattle manure site, the manure was spread over the plots manually and then incorporated immediately with a rototiller. Manure applications were made in the fall prior to the growing season (except the Dixon site, which received manure in the spring of 2003 due to unfavourable fall weather). The last manure application at the Dixon site prior to spring 2003 sampling was in the fall of 2001, while all other sites received manure in the fall of 2002.

Control treatments were disturbed by the coulter discs used on the manure treatments, but no amendments were added to the soil. Fertilizer treatments consist of urea N added at rates roughly equivalent to the manure based N (1x). Similar treatments were used for all five experimental sites (Table 3.1).

3.3 Basic Soil Properties

The four locations (five experimental sites) (Table 3.2) were chosen to represent the main agricultural soil zones in the province and provide a contrast of soil and environmental conditions to observe the effect of manure on soil physical and chemical properties. Plenty, located at SW5-33-18-W3, is mapped as a Dark Brown Chernozem formed on clayey lacustrine parent material (Saskatchewan Soil Survey, 1987). The surface 10 cm was highest in silt (44.4%) followed by clay (34.9%); while below 10 cm, clay content was over 52% and silt was approximately 32%. Riverhurst, located at SW20-24-5-W3 and irrigated out of Lake Diefenbaker, is mapped as a Brown Chernozem formed on sandy glacio-lacustrine parent material, with a sandy-loam texture (Ellis et al., 1970). Melfort, located at SW26-44-18-W2, is mapped as a Dark Gray Chernozem formed on

Table 3.1 Rates of manure application for the five experimental sites.

Treatment	Site†				
	Plenty‡	Riverhurst‡	Melfort	Dixon Swine	Dixon Cattle
Control	Undisturbed Check	Undisturbed Check	Undisturbed Check	Disturbed Check	----
Low	37 kL ha^{-1}	37 kL ha^{-1}	37 kL ha^{-1}	37 kL ha^{-1}	7.6 T ha^{-1}
High	74 kL ha^{-1}	74 kL ha^{-1}	111 kL ha^{-1}§	148 kL ha^{-1}	30.4 T ha^{-1}
Urea	80 kg N ha^{-1}	80 kg N ha^{-1}	80 kg N ha^{-1}	112 kg N ha^{-1}	----

† Dixon sites received manure for six years (seven for field study), Melfort for four years, Plenty and Riverhurst for five years.
‡ Plenty and Riverhurst manure rates in 1999 and 2000 were 56 kL ha^{-1} and 112 kL ha^{-1}.
§ Applied only in 1999 and 2002.

silty lacustrine parent material, with a clay-loam texture (Saskatchewan Soil Survey, 1989a). The Dixon trials are located at NW21-37-23-W2, and are mapped as a Black Chernozem, formed on silty lacustrine parent material, with a loam texture (Saskatchewan Soil Survey, 1989b). The liquid swine manure and solid beef cattle manure trials at the Dixon sites are located side-by-side, on the same field. Further details on soil texture for the sites are provided in Appendix A. In addition, soil temperatures were measured at Dixon in 2003 (Appendix B).

Table 3.2 Soil associations and textures from manure research sites (Ellis et al., 1970; Saskatchewan Soil Survey, 1987; Saskatchewan Soil Survey, 1989a; Saskatchewan Soil Survey, 1989b).

Site	Soil Zone	Soil Association Dominant (Significant)	Texture	Years of Manure Application†
Plenty	Dark Brown	Regina	Clay	5
Riverhurst	Brown	Birsay	Sandy Loam	5
Melfort	Gray	Kamsack	Clay Loam	4
Dixon Swine	Black	Cudworth	Loam	7‡
Dixon Cattle	Black	Cudworth	Loam	7‡

† Years of manure application up to and including the 2003 growing season.
‡ Fall application of manure was not possible in 2002. Manure was applied in spring 2003 after collecting lab samples; therefore only six previous manure applications were made.

The application of liquid swine manure at the four experimental sites has had little impact on pH, EC or SOC as reported by King (2007) (Table 3.3). There were small, but statistically significant increases in soil salinity (EC) at Melfort, Plenty and Riverhurst after manure application, but not in the urea treatments. The Plenty and Riverhurst sites

Table 3.3 Basic soil properties at the manure research sites (adapted from King, 2007).

Site	Treatment	pH	EC† dS m^{-1}	SOC‡ %
Plenty	Control	8.3	0.28	1.6
	Low	8.2	0.45	1.8
	High	8.1	0.52	1.8
	Urea	8.3	0.32	1.8
	LSD	0.1	0.05	0.1
Riverhurst	Control	7.1	0.18	1.5
	Low	6.8	0.22	1.6
	High	6.6	0.24	1.5
	Urea	7.1	0.17	1.5
	LSD	0.1	0.02	0.1
Melfort	Control	6.8	0.14	3.8
	Low	6.7	0.23	3.9
	High	---	---	---
	Urea	6.9	0.15	3.5
	LSD	0.1	0.02	0.3
Dixon Swine	Control	7.5	0.21	2.6
	Low	7.3	0.22	2.9
	High	7.2	0.27	2.7
	Urea	7.3	0.23	2.8
	LSD	0.3	0.07	0.4
Dixon Cattle	Low	7.5	0.35	3.2
	High	7.5	0.37	3.4
	LSD	0.4	0.15	0.3

† Electrical Conductivity (1:2 soil:water suspension extract)
‡ Soil Organic Carbon

are located in drier regions of the province, with less rainfall to leach salts away. Both the Plenty and Melfort sites have high clay content, which would also limit leaching of salts. King (2007) found no increases in salinity at the Dixon sites from liquid swine or solid cattle manure.

3.4 Manure Properties

Liquid swine manure was collected from an earthen storage unit near each experimental site. Solid cattle manure for the Dixon site was collected from nearby Poundmaker feedlot. Manure samples collected in fall 2002 and spring 2003 (Dixon only) were analyzed for nutrients (Appendix A). The Sodium Adsorption Ratio (SAR) of the manure was calculated because of the relationship of sodium to clay deflocculation (Equation 2.1 in Chapter 2). The SAR is relevant to soil strength and surface sealing (Table 3.4). A SAR value of 13 or greater is defined as a sodic (or saline-sodic) soil (Henry et al., 1992; Henry, 2003). Curtin et al. (1995) noted that some non-sodic Saskatchewan soils showed the negative physical effects of sodium accumulation. They evaluated SAR in a soil in southwestern Saskatchewan that had been irrigated with sodic waters showing structural deterioration consistent with a sodic soil. This structural deterioration was evident even though the surface SAR was only 7.4. They also noted that values for SAR lower than 13 are used as thresholds in Australia.

Table 3.4 The SAR of the manure applied to the experimental sites, as determined by measurement of manure added for the 2003 growing season.

Site	SAR†
Plenty	14.1
Riverhurst	6.9
Melfort	4.7
Dixon Swine	5.8
Dixon Cattle	1.7

† Sodium Adsorption Ratio

3.4.1 Sampling Procedure

Soil cores for general analysis were collected in the spring of 2003. At the Dixon site, soil samples were collected prior to manure application in the spring of 2003. The cores were collected using 10 cm diameter by 18 cm long PVC (polyvinyl chloride) pipe that was driven into the ground using a tamping device. Four sub-sample cores were taken from each experimental unit (plot) and combined in the lab. The samples were air-dried and ground to pass through a 2-mm sieve.

In addition, surface samples were taken at the same time for aggregate size analysis. Samples were carefully collected from the 0 to 15 cm depth with a shovel, transported to the lab in a plastic bag and air-dried. Samples were stored in the bags again until a later date when the aggregate size analysis tests were carried out.

3.4.1.1 Soil Strength

A recording cone penetrograph (Eijkelkamp Agrisearch Equipment, The Netherlands) was used to measure soil strength to 20 cm depth (Figure 3.1) on the experimental units only at the Dixon Swine and Dixon Cattle experimental sites; the sampling dates were May 28, June 16 and September 8, 2003 (20, 39 and 123 days after seeding). The strength of soil is a key factor that determines root growth. The pore space in soil provides a pathway for root growth. In weakly aggregated soils, the pore space allows displacement of soil particles as growing roots force soil aside. As penetrometer measurements are an index of soil strength they should be correlated with root growth (Bennie, 1996), with high strengths associated with reduced root penetration and exploitation. A penetrometer measures soil strength by measuring the force required to displace enough soil for the probe to pass through. Five sub-samples were taken per experimental unit. The resistance at 5, 10, 15 and 20 cm was assessed.

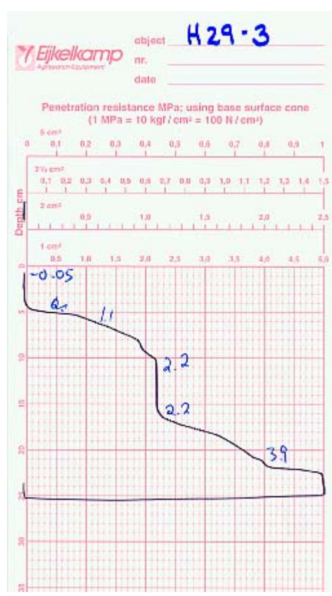


Figure 3.2 An example of the readings from the recording cone penetrograph.

Soil moisture has an inverse influence on soil strength (Lowrery and Morrison, 2002). Increased soil moisture is associated with decreased soil strength compared with the same soil at lower moisture content. To account for differences in water content, gravimetric soil moisture was determined from five soil samples taken from the 0 to 15 cm depth at each sampling location at each measurement time. Due to the small plot size, only three soil samples were taken in the cattle manure trial.

The sampling location was marked for each sub-sample during the May sampling. Subsequent samplings were made near the same location, except that during the sampling in June, it became apparent that Plot 37 (Rep 3, Trt 2) had been marked incorrectly in the May sampling. Therefore, this data was not considered in the analysis.

3.4.1.2 Barley Emergence

Barley was sown on May 8 2003. Emergence was measured only at the Dixon sites. Plant counts using 0.25-m^2 quadrats were taken May 28 at Dixon, at approximately the three leaf stage of the barley. Five sub-samples were taken per plot on the swine manure experimental site, while three were taken per plot on the cattle manure experimental site.

3.4.1.3 Aggregate Size

A separate set of surface soil samples to a depth of 15 cm was taken with a shovel from the five experimental sites in late April 2003 and dried to air dry moisture content. A rotary sieve to separate out seven size fractions was used to determine the mean weight diameter (MWD) of the aggregates. The samples (approximately 3 kg) were placed, one at a time, in a rotary sieve that sorted the aggregates into seven size classes. The mean diameters of the size classes from largest to smallest were: 44.06, 26.05, 12.36, 4.89, 1.94, 0.90 and 0.25 mm. After the samples were sieved, each size class was weighed. From those weights, the MWD (Equation 3.1) was determined.

Equation 3.1 (van Bavel, 1949; Assefa, 2002; Zeleke, 2003)

$MWD = \sum_{i=1}^{n} x_i w_i$, where the mean diameter for each size fraction is represented by x_i and the proportional weight of that size fraction to the total sample weight is represented by w_i.

3.4.2 Statistical Analysis

An analysis of variance (ANOVA) was used to determine differences between treatments on each site. The SAS GLM procedure was performed using SAS™ (Statistical Analysis

Software) (SAS Institute, Cary, NC, USA). Least-squares means were used to account for missing data in the soil strength portion of the study. Soil strength and moisture sub-samples were averaged prior to analysis. Gravimetric soil moisture was used as a covariant for the soil strength measurements in the field. A probability level of 0.10 was used to test for significant differences in soil physical properties owing to higher inherent variability while a level of 0.05 was used for emergence.

3.5 Results and Discussion

3.5.1 Soil Strength: Dixon Experimental Sites

Root growth inhibition is believed to begin when soil strength is 2.0 MPa or greater. However, the point of root inhibition varies depending on crop and soil type. Taylor et al. (1966) found that while root penetration was good at 1.9 MPa, no roots penetrated the soil at a penetration resistance of 2.5 MPa or greater.

3.5.1.1 Dixon Swine Manure Site

Early plant development will be impaired if roots are not able to grow and develop properly. The May 28 sampling (Figure 3.2) is likely most representative of the time when soil strength variation would have the greatest influence on root growth as the roots are small and entering into a period of rapid development. Although root growth is impeded by high soil strength, pressure is also exerted on the soil as the roots grow. Bennie (1996) indicates that the pore space in most soils is smaller than the root tip; therefore as the root tip grows, soil particles are displaced. After the May 28 sampling, the effect of manure may be more evident as a result of increased soil fertility which would enhance root proliferation.

At 5 cm depth, the Low and High rates of liquid swine manure treatments had significantly greater soil strength than the Control treatment. There were no significant differences at the 10, 15 or 20 cm depths. At 5 cm depth, the difference is not substantial and therefore is anticipated to be inconsequential in its effect on root growth and development.

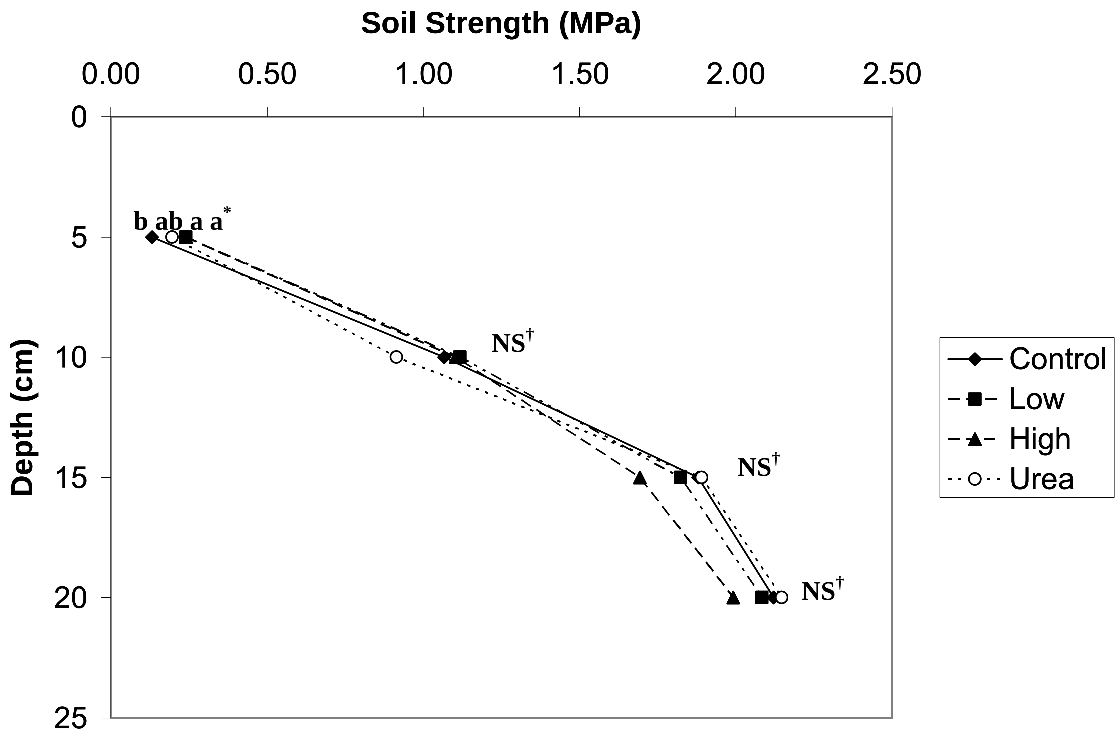


Figure 3.3 Penetration resistance (soil strength) in four swine manure treatments measured on May 28, 2003 (20 days after seeding) at four different depths in a barley crop at the Dixon Swine experimental site.

* Values with the same letter are not significantly different at the 90% confidence level according to Least-Squares Means. n = 4.
† No points are significantly different.

At the June 16 sampling the Control treatment had the lowest soil strength at all depths except 15 cm, although the difference was not always significant (Figure 3.3). At 10 cm depth, the Low rate of liquid swine manure had significantly greater soil strength than the Control. At 15 cm depth, the Urea and Low rate manure treatments had significantly greater soil strength than the Control. The lower soil strength in the Control treatment is in part due to greater soil moisture content. The reduced crop growth in the Control treatment (as confirmed by reduced yield) likely resulted in less soil water use (Appendix A). With less above ground growth, there would have been less root proliferation and less transpiration to dry out the soil and increase soil strength.

The Low rate of liquid swine manure treatment had a grain yield in 2003 of 3708 kg ha^{-1}, while the High rate of liquid swine manure and Urea treatments yielded 3375 kg ha^{-1} and

3000 kg ha^{-1} respectively, and the Control yielded 1570 kg ha^{-1} (King et al., 2004). Long term nutrient deficiency in the Control treatment had suppressed crop growth, and likely had reduced root growth as well, resulting in roots having less impact on soil strength. As roots grow, they displace soil so they have room, thereby increasing soil strength (Bennie, 1996). The Low rate of liquid swine manure resulted in significantly greater soil strength than the Control treatment at the 10 and 15 cm depths. This may be due to lush, vigorous above-ground growth and expected corresponding root growth causing an increase in soil strength.

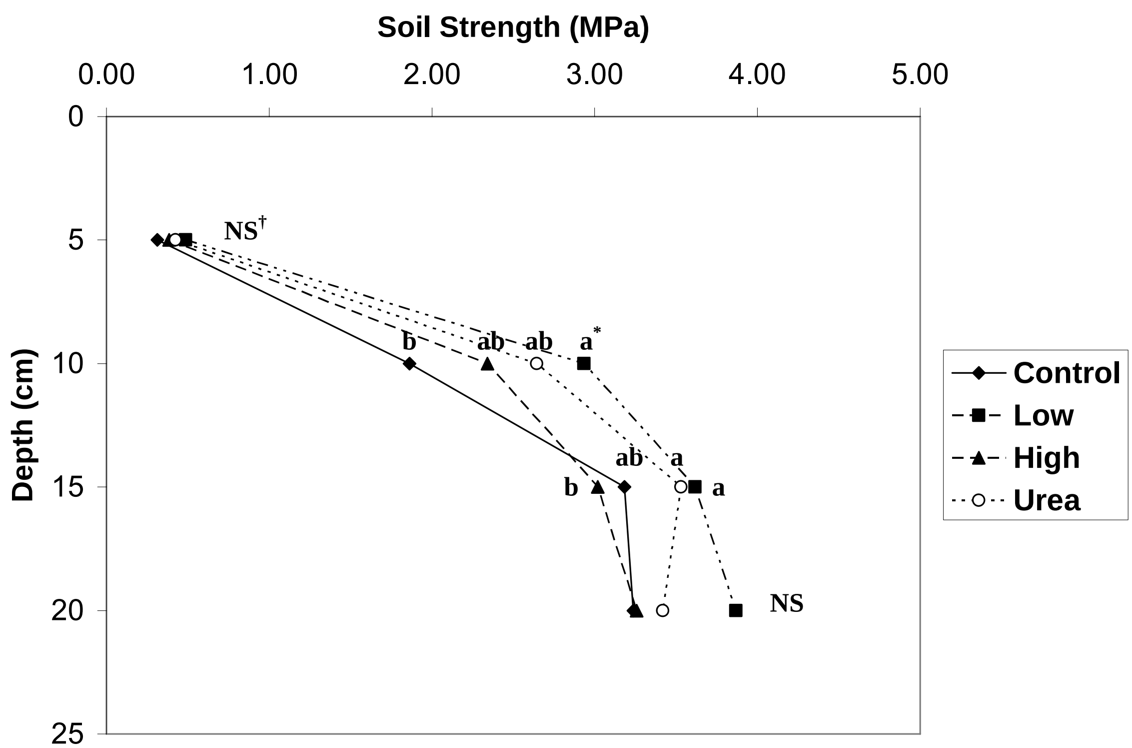


Figure 3.4 Penetration resistance (soil strength) in four swine manure treatments measured on June 16, 2003 (39 days after seeding) at four different depths in a barley crop at the Dixon Swine experimental site.

* Values with the same letter are not significantly different at the 90% confidence level according to Least-Squares Means. n = 4
† No points are significantly different.

The High rate of liquid swine manure treatment had soil strength that was typically less than the Low rate. This may be related to lower root growth and water use in the High rate treatment. Overall, it appears that the main influence of manure on soil strength is its relationship to plant growth, including roots. This in turn affects soil moisture, and the pressure root growth exerts on the surrounding soil.

The penetrometer measurements made after harvest on September 8, 2003 showed greater soil strength at depths below 5 cm than the earlier samplings (Figure 3.4). The overall increase is likely due to a combination of moisture removal by the crop and increased root biomass exerting pressure on the soil (Bennie, 1996). Zeleke (2003) measured the effects of manure on soil penetrability using a hand-held penetrometer in 2001 at Plenty and Riverhurst and found no significant differences at either site. Dixon has been established longer, has higher SOC, and has a different manure source.

In the September post-harvest sampling, at the 5 cm depth, the Control treatment had significantly greater soil strength than the Low and High rates of liquid swine manure treatments. At the 10 cm depth, the Control treatment had significantly greater soil strength than the High rate of liquid swine manure and the mean was greater than the Low rate. The lack of ground cover on the Control treatment, caused by poor crop growth under nutrient deficient conditions, likely led to greater evaporative losses near the surface in the late summer and fall. Since 1997, the Control treatment has had reduced crop biomass due to declining fertility (Mooleki et al., 2002). The greater amount of biomass and residue returned to the soil due to the fertility effect (King et al., 2004) with manure compared to the Control treatment could explain why the manure treatments had lower soil strength. In support of this concept, the soil strength of the manure treatments never significantly differed from the Urea treatment (Figure 3.2).

The soil strength was higher in June than at the May sampling and higher in September than June. Root development in the surface 20 cm of soil was further advanced as the year progressed, adding to soil strength. According to Bennie (1996), higher penetrometer pressures will be recorded as the angle of impact flattens; this may have occurred due to progressive flattening of the tip over the season. The author also notes that although penetrograph measured resistance may be high, continuous biopores formed by old root channels and soil fauna, as well as large spaces around aggregates are channels the plant root can easily follow and benefit from lower resistance.

During all three sampling periods, soil strength values exceeded the threshold for root growth (2.0 MPa) at some depth(s) for at least some of the treatments. Reinert et al. (2001 *In* Lowery and Morrison, 2002) found similar soil strength values, even at higher soil moisture contents than in the current study. These authors measured soil strength under wet conditions and found soil strength to be considerably lower than their previous measurements.

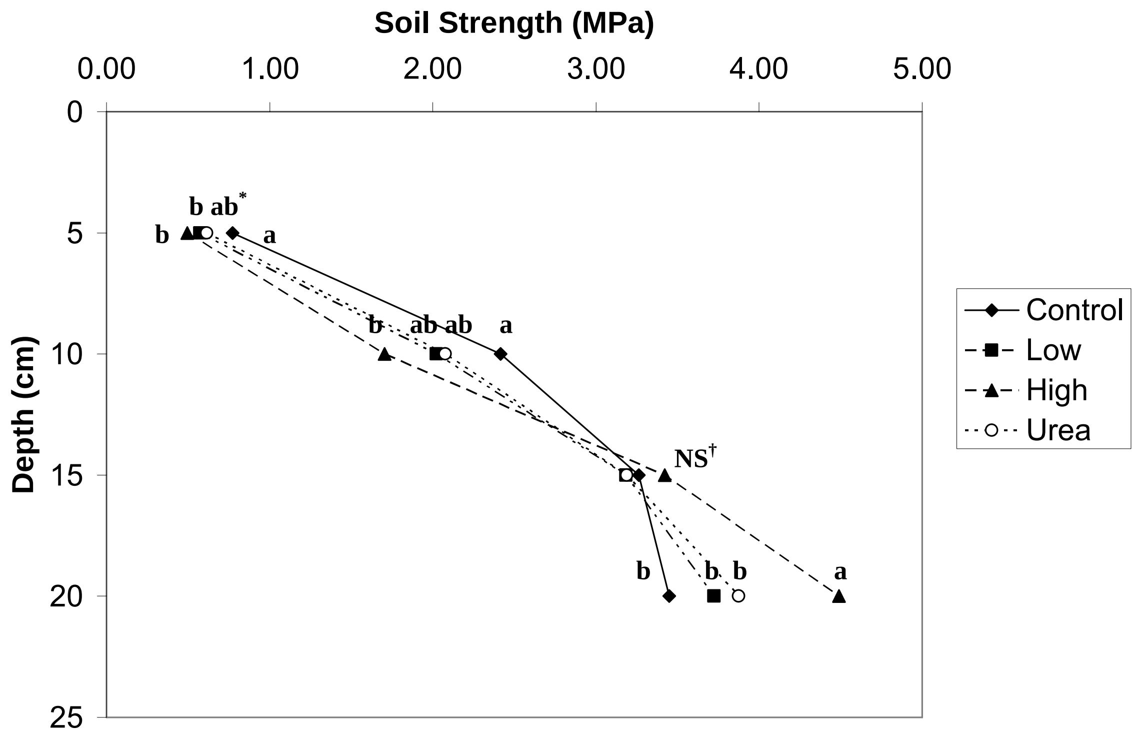


Figure 3.5 Penetration resistance (soil strength) in four swine manure treatments measured on September 8, 2003 (123 days after seeding) at four different depths in a barley crop at the Dixon Swine experimental site.

* Values with the same letter are not significantly different at the 90% confidence level according to Least-Squares Means. n = 4.
† No points are significantly different.

In the current study, soil moisture contents in the plots decreased from about 18% (g g^{-1}) in May to about 12% in June while post-harvest rain increased soil moisture to approximately 16% in September (Appendix A). Considering the results from this analysis, it can be deduced that the liquid swine manure treatments had little or no effect on soil strength.

3.5.1.2 Dixon Cattle Manure Site

On May 28th, the Low rate of solid cattle manure had significantly greater soil strength than the High rate at the 5 cm depth (Table 3.5). At the other depths (10, 15 and 20 cm) there were no differences between treatments. On June 16th, the High rate had greater soil strength at the 5 cm depth, but lower soil strength at the 15 cm depth, compared with the Low rate. There were no treatment effects for the 10 and 20 cm depths. On September 8th, there were no significant differences in soil strength due to treatment. Mazurak et al. (1975) found that shallow incorporation of cattle manure resulted in a decrease in soil crust strength. Conversely, an Alberta study found that 24 annual applications of manure did not cause any significant changes in soil penetrability at any measured depth (Miller et al., 2002); however, under irrigated conditions, manure did reduce soil strength.

Table 3.5 Soil strength of the two cattle manure treatments as measured on May 28, June 16 and September 8 (20, 39 and 123 days after seeding) at four different depths in a barley crop at the Dixon Cattle experimental site.

		Penetration Resistance			
Sampling Date	Treatment†	5 cm	10 cm	15 cm	20 cm
		-------------------MPa-------------------			
May 28	Low	0.368*a*	1.144*a*	1.742*a*	1.737*a*
	High	0.249*b*	1.178*a*	1.746*a*	1.758*a*
June 16	Low	0.415*b*	3.040*a*	4.073*a*	3.534*a*
	High	0.663*a*	2.797*a*	3.543*b*	2.953*a*
September 8	Low	0.425*a*	2.092*a*	2.997*a*	3.591*a*
	High	0.498*a*	2.340*a*	3.285*a*	3.957*a*

* Values followed by the same letter within a column for a sampling date are not significantly different at the 90% confidence level according to Least-Squares Means. n = 4..

† Low refers to 7.6 T ha^{-1} and High refers to 30.4 T ha^{-1} of incorporated cattle manure

Unlike liquid swine manure, cattle manure contains substantial amounts of organic matter useful for improving soil tilth (Hao et al., 2003).

3.5.2 Barley (*Hordeum vulgare*) emergence

Plant emergence is related to and may be used as another indicator of crust strength in the field. Barley is a relatively vigourous and salt tolerant crop (Henry et al., 1992).

3.5.2.1 Dixon Swine Manure Site

Barley emergence at the Dixon liquid swine manure experimental site showed no statistical differences between the manure treatments and the Control (Table 3.6). However, the emergence on the High rate of liquid swine manure treatment was significantly lower than the Urea treatment. This may be indicative of some salt effect from the excessively high rate of manure hindering emergence. The difference does not seem to be biologically critical as grain yield ended up greater for the High rate of liquid swine manure (3375 kg ha^{-1}) compared with the Urea treatment (3000 kg ha^{-1}). The Low rate of liquid swine manure had the greatest yield (3708 kg ha^{-1}) (King et al., 2004).

Table 3.6 Barley emergence 20 days after seeding, at the 2-3 leaf stage at Dixon, 2003.

Treatment	Emergence
	----Count per 0.25-m^2----
Control	38*b*
Low Manure Rate	42*ab*
High Manure Rate	38*b*
Urea	46*a*

* Values with the same letter are not significantly different at the 95% confidence level according to Least Significant Differences. n = 4.

3.5.2.2 Dixon Cattle Manure Site

Barley emergence at the Dixon cattle manure experimental site did not differ significantly between the two rates of manure application (data not shown). The Low rate of cattle manure count was 44 and the High rate was 39 counts per 0.25-m^2. These emergence numbers are similar to the swine manure experimental site.

3.5.3 Aggregate Size

There were no differences in MWD between the manure treatments and the Control for any of the sites (Table 3.7). At the Riverhurst experimental site, the Urea treatment had significantly lower aggregate MWD than the Control. At the Dixon swine manure experimental site, the Urea treatment had significantly greater aggregate MWD than the Control. At the Dixon site, the Urea treatment resulted in a significant yield increase compared with the Control. At the Riverhurst site, the Urea treatment resulted in a yield penalty, as the Control yielded 1803 kg ha^{-1} while the Urea yielded 1697 kg ha^{-1}. The Urea treatment at Riverhurst may have injured plant growth.

Overall, the effect of treatment on aggregate size was small. Assefa et al. (2004) measured soil aggregation in 2002 and found a significant decrease in aggregate size following a medium rate cattle manure application and following a high rate of liquid swine manure application at Burr, SK.

Table 3.7 Aggregate mean weight diameter (MWD) for five experimental sites.

	Plenty	Riverhurst	Melfort	Dixon Swine	Dixon Cattle
			----------------mm----------------		
Control	6.60	10.41*a*	10.57	8.12*b*	n/a
Low	7.35	8.34*ab*	13.95	8.29*ab*	8.97
High	7.11	8.60*ab*	12.74	8.75*ab*	7.78
Urea	7.10	7.39*b*	12.05	9.86*a*	n/a
LSD α = 0.1	1.87	2.46	4.12	1.64	1.54

* Values followed by the same letter within a column are not significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty and Riverhurst); n = 4 (Melfort, Dixon Swine and Dixon Cattle).

The lack of differences in soil aggregation between the manure and the control treatments suggests that repeated applications of manure for the duration evaluated in this study (four to six years) will have limited effect on soil aggregation. Longer periods of application may be necessary to show significant effects.

3.6 Conclusions

The objectives of this study were to determine the effects of manure application on soil strength parameters, including soil penetration resistance and crop emergence in the field at two experimental sites (Dixon Swine and Dixon Cattle), as well as on aggregation at all five experimental sites across Saskatchewan. At Dixon, two liquid swine manure application rates (37 and 148 kL ha^{-1}) applied annually were compared to an untreated control and annual urea fertilizer application. At Plenty, Riverhurst, Melfort and Dixon Swine, two manure application rates (high and low agronomic N rate) applied annually over four to seven years were compared to an untreated control and a urea fertilizer application. In addition, two rates of cattle manure at Dixon were compared.

Early in the growing season, repeated applications of liquid swine manure at low and high rates at Dixon increased soil strength at the 5 cm depth; the differences, however, were small and well below the threshold that would hinder root proliferation. In mid-summer, there were no differences at the 5 cm depth, but at the 10 cm depth the Low rate of liquid swine manure application resulted in greater soil strength than the Control. In the fall, the manure treatments reduced soil strength at the 5 cm depth, and the High rate liquid swine manure application also reduced soil strength at the 10cm depth. The results can be explained mainly by the influence of manure on root proliferation and soil moisture, both of which influence soil strength. Following four to seven years of repeated applications of liquid swine manure, there appears to be little influence of the manure constituents themselves, apart from fertility, plant growth and moisture use, on soil strength. Supporting these findings, barley emergence was not affected by manure application. Soil aggregation (MWD) was also not affected by manure application compared with the control treatment at any of the sites.

Medium term (four to seven years) application of liquid swine manure seems to have only minor effects on soil physical properties that would influence plant emergence and early crop development. Any changes were either favourable to the soil condition or were well below critical or threshold values where injury may occur. Longer-term research on the effect of repeated applications of liquid swine manure, as well as including other soil associations is warranted to better understand the influence of manure on soil physical properties relating to early plant development.

3.7 References

Assefa, B. 2002. Single and repeated applications of hog and cattle manure and their effects on soil conditions and plant growth in gray luvisolic and black chernozemic soils. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 131 p.

Assefa, B.A., J.J. Schoenau, and M.C.J. Grevers. **2004.** Effects of four annual applications of manure on Black Chernozemic soils. Canadian Biosystems Engineering **46**:6.39-6.46.

Bennie, A.T.P. 1996. Growth and mechanical impedance. p. 453-470. *In* Y. Waisel, et al. (eds.) Plant roots: The hidden half, 2nd ed. Marcel Dekker, New York.

Curtin, D., H. Steppuhn, A.R. Mermut, and F. Selles. **1995.** Sodicity in irrigated soils in Saskatchewan: Chemistry and structural stability. Can. J. Soil Sci. **75**:177-185.

Ellis, J.G., D.F. Acton, and H.C. Moss. **1970**. The Soils of the Rosetown Map Area (72-0) Saskatchewan (SKS3). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sks3/index.html

Hao, X., and C. Chang. **2002.** Effect of 25 annual cattle manure applications on soluble and exchangeable cations in soil. Soil Sci. **167**:126-134.

Hao, X., C. Chang, G.R. Travis, and F. Zhang. **2003.** Soil carbon and nitrogen response to 25 annual cattle manure applications. J. Plant Nutr. Soil Sci. **166**:239-245.

Henry, L. 2003. Henry's handbook of soil and water Houghton Boston, Saskatoon, SK. pp.218

Henry, L., B. Harron, and D. Flaten. **1992**. The nature and management of salt-affected land in Saskatchewan). Saskatchewan Agriculture.

King, T. 2007. Effect of repeated applications of manure on soil organic carbon and enzymes.. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 112 p.

King, T., J.J. Schoenau, M. Grevers, S.S. Mahli, and G. Hultgreen. 2004. Surface soil nutrient contents and crop yields after four to seven annual applications of manure. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 19-20 Feb 2004.

Lowrery, B., and J.E. Morrison, Jr. 2002. Soil penetrometers and penetrability. p. 363-388. *In* J. H. Dane and G. C. Topp (eds.) Methods of soil analysis. Part 4., 2nd ed. Soil Science Society of America, Madison, WI.

Mazurak, A.P., L. Chesnin, and A.E. Tiarks. **1975.** Detachment of soil aggregates by simulated rainfall from heavily manured soils in eastern Nebraska. Soil Sci. Soc. Am. Proc. **39**:732-736.

Miller, J.J., N.J. Sweetland, and C. Chang. **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., J.J. Schoenau, G. Hultgreen, G. Wen, and J.L. Charles. **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.

Natural Resources Canada. 2005. Saskatchewan with names [Online]. The Atlas of Canada. Natural Resources Canada. http://atlas.nrcan.gc.ca/site/english/maps/reference/outlineprov_terr/sask_outline_names/map.pdf Verified 9 July 2007.

Reinert, D.J., R.P. Wolkowski, B. Lowrery, and F.J. Arriaga. 2001. Compaction effects on plant water use. p.222-232. 2001 Fertilizer, Aglime and Pest Mgmt. Conf., Madison, WI.

Saskatchewan Soil Survey. 1987. Rural Municipality of Mountain View Number 318: Preliminary soil map and report (SK318). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sk318/index.html

Saskatchewan Soil Survey. 1989a. Rural Municipality of Star City Number 428: Preliminary soil map and report (SK428). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sk428/index.html

Saskatchewan Soil Survey. 1989b. Rural Municipality of Humboldt Number 370: Preliminary soil map and report (SK370). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sk370/index.html

Taylor, H.M., G.M. Roberson, and J.J. Parker, Jr. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. **102**:18-22.

van Bavel, C.H.M. 1949. Mean weight-diameter of soil aggregates as a statistical index of aggregation. Soil Sci. Soc. Am. Proc. **14**:20-23.

Weiterman, G., L. Bohrson, H. Steppuhn, and W. Eilers. 2000. Can land utilization of swine effluent pose a soil sodicity hazard? p.669-673. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 24, 25 Feb 2000.

Whalen, J.K., and C. Chang. **2002.** Macroaggregate characteristics in cultivated soils after 25 annual manure applications. Soil Sci. Soc. Am. J. **66**:1637-1647.

Zeleke, T.B. 2003. Surface soil physical properties after crop residue incorporation and injection of liquid swine effluent. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 104 p.

CHAPTER 4

SOIL CRUST PROPERTIES AS AFFECTED BY REPEATED MANURE APPLICATIONS – LABORATORY EXPERIMENT

4.1 Introduction

In addition to the *in situ* measurements made at Dixon Swine and Dixon Cattle trials and aggregate size measurements discussed in Chapter 3, laboratory experiments were conducted on soil cores removed from the field and subjected to simulated rainfall in the laboratory in order to observe the effects of manure on soil conditions after a simulated rainfall. The objective of the laboratory experiments discussed in this chapter was to determine the effect on crusting, emergence, surface seal, infiltration, sodicity and salinity from repeated applications liquid swine manure and solid cattle manure. Parameters assessed included water infiltration characteristics, soil crust strength and changes in important structural indices measurable in the soil, including ESP, EC, COLE and modulus of rupture. Emergence of canola and flax after the rainfall simulation was also assessed.

4.2 Materials and Methods

4.2.1 Description of Sites and Soil Properties

A complete description of experimental design of the field manure trials, site description and soil properties is found in Chapter 3.

4.2.2 Sampling Procedure

A set of soil cores to be used specifically for rainfall simulation and infiltration studies were taken from the field plots (Chapter 3) at the end of April, 2003. The core sleeves were made from PVC, 18 cm long and 15 cm diameter. For comparison purposes, soil cores from select locations in southern Saskatchewan were also taken in May 2003 (see Appendix C for details). The cores were driven into the ground using a tamping device.

The intact cores were then carefully removed with a shovel. All soil cores were dried intact, to air-dry moisture content. The soil cores were fitted with cheesecloth around the base and supported by expanded metal to prevent soil loss during subsequent experiments.

4.2.3 Rainfall Simulator Experiment

Using the formulas presented in Tossell et al. (1987) (Equation 4.1 and Equation 4.2), rainfall intensity and uniformity of three different nozzles were tested (Table 4.1) for the Guelph Rainfall Simulator II (GRSII). The simulator was calibrated with eight rain gauges spread in a 1 m x 1 m square (Figure 4.1). At full pressure, the 1/4GG 14W nozzle (Spraying Systems Co., Wheaton Ill.) was found to be the most suitable of those tested, with a rainfall intensity of approximately 91 mm h^{-1} and uniformity of 85% (mean values for this nozzle are provided in Table 4.1). The other nozzles had poor uniformity (1/4GG 10W) and inconsistent rainfall intensities (1/8GG 4.3W) (Table 4.1).

Equation 4.1 (Tossell et al., 1987)

$$Ip = 10\left[\left(\sum_{i=1}^{n}(Vi / Ag)n\right)\times {}^{60}\!/_{t}\right], \text{ where:}$$

Ip = Plot Average Intensity (mm h^{-1})
Vi = volume in the i^{th} gauge (cm^3)
Ag = gauge collection area (cm^2)
n = number of gauges
t = time collected (minutes)

Equation 4.2 (Tossell et al., 1987)

$$UC = 100\left(1.0 - \sum_{i=1}^{n} {}^{|Xi|}\!/_{mn}\right), \text{ where:}$$

UC = Uniformity Coefficient (%)
Xi = deviation from mean
m = mean
n = number of gauges

Figure 4.1 The Guelph Rainfall Simulator II set-up during calibration.

4.2.3.1 Canola Experiment

Ten canola seeds (2002 bin run seed; 89% germination) were placed on one side of each core (Figure 4.2). Canola was used as a test crop to indicate the treatment effects on soil crust strength and seedling emergence. Canola was chosen because of the small seed size and low seedling vigour, making the crop sensitive to crust formation.

The other side of the core was reserved for penetrometer measurements. Some problems were encountered with seeding because the soils at Plenty and Riverhurst were extremely hard at air-dry moisture content, partly due to the low SOC content of the soils.

Table 4.1 The rainfall intensity and uniformity tests to select an appropriate nozzle and calibrate the rainfall simulator.

	Test†		1/4GG 14W			1/4GG 10W			1/8GG 4.3W	
		Run	Intensity mm/h	Uniformity %	Run	Intensity mm/h	Uniformity %	Run	Intensity mm/h	Uniformity %
Pre-experiment calibrations	**Canola**	1	116.0	85.4	3	58.6	66.8	2	51.6	80.2
		8	91.1	85.0	4	62.6	55.4	5	25.1	71.3
		9	96.8	85.8	7	60.1	55.2	6	16.1	86.9
	Flax		92.7	87.3						
			94.5	86.2						
Measurements taken during flax experiment	**Plenty, Riverhurst**		78.0							
	Dixon		69.8							
	Swift Current		79.9							
	Melfort		71.0							

† The crops are in relation to calibrations before each rainfall simulation. The sites listed are single gauges during the rainfall simulation for flax.

Figure 4.2 Canola seedlings on one half of the soil core, with the other half used for penetrometer measurements.

Therefore, the Plenty and Riverhurst soil cores were seeded after the rainfall simulation, while the soil cores at Dixon and Melfort were seeded before the rainfall simulation.

A rainfall of 20 minutes was applied using distilled water. Distilled water was used because the soil in the cores would be measured for cations and EC, and added ions in tap water would potentially impact those measurements. As there were too many cores to run all at once, all the cores from an experimental site were run at once under the same rainfall (Table 4.1). Cores were weighed prior to rainfall while still at air-dry moisture content. Water samples were taken from all rainfall events and the water was tested for EC (Table 4.2). Distilled water at the University of Saskatchewan does contain a very small amount of sodium (data not shown) ranging from 0.0015 to 0.0017 g L^{-1}.The water samples were also tested for Ca, Mg, K and Na, which are the same cations required for SAR calculations.

After the rainfall event, the cores were weighed, covered with aerated plastic to reduce evaporative losses, and placed in a growth chamber set to a 14 hour, 18ºC day and a 10 hour, 12ºC night. The cores were re-randomized every day after sampling to reduce location effects within the growth chamber. A CL-700 pocket penetrometer (Soiltest Inc., Chicago, USA) (Figure 4.3) was used to measure the crust strength of the soil each day for 10 days. As crust strength increased, an attachment was devised to reduce the surface area of the penetrometer allowing it to measure greater crust strengths. The ratio

Table 4.2 The electrical conductivity of water used for rainfall simulation and infiltration.

Site	Sample	Canola	Flax (soak)	Flax (rain)	Infiltration
			------------ µS cm^{-1} ------------		
Plenty and Riverhurst	A	8.58	7.96	8.58	3.55
	B	8.42	7.88	8.50	3.50
Dixon (swine and cattle)	A	7.80	7.96	8.27	†
	B	8.42	7.88	8.11	†
Melfort	A	7.80	8.58	7.80	4.50
	B	7.64	8.27	7.80	4.50
Swift Current‡	A	7.64	8.58	7.88	4.50
	B	7.64	8.27	7.88	4.50

† For the infiltration study, the swine and cattle sites were run on different water sources (i.e. Refilled the tank). The swine site was from the same water as Melfort and Swift Current and the cattle site was from the same water as Riverhurst and Plenty
‡ Swift Current cores are taken from southwestern Saskatchewan in locations with known structural problems.

was 1:1.81. Canola plant counts and soil weights (to account for water loss) were also recorded each day. Weed presence was noted, but not counted until the end of the experiment. A qualitative rating of the general vigour and health of the canola plants emerged was conducted after the experiment, where four was assigned to all plants healthy and beyond the cotyledon stage, three for more than half the plants healthy and beyond the cotyledon stage, two for less than half the plants healthy and beyond cotyledon stage and one where all plants were diminutive and generally in poor health.

Figure 4.3 The pocket penetrometer used, with modification, to increase the maximum measurable resistance of the penetrometer for extremely hard crusts.

As the experiment progressed, it became clear that there were problems with uneven canola seeding rates and placement, and consequently, emergence. Because the air-dried soils were so hard, placing the seeds in the soil at a consistent depth was difficult to the extent that the soil did not always cover the seed after the rainfall. Canola seeds were difficult to handle, resulting in some lost seeds. As such, the experiment was repeated using the same cores used in the canola experiment at the end of the ten day crust measurement period, using flax as an alternative small seeded crop sensitive to crusting.

4.2.3.2 Flax experiment

Flax was chosen as an alternative to represent a crop with low seedling vigour and small seed size. One Melfort sample (Rep 1, Treatment 2) was spilled during preparation.

In this experiment, the soil cores were rained on first for seven minutes with distilled water, and then placed in the growth chamber to dry down overnight before seeding. This softened the surface so that flax (AC Macduff; 84% germination) could be seeded without difficulty. Ten flax seeds were placed in one half of the core, seeded to 2 cm depth, and then the soil surface was pressed down 0.5 cm to seal the opening. A subsequent rainfall of 15 minutes duration was then applied. Sampling began on the third day after the rainfall.

As in the previous experiment with canola seed, after the rainfall event, the cores were weighed, covered with an aerated plastic bag to reduce evaporative losses, and placed in a growth chamber, set to a 14 hour, 18ºC day and a 10 hour, 12ºC night. The cores were re-randomized every day after sampling to reduce location effects within the growth chamber. Soil strength measurements were carried out, as in the canola experiment (4.2.3.1).

Flax plant counts and soil weights (to account for water loss) were also taken each day. Weed presence was noted, but not counted until the end of the experiment. After the experiment, the flax and weeds were harvested and the dry matter weight was determined. Plant samples were oven dried to constant moisture content at 50ºC.

4.2.4 Infiltration Experiment

A watering system was devised (Figure 4.4) to supply a constant rate of water to the soil cores to measure the effect of manure treatment on infiltration rate. After the rainfall simulation and all emergence and crust strength experiments were complete, extensions were added to the soil cores to allow water to pond to a constant depth of 3.75 cm. The cores were marked so the 3.75 cm height could be easily observed. The water was allowed to fall from a height of 12.5 cm above the core extension. Measurements were made to determine how fast water ponded on the surface (surface seal), the time when the water reached the desired depth of 3.75 cm and the time when the water had infiltrated completely. Some samples did not work well for this experiment as water would run down the sides of the core, making the results difficult to interpret.

Water samples were also taken during this experiment and analyzed for electrical conductivity and the cation concentrations (required for SAR calculations). Electrical conductivity values are reported in Table 4.2 and the Na content was 0.0015 g L^{-1}. The EC of the water during the infiltration experiment was about half of that observed for the rainfall simulator experiments. These samples were taken approximately 1 week after the rainfall simulator water samples. At EC levels this low, the difference is not important.

4.2.5 EC, ESP, COLE, Modulus of Rupture

After the infiltration experiment was completed, the cores were weighed. The core extensions were cut off, and the soil was removed from the core in increments using a specially made press device (Figure 4.5). The top 0-3 cm was removed separate from the rest of the soil. The top 0-3 cm segment was used for the EC, ESP, modulus of rupture, and COLE measurements. This depth was chosen because the properties in the 0-3 cm depth increment would have the greatest influence on crusting and emergence. Soil was separated out for the EC and ESP tests and ground to 2 mm.

4.2.5.1 Electrical Conductivity

A 1:2 soil:water suspension extract was prepared to measure electrical conductivity (EC). Twenty g of soil was added to a plastic bottle, followed by 40 ml of distilled water. The bottles were sealed and put on a shaker at 143 rpm for 20 minutes. After shaking, the bottles were allowed to stand for 1 hour. Without disturbing the settled soil, the extractant was poured through a Whatman No.1 filter to obtain the extract. The EC was measured using a Horiba conductivity meter (Hendershot et al., 1993a).

The results were then standardized to saturated extract values using the conversion equations prepared by Hogg and Henry (1984). For the purposes of conversion, Plenty and Melfort soils were considered fine soil textures, Dixon soils were considered medium textured, and Riverhurst soils were considered coarse textured.

a

c

b

d

Figure 4.4 Water infiltration measurement system. (a) A tray ensured the core remained undisturbed until a constant flow rate was set using the valve on the water vessel; (b) establishing a constant height in the shower chamber; (c) then, allowing free water flow onto the soil core until the desired water depth of 3.75 cm was achieved; (d) and allowing the standing water to infiltrate.

Figure 4.5 Press device made to remove soil from cores so specific layers could be sampled separately.

4.2.5.2 Exchangeable Sodium Percentage

Five g of each soil sample was weighed into Erlenmeyer flasks. Fifty ml of 1M NH_4-Ac was then added to the flasks. The flasks were sealed and shaken for 30 minutes on a reciprocating shaker. Thirty ml of each sample was filtered off and stored in sealed vials to reduce evaporation until analysis. The cations were analyzed by flame emission and atomic absorption spectrophotometry (Perkin Elmer Model 3100). Known standards for Ca, Mg, and Na and K were used to develop the standard curve (Hendershot et al., 1993b).

The cation concentrations were converted to cmol(+) per kg of soil. Sodium concentration was corrected for by averaging the amount of Na measured in 'blank' samples and subtracting this number from the treatment measured sodium levels. The four cations were summed to give the cation exchange capacity (CEC) and using Equation 2.2 (in Chapter 2), the exchangeable sodium percentage (ESP) was calculated.

4.2.5.3 Modulus of Rupture

Using the surface 0-3 cm depth increment of soil removed from the soil cores, the <2-mm fraction was sieved out using gentle hand sieving. Following Richards (1953) Briquet molds were prepared on trays with screened bottoms. Filter paper was placed underneath each mold. A film of petroleum jelly was applied to the molds to reduce soil adhesion to the mold. The sieved soil was then poured into briquet molds using a funnel (Dimensions: 1 cm Internal Diameter at base, 7 cm I.D. at mouth, 15 cm neck) (Figure 4.6). The funnel ensured that the soil fell from the same height into the mold. The soil was scraped level with the top of the mold, then the molds were placed in tubs. Tap water was added to the bottom of the screen trays, ensuring it never reached higher than the top of the molds. After the wetting, the trays of briquets were placed in a forced-draft oven at 50ºC. After 1 hour, molds were removed, and briquets were placed back in the oven to continue drying.

After the briquets were dry, a constant force was applied to the briquets on the breaking machine (Figure 4.7). The weight of water added at the point of breaking was converted to kPa.

4.2.5.4 Coefficient of Linear Extensibility

The coefficient of linear extensibility (COLE) was determined using the same briquets used in the modulus of rupture test. Calipers were used to measure the length of the briquet when the briquet was formed and dry. The wet length was determined by measuring the inside length of the briquet mold (70 mm). The formula for determining COLE is shown in Equation 4.3

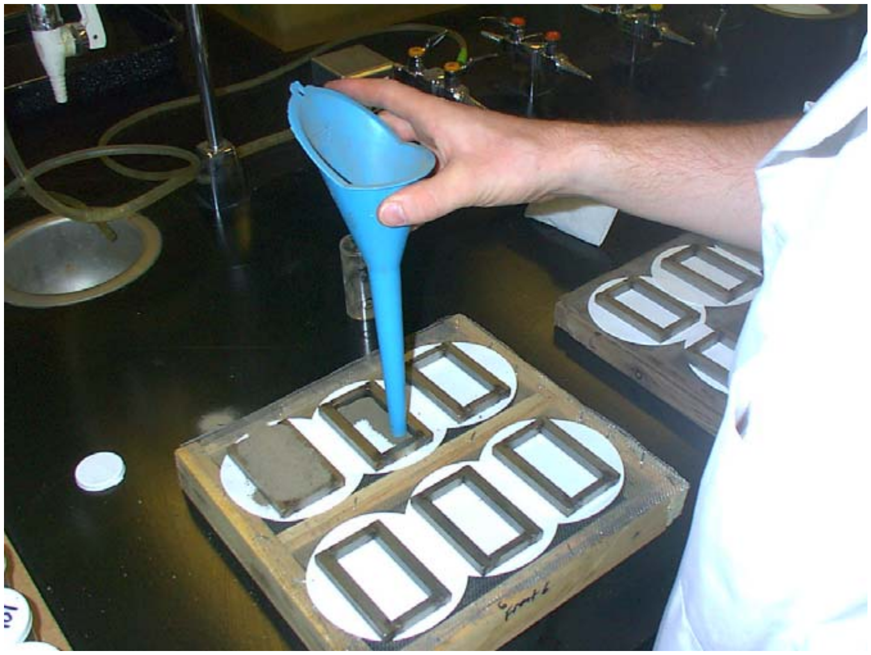


Figure 4.6 The briquet molds, layout and a demonstration of the ‘fall from a height’ requirement for settling the soil for briquet making are shown.

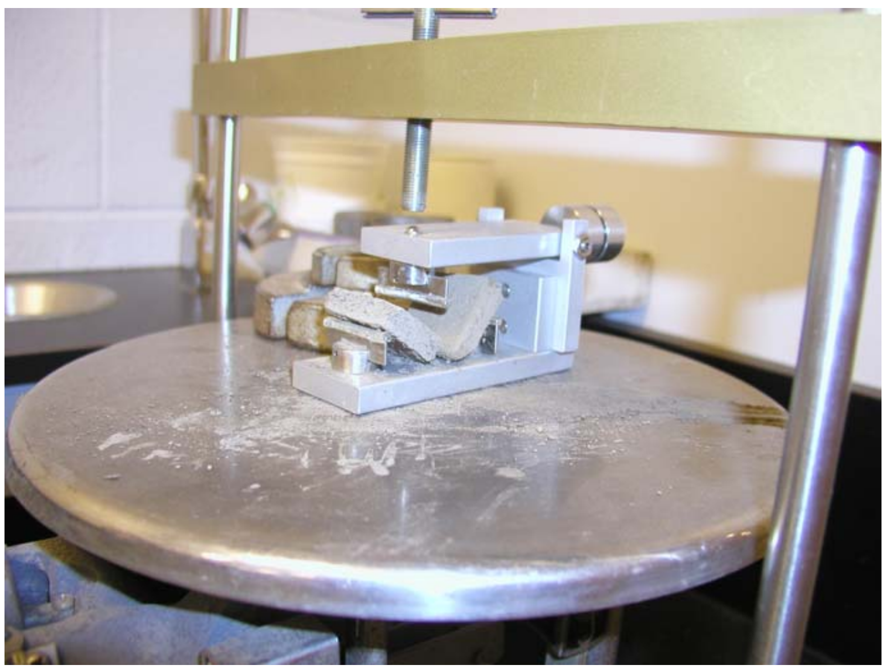


Figure 4.7 The machine breaking a briquet.

4.2.6 Statistical Analysis

An analysis of variance (ANOVA) was used to determine differences between treatments on each site. The SAS GLM procedure was performed using SAS™ (Statistical Analysis

Equation 4.3 (Sheldrich, 1984)

$$COLE = \frac{Lm - Ld}{Ld}$$, where:

Lm = Length of the soil rod when moist
Ld = Length of the soil rod when dry

Software) (SAS Institute, Cary, NC, USA). A probability level of 0.10 was used to test for significant differences in soil physical properties owing to higher inherent variability while a level of 0.05 was used for chemical properties (EC and ESP).

4.3 Results and Discussion

4.3.1 Crusting Induced by a Rainfall Simulator

The interaction between treatment and potential crust formation was examined using a Guelph Rainfall Simulator II (Tossell et al., 1987), as heavy rainfall will enhance surface crust development. Rainfall rates of 91 mm h^{-1} were used in this study to encourage crusting and represent a rainfall intensity that may occur during a short duration thunder shower on the prairies. Tattleman and Willis (1985 *In* Tossel et al. (1990)) studied natural rainfall events up to 1872 mm h^{-1} and Cutforth et al. (2001) indicated that the majority of rainfall on the prairies comes in large rainfall events.

4.3.1.1 Soil Crusting: Canola Experiment

The canola experiment involved soils sampled from five different long-term experimental sites, treated with two rates of manure and/or urea fertilizer. The sites sampled were Plenty (swine and urea), Riverhurst (swine and urea), Melfort (swine and urea), Dixon (swine and urea) and Dixon (cattle).

Arndt (1965) determined that seedlings can tolerate up to 0.63 to 0.94 MPa dry soil crust strength before emergence begins to suffer. The crust strengths at all four study sites were well below this critical limit (Figure 4.8).

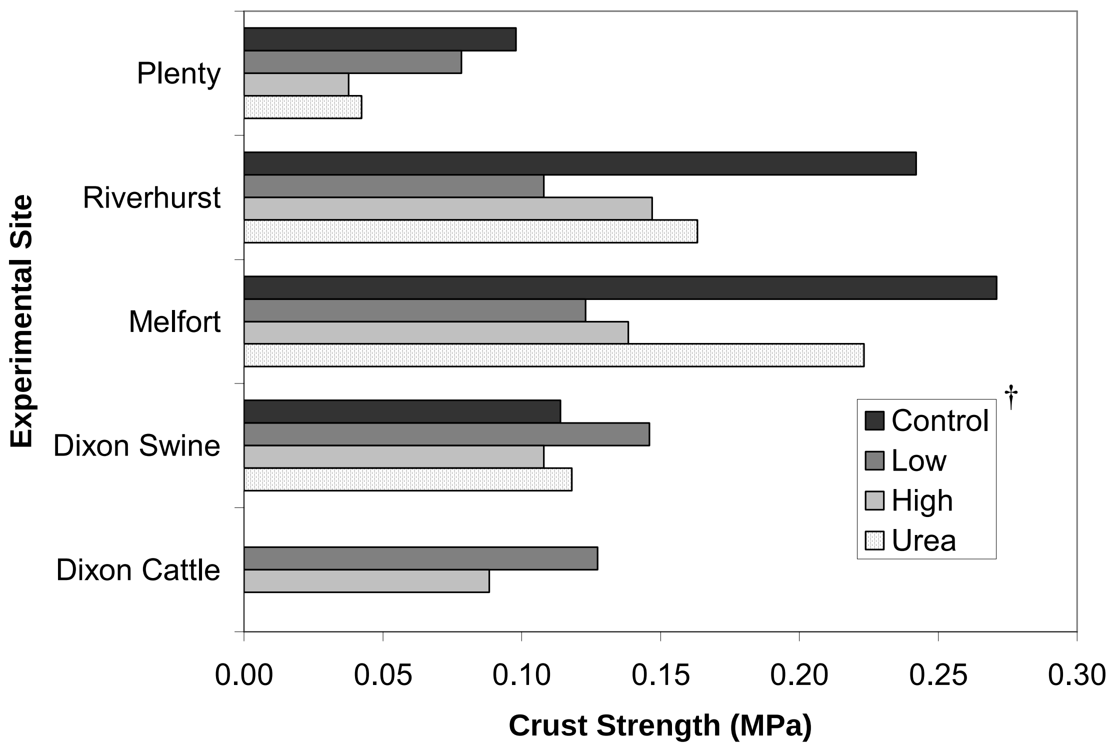


Figure 4.8 Soil crust strength for the four treatments at all experimental sites on Day 10 for the canola emergence and crusting experiment. No statistical tests were performed.

† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

Indeed, at soil strengths as low as 0.063 MPa, cracks can form naturally in the crust, allowing for emergence (Arndt, 1965). At Day 10, for the Plenty, Riverhurst and Melfort sites, the crust strengths for the High rate of liquid swine manure were less than half of those in the Control plots.

Except for Day 9 and 10, the Plenty soils (Figure 4.9) never had soil strengths greater than 0.06 MPa. Even on Day 10, only for the Low rate of swine manure and Control treatments did the crust strength become greater than the 0.063 MPa threshold. The effect of different treatments was most pronounced seven to eight days following the rainfall event. Early on, the mean crust strength was lower on the Low rate of swine manure treatment compared to the High rate and Urea treatment. At Day 3, it was significantly lower than the High rate of swine manure treatment. But by Day 8, the trend had reversed, such that the High rate of swine manure treatment was lower than all the other treatments. However, looking at crust strengths over the course of the experiment, there were no major differences between treatments. Overall, swine manure addition had no major impact on soil crusting at this site. On the other hand, cattle manure can dramatically decrease soil crust strength (Mazurak et al., 1975).

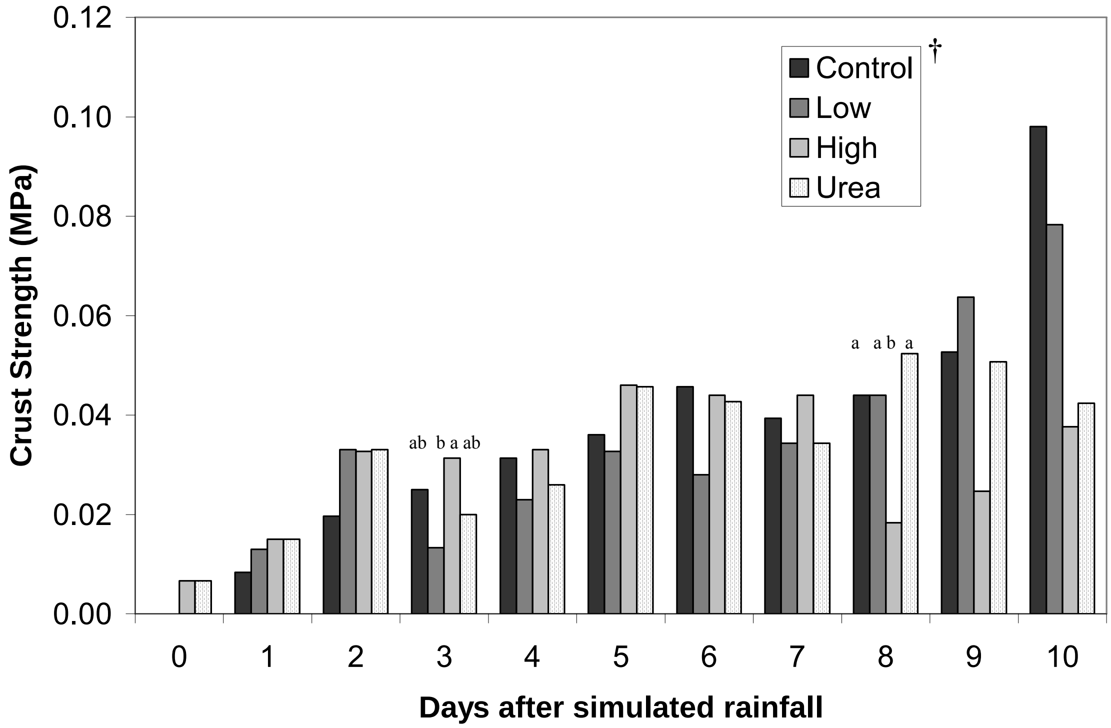


Figure 4.9 Soil crust strength for the four treatments at the Plenty site during the canola crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1}) and high (74 kL ha^{-1}) annual application rate of injected liquid swine manure. Urea refers to the treatment that had 80 kg N ha^{-1} applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

The crust strengths at the Riverhurst site (Figure 4.10) were generally twice as high as the ones in Plenty, and showed significant differences in the first few days, where the Low and High rates of swine manure treatments had crust strengths significantly lower than those of the control. In some cases, especially for the Low rate of swine manure treatment, they were lower than the Urea treatment as well. The trend continued into later time periods when the Low rate of swine manure treatment had the lowest crust strength, generally followed by the High rate, Urea and then Control treatments. One year prior to this study year, Zeleke (2003) found no significant differences in crust strength at either the Plenty or Riverhurst sites. Although variability is high, this study indicates cumulative manure application could lead to an increased effect on soil crust strength.

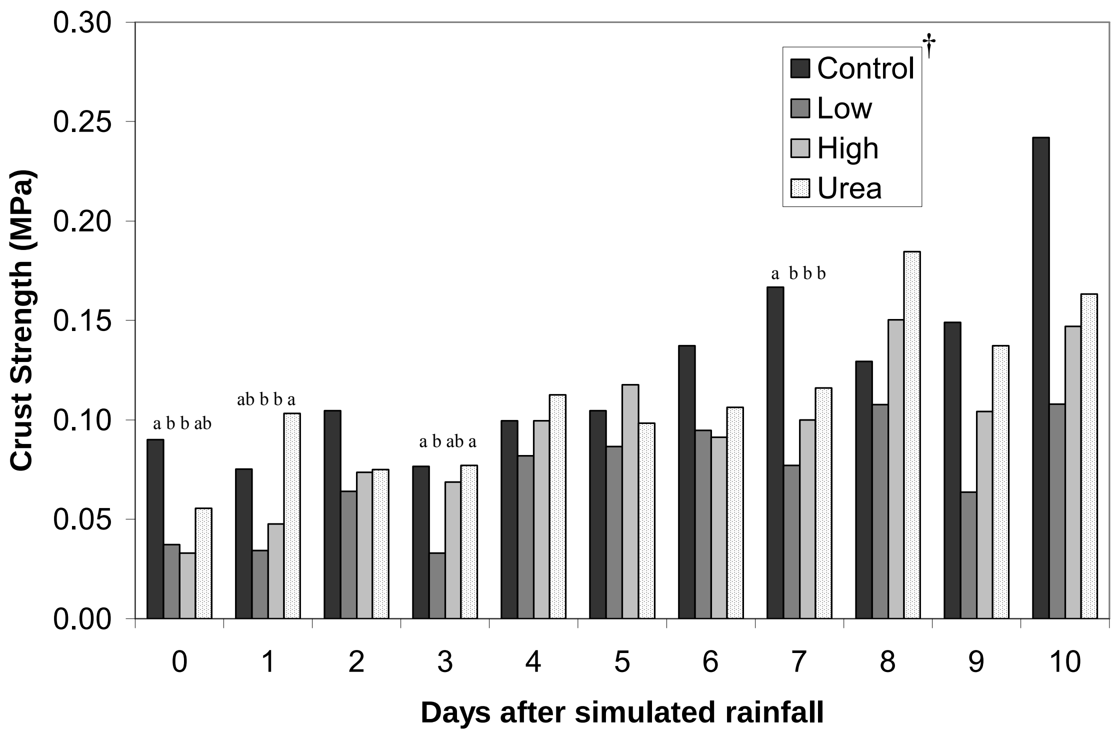


Figure 4.10 Soil crust strength for the four treatments at the Riverhurst site during the canola crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1}) and high (74 kL ha^{-1}) annual application rate of injected liquid swine manure. Urea refers to the treatment that had 80 kg N ha^{-1} applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

The range of crust strengths encountered at Melfort (Figure 4.11) was higher than that of any of the other sites. The Melfort clay had shrunk considerably in the core compared to the Plenty clay. The surface horizon of the Melfort site has greater clay content than the other sites (Plenty surface has a high silt content; Dixon and Riverhurst are loams). Therefore, there were large gaps between the Melfort soil core and the PVC sleeve and it also appeared that the Melfort soil became hydrophobic. Similar to Plenty and Riverhurst, at the Melfort site the trend was for the swine manure treatments to have a lower crust strength than the control, with both the Low and High rates of swine manure significantly lower than the Control treatment on Days 2 and 6; and for the Low rate only on Day 10. At the Melfort site, it is not unexpected that the High rate of swine manure is closer to that of the Low rate than the other sites, because it is applied only once every third year, making the average application rate, over time, the same as the Low annual rate. On Day 2, the Urea treatment was also significantly lower than the Control. Generally, the trend was for the crusts on Low and High rates of swine manure treatments to be similar in strength, and lower than both the Control and Urea treatments, with the Control treatment usually highest.

At the Dixon liquid swine manure site (Figure 4.12), on Days 0 to 3, the Low rate of swine manure had significantly higher crust strength than the Control and/or the High rate. This trend continued to Day 10, but the differences among treatments were no longer significant. The last manure application at the Dixon site was approximately 18 months prior to sampling, versus six months for the other sites. This could explain why trend is reversed for Low rate manure treatment compared with the Control. The High rate at this site is also the highest of any at 4x the agronomic (low 1x) rate, leaving lingering effects 18 months after application. Based on research at Dixon two years earlier, Assefa et al. (2004) found no significant differences in crust strength using a modulus of rupture test. Similarly, at the other three sites in that study, there were no significant differences in crust strength.

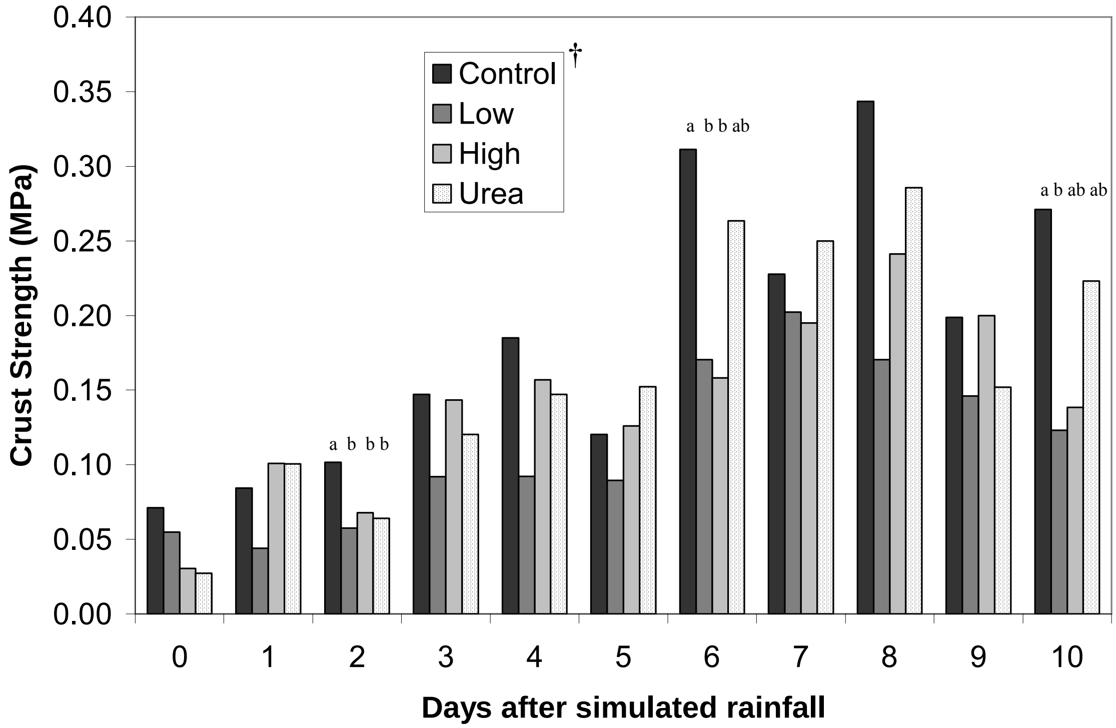


Figure 4.11 Soil crust strength for the four treatments at the Melfort site during the canola crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 4. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1} annual) and high (111 kL ha^{-1} tri-annual) application rate of injected liquid swine manure. Urea refers to the treatment that had 80 kg N ha^{-1} applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

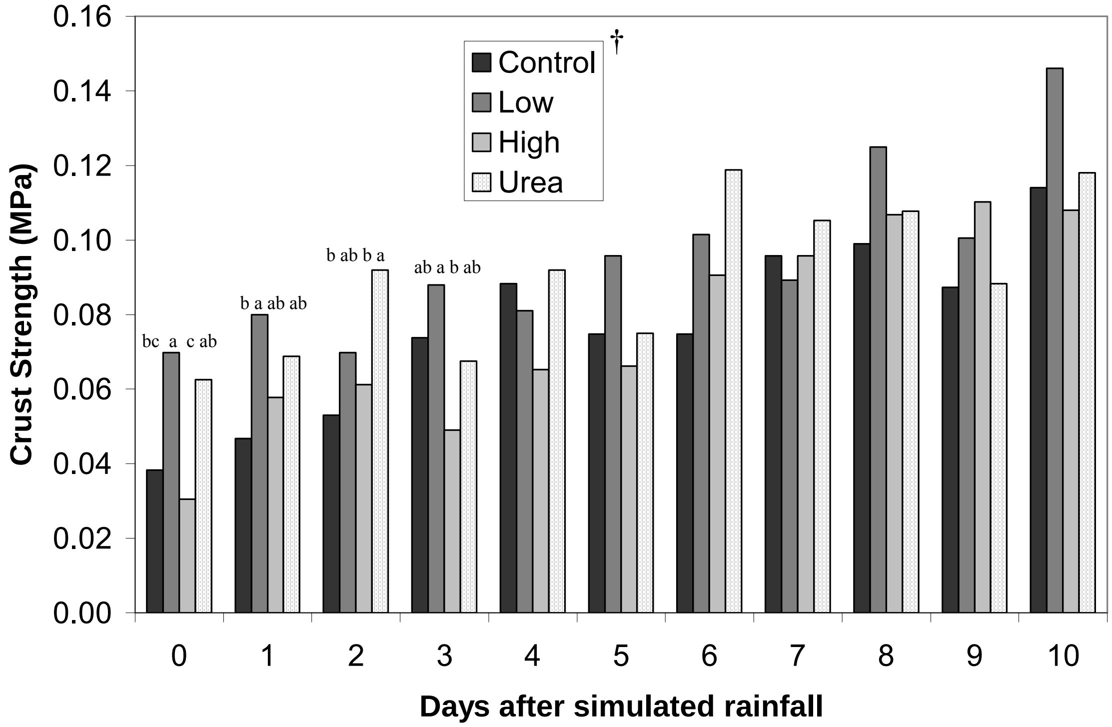


Figure 4.12 Soil crust strength for the four treatments at the Dixon swine manure site during the canola crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 4. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1}) and high (148 kL ha^{-1}) annual application rate of injected liquid swine manure. Urea refers to the treatment that had 112 kg N ha^{-1} applied as urea. Control had no fertilizer and was disturbed with coulters. For further detail, refer to Table 3.1.

For the Dixon cattle manure site (Figure 4.13), the Low rate of cattle manure tended to have higher crust strength than the High rate, but this difference was only significant on Days 3 and 7. Previous research at Falher, AB showed a decrease in soil crust strength of up to 430 kPa with the addition of cattle manure as measured by modulus of rupture (Assefa, 2002). Other research out of Lethbridge, AB showed a decrease in soil crust strength of up to 1.31 MPa after 24 years of cattle manure application under irrigated conditions (Miller et al., 2002).

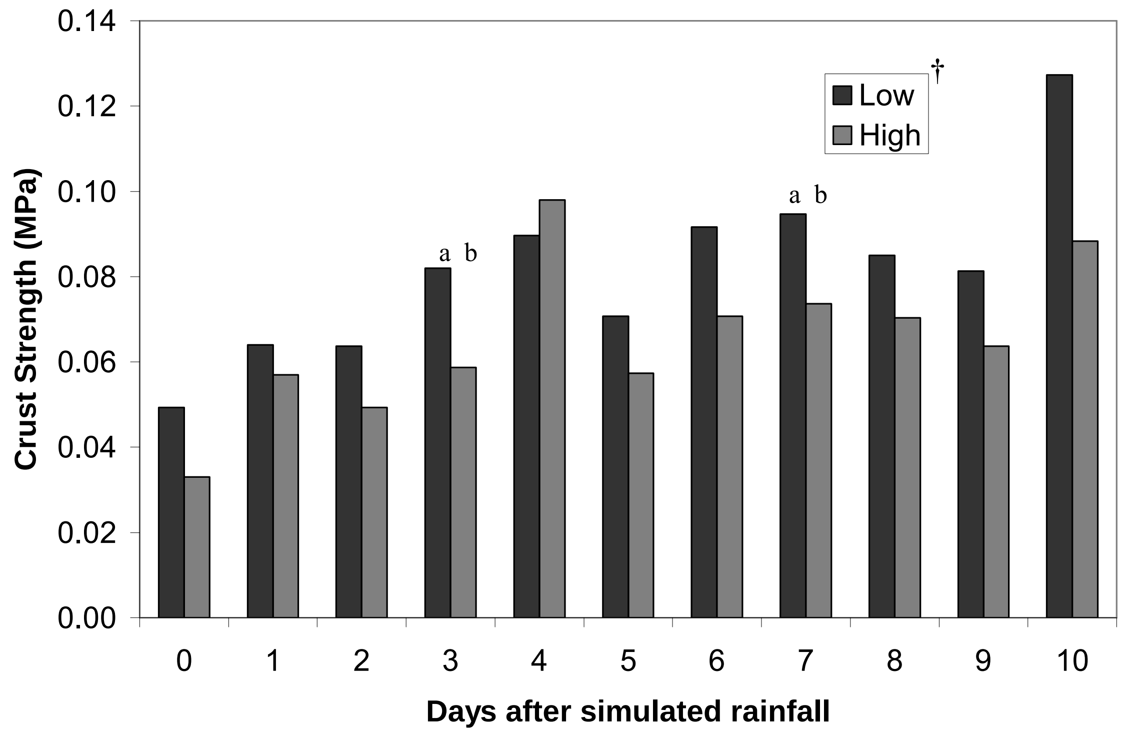


Figure 4.13 Soil crust strength for the two treatments at the Dixon cattle manure site during the canola crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (7.6 T ha^{-1}) and high (30.4 T ha^{-1}) annual application rate of broadcast and incorporated cattle manure. For further detail, refer to Table 3.1.

The Melfort site, followed by the Riverhurst site had the highest crust strengths of all sites. The Low rate of manure treatment tended to have greater crust strength than the High rate at both Dixon swine and cattle manure sites, and the Melfort site. For the Plenty soil, crust strength fluctuated over time, but at the end of the 10 days, the Low rate tended to have higher crust strength (Figure 4.8). The Melfort site had the greatest application of manure in 2002 at 111 kL ha^{-1}, as the 148 kL ha^{-1} rate at Dixon was not applied until spring 2003, after sampling. The last application of the high rate at Dixon was 2001. The Riverhurst soil has the coarsest texture of all the soils sampled.

Crust strength tended to increase with time at all sites. The further from the time of rainfall, and therefore, the drier the soil became, the greater the strength of the crust.

However, considering none of the soils came close to Arndt's (1965) threshold of 0.63 – 0.94 MPa is encouraging. With the exception of the Melfort site, all treatments had plants emerged within four days of the rainfall. Soils that were seeded for a few days prior to a rainfall event and in which germination had already taken place might emerge even faster. A situation where germination was induced only by rainfall, followed by drying and cool temperatures that delayed further development and emergence may be expected to be impacted the greatest by the increase in soil strength. The crust strengths measured in the Plenty and Dixon soils were very low, with a range of only 0.06 MPa between highest and lowest, compared with 0.15 MPa in Riverhurst and Melfort soils.

There are two experiments: liquid swine manure at four sites with two rates of liquid swine manure compared to a control and urea treatments, and cattle manure applied at one site comparing high rates to low rates. Except for Dixon, there is a clear decrease in crust strengths, especially in the High rate of swine manure compared to the Control treatment.

Crust strength appeared to fluctuate over time, although it generally increased as the soil dried out. Visual observations were that the soil surface was generally uneven; in some cases large clods dominated the surface. This highly irregular form likely contributed to the inconsistencies in crust strength measurements over time.

4.3.1.2 Soil Crusting: Flax Experiment

The flax experiment involved soils sampled from five different long-term experimental sites, treated with two rates of manure and/or urea fertilizer. The sites sampled were Plenty (swine and urea), Riverhurst (swine and urea), Melfort (swine and urea), Dixon (swine and urea) and Dixon (cattle).

The crust strength at Plenty (Figure 4.14) during the flax crusting and emergence experiment showed similar effects on Day 8 to that observed in the canola crusting and emergence experiment. However, the crust strength was generally higher. In the flax experiment, the soil had a higher initial water content before the larger rainfall, because of the pre-soak rain to soften the seed bed. Truman (1990) concluded that increased initial water content will decrease soil detachment from rain drops. However, the soils in this study were exposed to three different rainfall events, resulting in a cumulative soil detachment, increasing soil crust strength. By Day 7, most of the treatments had crust strengths greater than 0.06 MPa. The High rate of swine manure tended to have lower crust strength than the Control, but the difference was significant only on Day 8. Although there were noted differences on certain days, overall, there appeared to be little difference between the manure treatments and the control or urea treatments at this site.

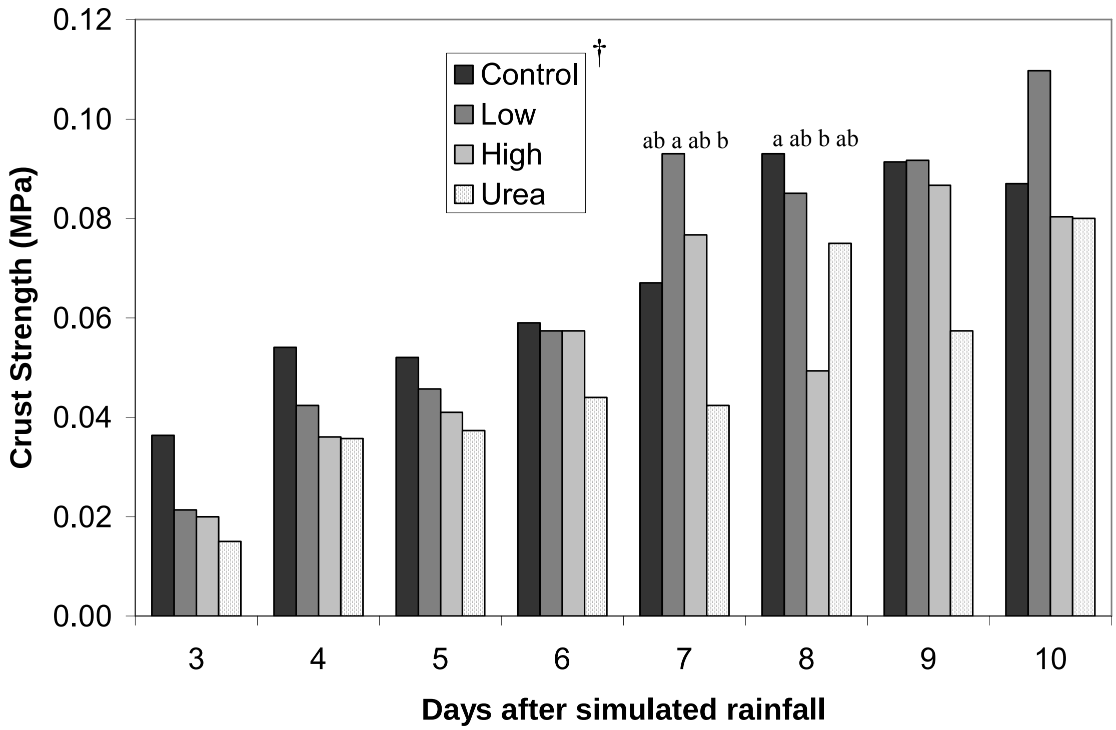


Figure 4.14 Soil crust strength for the four treatments at the Plenty site during the flax crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1}) and high (74 kL ha^{-1}) annual application rate of injected liquid swine manure. Urea refers to the treatment that had 80 kg N ha^{-1} applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

The Riverhurst site (Figure 4.15) also showed similar trends in crust strengths between the two experiments. By Day 7, most of the treatments had crust strength above 0.15 MPa, compared to closer to 0.1 MPa during the canola experiment. As in the first experiment, both the Low and High rate of swine manure treatments tended to have lower crust strength than the Control and Urea treatments. The Low rate of swine manure treatment was significantly lower than the control on Days 5 and 8. The Plenty and Riverhurst sites received the same rates of manure, but the Riverhurst site is irrigated and its soil texture is coarser. The Plenty site has a high surface silt content that breaks down and the manure applied has a high SAR (Table 3.4).

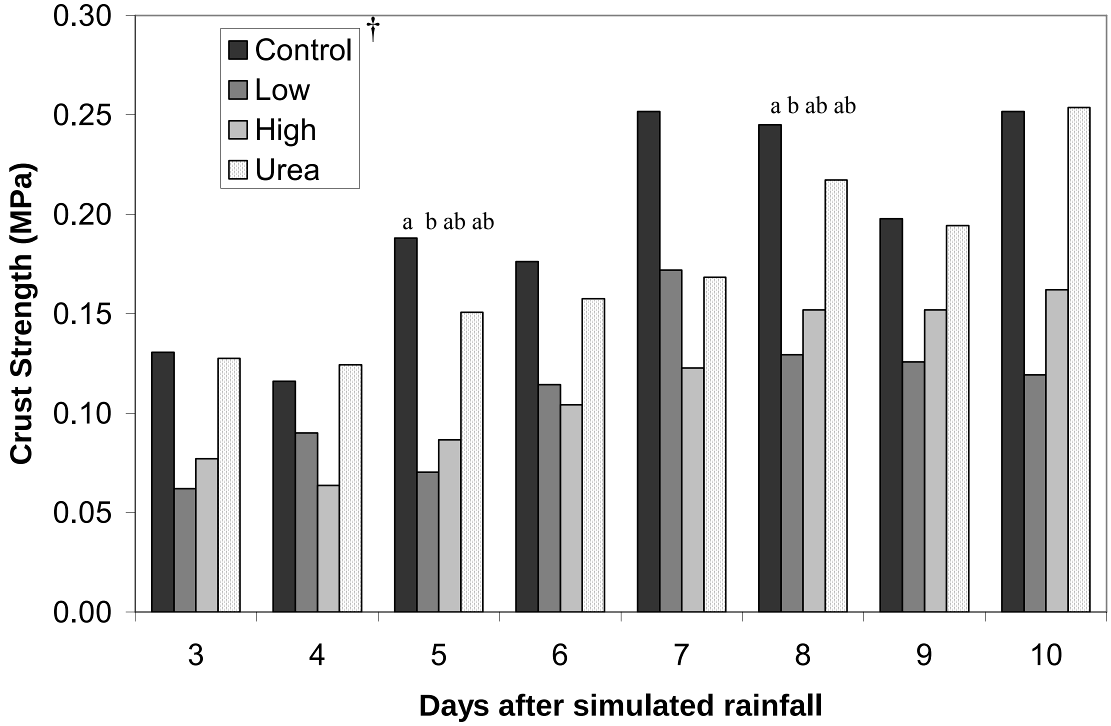


Figure 4.15 Soil crust strength for the four treatments at the Riverhurst site during the flax crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1}) and high (74 kL ha^{-1}) annual application rate of injected liquid swine manure. Urea refers to the treatment that had 80 kg N ha^{-1} applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

The Melfort site (Figure 4.16) generally had reduced crust strength during the flax crusting and emergence experiment compared with the canola crusting and emergence experiment. Considering that more water was added during the flax experiment, because of the pre-seeding rainfall of seven minutes and the post-seeding rainfall of 15 minutes, the initial rain may have allowed the soil to swell enough that more of the second rain was retained in the soil. In this experiment, no significant differences were detected, but some similar trends emerged, parallel to the canola experiment. The trend was for the Low rate of swine manure to have a lower crust strength than the other treatments, which was found to be statistically significant during the canola crusting and emergence experiment, but was not significant in the flax experiment. The High rate of swine manure appeared lower than the Control and Urea treatments early on, but only lower than the Urea treatment later on. The High rate was applied the fall prior to sampling, perhaps leading to greater soil crust strength.

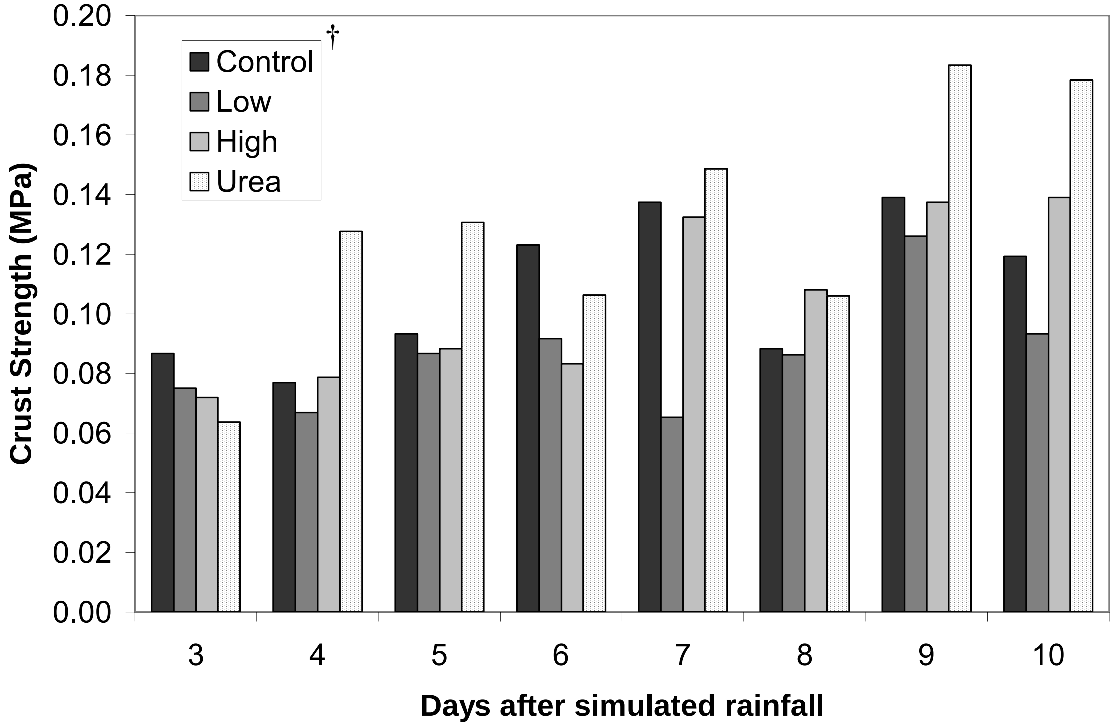


Figure 4.16 Soil crust strength for the four treatments at the Melfort site during the flax crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1} annual) and high (111 kL ha^{-1} tri-annual) application rate of injected liquid swine manure. Urea refers to the treatment that had 80 kg N ha^{-1} applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

The Low rate of swine manure treatment at Dixon has the greatest crust strength of all treatments (Figure 4.17), similar to the canola experiment. In this experiment the crust strength of the Low rate is significantly higher than the Control, High rate and Urea treatments on Days 6 and 9, and higher than the Control and High rate on Day 10. On Day 3, the Low rate is significantly higher than the High rate and Urea treatments. On Day 6, the High rate was significantly higher than the Control. Overall, the manure treatments appear to trend higher than the control treatment. The 18 month time period that lapsed since the last manure application may be causing the reversed trend at this site compared with the others. The High rate is not as substantial because there may be a lag effect from the higher rate. The difference in range of crust strengths between this experiment and the canola experiment does not appear substantially large.

At the Dixon Cattle experimental site, the Low rate of cattle manure tended to have higher crust strengths than the High manure rate (Figure 4.18), similar to that observed with the swine manure. This trend is similar to the observations for cattle manure in the canola crusting and emergence experiment.

Overall, the trends observed in treatment effects among experimental sites agreed well between the two experiments. At the Riverhurst and Melfort sites, which have the highest rainfall rates (irrigation and climatic zone) and are coarse and fine textured surfaces, the Low rate of swine manure tended to have the lowest crust strength and the two manure treatments tended to be lower than the Control and Urea treatments. At the Plenty, Dixon Swine, and Dixon Cattle sites, which are all medium textured soil surfaces, the Low manure application rate treatment tended to have the greater crust strength (Figure 4.19). It is most important to note the SAR of the manure applied at the Plenty site was high, and the high surface silt content will increase soil detachment, and the 18 month period since manure was applied at the Dixon sites. Again, similar to the canola crusting and emergence experiment, none of the crust strengths measured approached the values of 0.63 to 0.94 MPa (Arndt, 1965). This indicates that while there are significant differences, none of the treatments are associated with crusting beyond a threshold which is expected to inhibit plant emergence. However, there are some differences among the sites in how manure application affects crusting that may be related to differences in manure characteristics and soil properties among the sites. McInnis (2001) found that soil crust strength decreased with increased soil residue cover. No residue cover assessments were made in this study. The results of the crust strength study would seem to indicate that different soils may react differently to manure application and/or different barn management systems/water sources. As a result, generalizations about the effects of manure application on soil structure, without specifying soil type or manure source, could be risky.

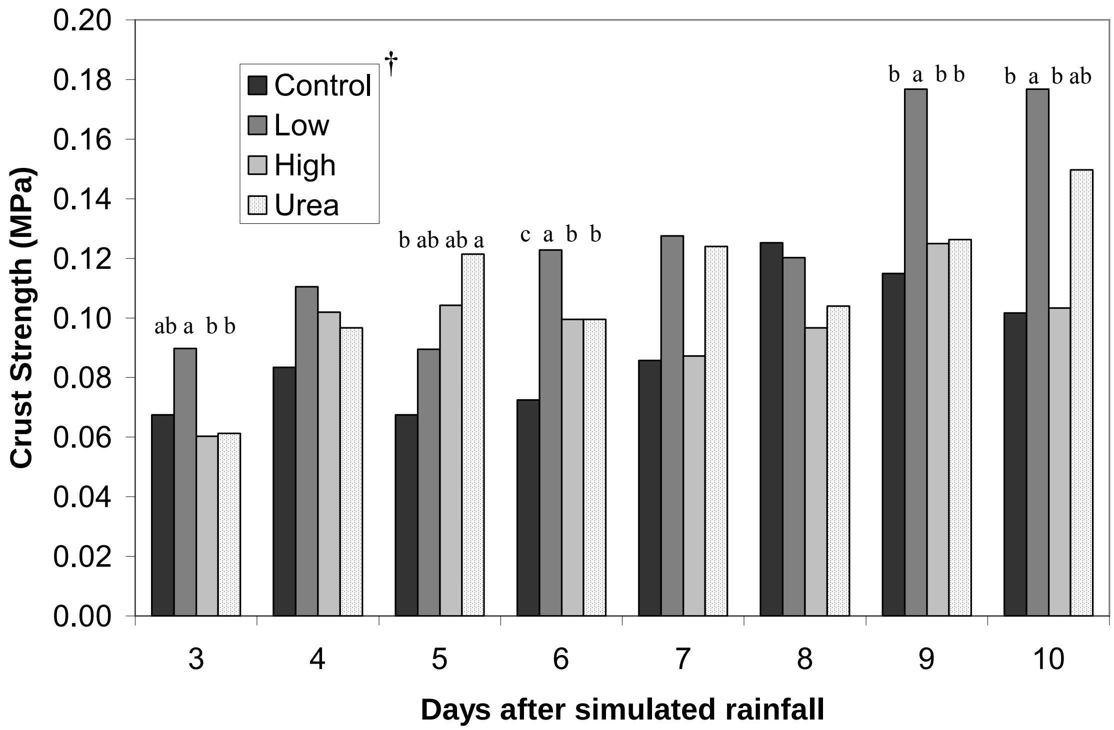


Figure 4.17 Soil crust strength for the four treatments at the Dixon swine manure site during the flax crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 4. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (37 kL ha^{-1}) and high (148 kL ha^{-1}) annual application rate of injected liquid swine manure. Urea refers to the treatment that had 112 kg N ha^{-1} applied as urea. Control had no fertilizer and was disturbed with coulters. For further detail, refer to Table 3.1.

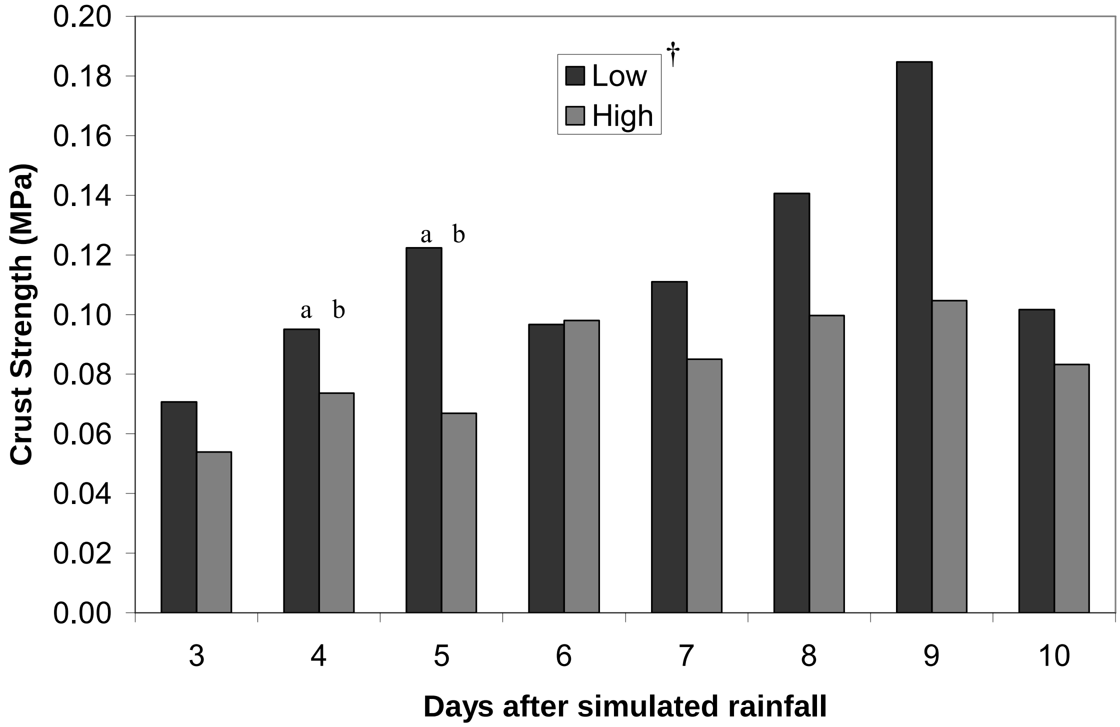


Figure 4.18 Soil crust strength for the two treatments at the Dixon cattle manure site during the flax crust strength and emergence experiment.

* For a given measurement day, columns with different letters are significantly different at the 90% confidence level on that day of measurement according to Least Significant Differences. n = 3. Columns without letters are not significantly different. There are no statistical comparisons drawn between days.
† Low and High refer to the low (7.6 T ha^{-1}) and high (30.4 T ha^{-1}) annual application rate of broadcast and incorporated cattle manure. For further detail, refer to Table 3.1.

4.3.2 Plant Emergence After a Rainfall Simulation

4.3.2.1 Emergence: Canola Experiment

Some problems with seeding the canola gave rise to high variability and made even trends difficult to determine, therefore the flax experiment may be considered more reliable and representative of field conditions. Only canola plant vigour ratings are shown (Figure 4.20).

The Melfort site had very poor emergence (data not shown) with a low proportion of seeds germinating. As previously indicated, the Melfort soil cores did not take on as much water as the others, due to water running down the sides of the cores due to shrinkage. All the other cores gained approximately 600 g after the rainfall simulation, while Melfort soils gained only 200 - 300 g. The lower water content of the soil delayed germination beyond the measurement period. The low germination of the manure treatments at Melfort may be from the effect of salts from the manure, aggravated by low moisture content and limited leaching.

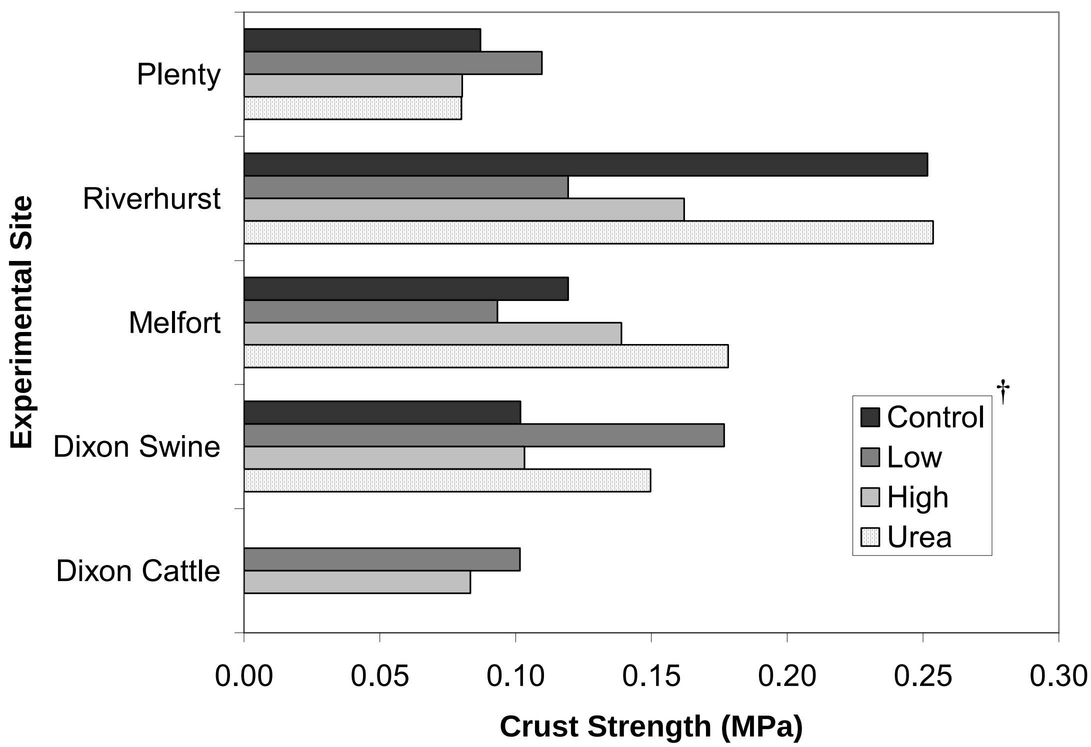


Figure 4.19 Soil crust strength for the four treatments at all experimental sites on Day 10 for the flax experiment. No statistical tests were performed.

† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

Greater plant health of canola plants on the Low rate of swine manure compared to the High rate of swine manure and Urea treatments was observed for the Riverhurst site (Figure 4.20). Both the canola and flax experiments showed lowest soil crust strengths for the Low rate of swine manure at the Riverhurst site. Although seedlings may emerge, the stress of emerging through a harder crust may have resulted in poorer plant health and vigour in the other treatments.

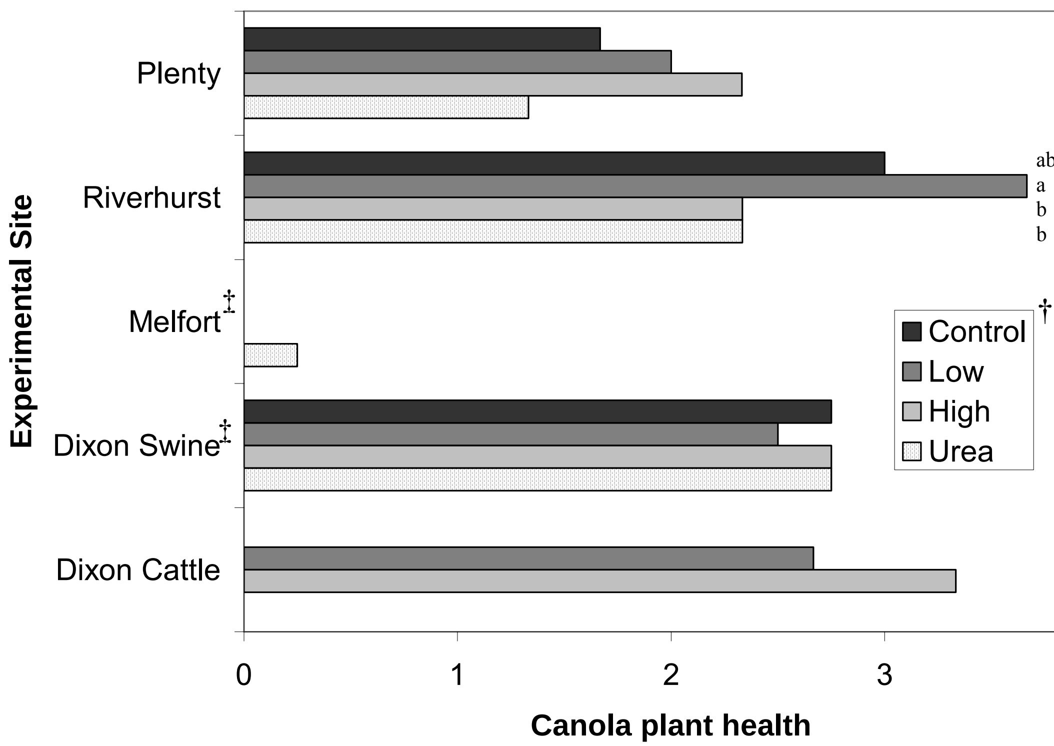


Figure 4.20 Rating of canola vigour (scale 1-4) based on visual observations made 10 days after the simulated rainfall for four treatments at each of the four swine manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, and Dixon Cattle); n = 4 (Melfort and Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.
‡ Data does not conform to a normal distribution for this site.

4.3.2.2 Emergence: Flax Experiment

At the Plenty site (Figure 4.21), patterns in emergence were consistent with crust strength. Although no significant differences were detected, the Low rate of swine manure had lower emergence than the High rate of swine manure– consistent with a greater crust strength in the Low rate of swine manure treatment.

At the Riverhurst site, the flax on the Low rate of swine manure had significantly lower emergence than the Control treatment, despite having the lowest crust strength and best rating for canola vigour and health.

The Melfort site shows some relationship with crust strength measurements. This site had little difference in emergence between the two manure rates, as the High rate of swine manure at this site is applied only once every third year, making the average application over time the same as the annual rate of swine manure application.

The Dixon swine manure site had significantly higher emergence of flax in the Low rate of swine manure than the High rate of swine manure and Urea treatments. This is in contradiction to crust strength measurements for this soil, as the Low rate of swine manure treatment had significantly greater crust strength than all three other treatments, depending on the day measured.

There appear to be other factors affecting emergence apart from crust strength. The absence of a direct relationship between crust strength and emergence is consistent with all crust strengths being below critical values where impedance to emergence is likely to occur. Both the Riverhurst and Plenty sites had greater emergence in the High rate of swine manure than the Low rate of swine manure. The High rate of swine manure would have more residual nutrients in the soil. At the Dixon swine manure site, the 18 months since the last manure application may have allowed greater leaching and nutrient removal, reducing any potential salt or toxicity effects on germination and early plant growth. This is especially true on the Low rate treatment where emergence was greatest.

Rather than making plant ratings based on visual observations, which can be subjective, in the second experiment with flax, the dry matter of the flax plants was weighed (Figure 4.22). No significant differences in plant dry matter between treatments were observed. However, patterns in plant dry matter tended to be consistent with emergence.

4.3.3 Ponded Infiltration

The soils from the Plenty swine manure experiment took longer to form a surface seal than the other sites (Figure 4.23), but once formed, infiltration was very slow (Figure

4.24). Plenty has a high clay content, which is known to be a contributing factor to reduced infiltration rate (Wace and Hignett, 1991). The surface horizon at Plenty is high in silt as well, which would contribute to a relatively fast breakdown of soil structure (Dr. Mike Grevers, personal communication, 2007). The surface seal formed faster in the High rate of swine manure treatment compared to the Low rate of swine manure and Urea treatments. This may be related to added sodium leading to increased dispersion of

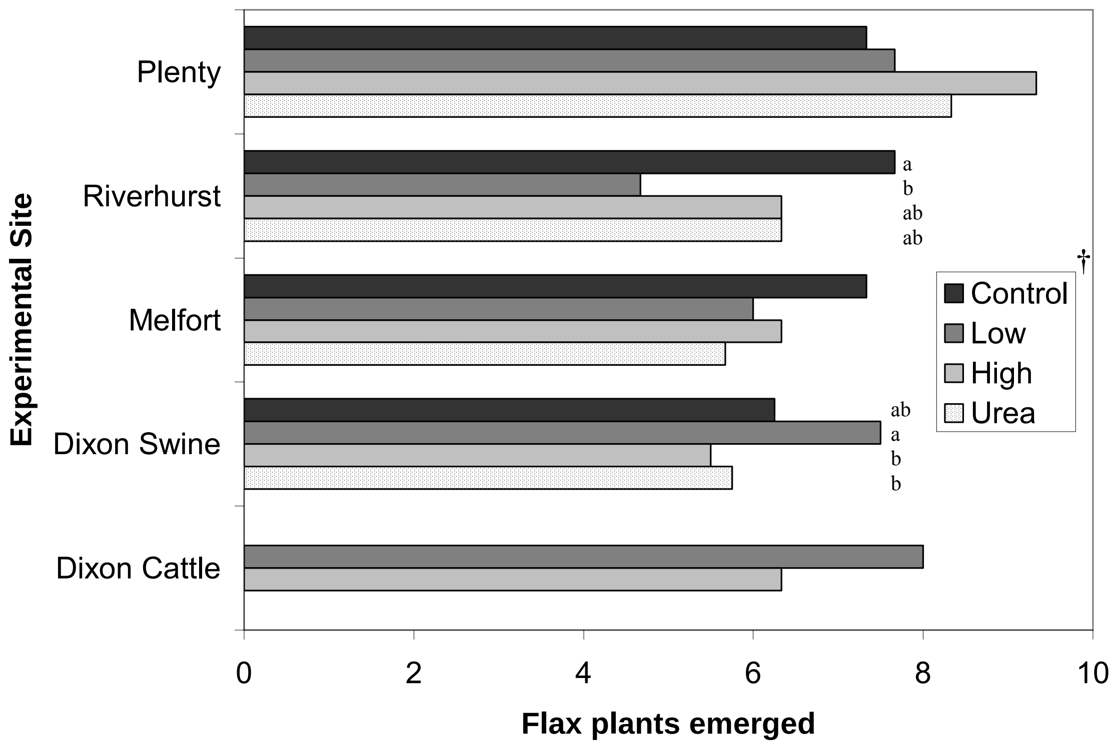


Figure 4.21 Emergence of flax plants (10 seeds per core) 10 days after the simulated rainfall for four treatments at each of the four swine manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

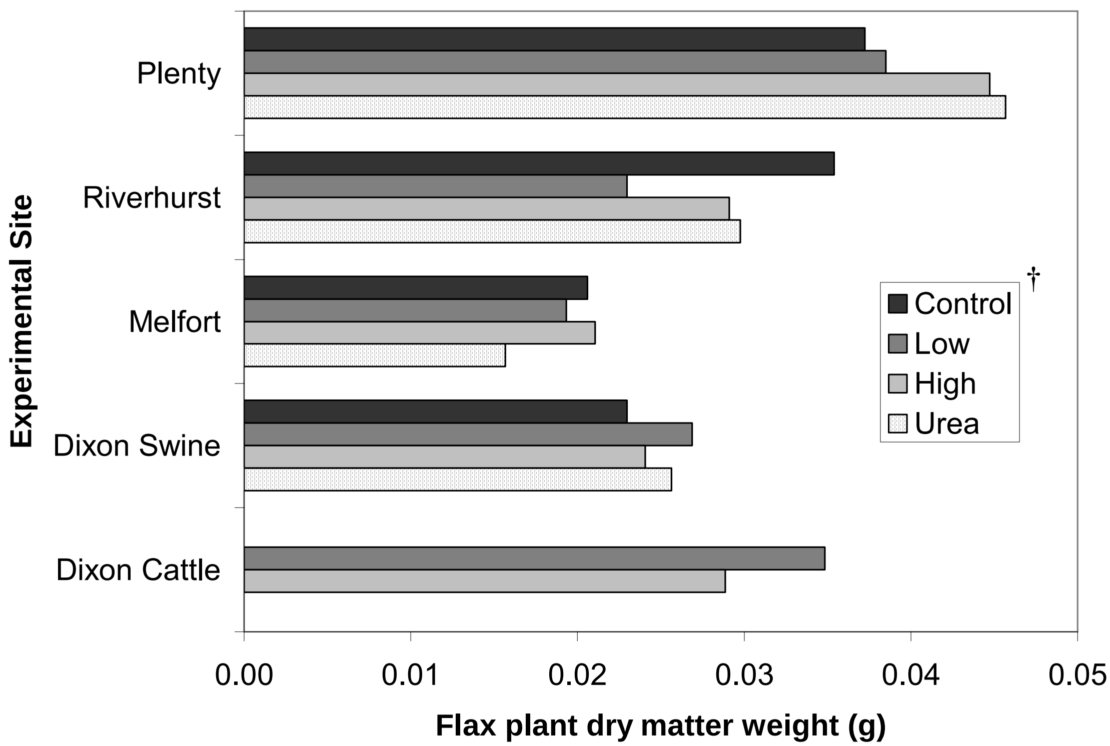


Figure 4.22 Flax plant dry matter weights per core, 10 days after the simulated rainfall for four treatments at each of the four swine manure and one cattle manure experimental sites. Plants were oven dried at 50ºC.

* For a given measurement day, bars with different letters are significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

soil aggregates. For other soils, there was little effect of treatment on time to seal. Once the surface seal was formed, there was no difference in time between treatments to reach the desired pond level. At the Plenty site, there were no significant differences between treatments in infiltration time (Figure 4.25). The Plenty site has the greatest concentration of silt and clay, thereby reducing infiltration rate. Sodic soils are likely to form surface seals or crusts (USA, 1954; Henry et al., 1992; So and Aylmore, 1993; Henry, 2003). The sodicity of the manure at the Plenty site is also high (SAR = 14.07) compared with the sodicity (SAR 1.67 to 6.87) of the manure of the other sites.

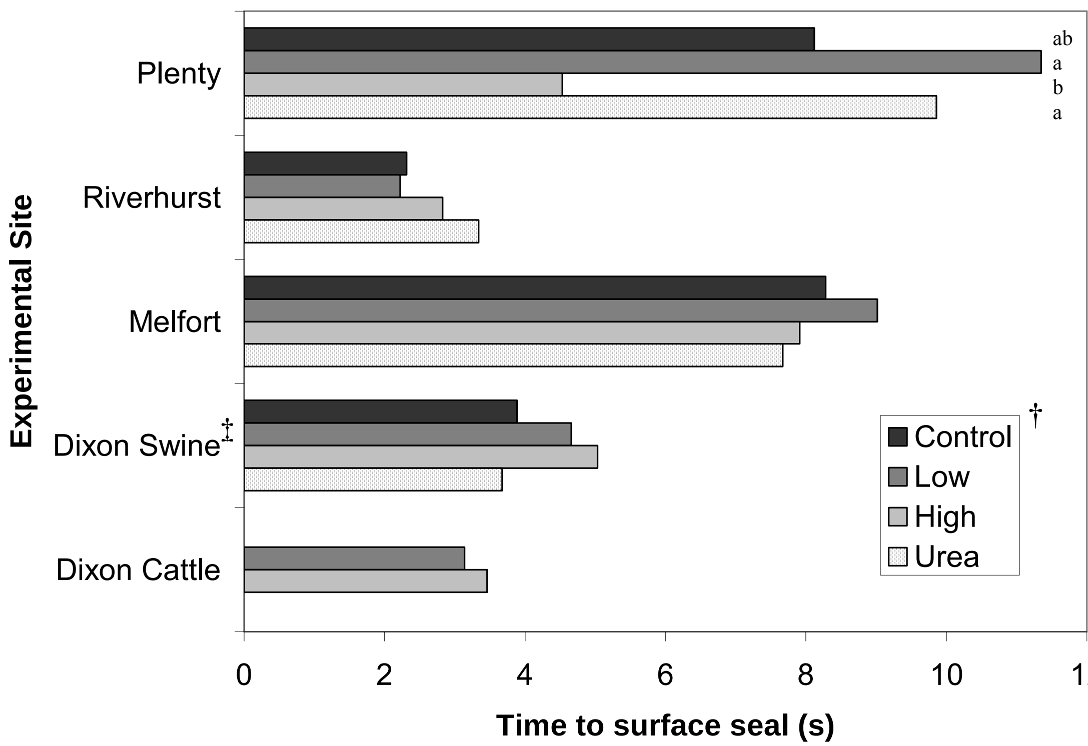


Figure 4.23 Time for the soil surface to seal and allow water to start ponding on the surface for four treatments at each of the four swine manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.
‡ Data does not conform to a normal distribution for this site.

The difference in time to reach a ponded depth of 3.75 cm recorded for the low and high rates of cattle manure at the Dixon site in Figure 4.24 is not substantial, but was statistically significant ($p<0.10$). No other significant differences were detected.

The Riverhurst soils had the fastest infiltration rate among the sites, likely due to high sand content. This was the only site with significant treatment differences in infiltration time (Figure 4.25). The Urea treatment had slower infiltration than the Control treatment. Reasons for the differences are not clear, but the Urea treatment did yield lower than the Control at this site in 2003. However overall differences were not large. After the infiltration was complete, visual observation indicated that little, if any surface structure remained and the surface aggregates had been destroyed.

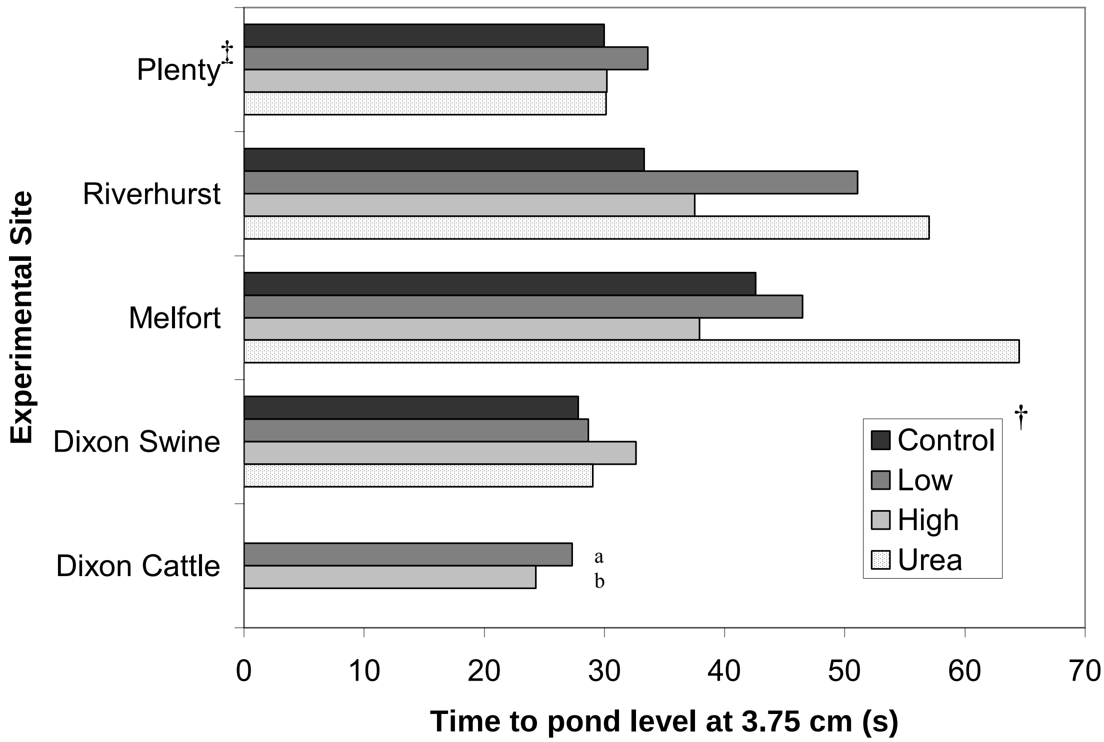


Figure 4.24 Time for the ponded water to reach 3.75 cm above the soil surface for four treatments at each of the four swine manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.
‡ Data does not conform to a normal distribution for this site.

McIntyre (1958) observed that with more stable soil structures, the effect of the 'washed-in region', located under the 'skin seal', is reduced. The permeability of a stable soil structure would be less influenced by the surface seal than a weaker soil structure.

Clay dispersion, as measured by shaking in water, was found to increase with increasing soil ESP, but dispersion was prevented when shaken with tap water containing electrolytes (Shainberg et al., 1992). This explains how the manure treatments could show increases in EC and ESP, but not be associated with increased crusting or reduced infiltration rates, as the influence of ESP on the soil surface is offset by the increase in electrolytes.

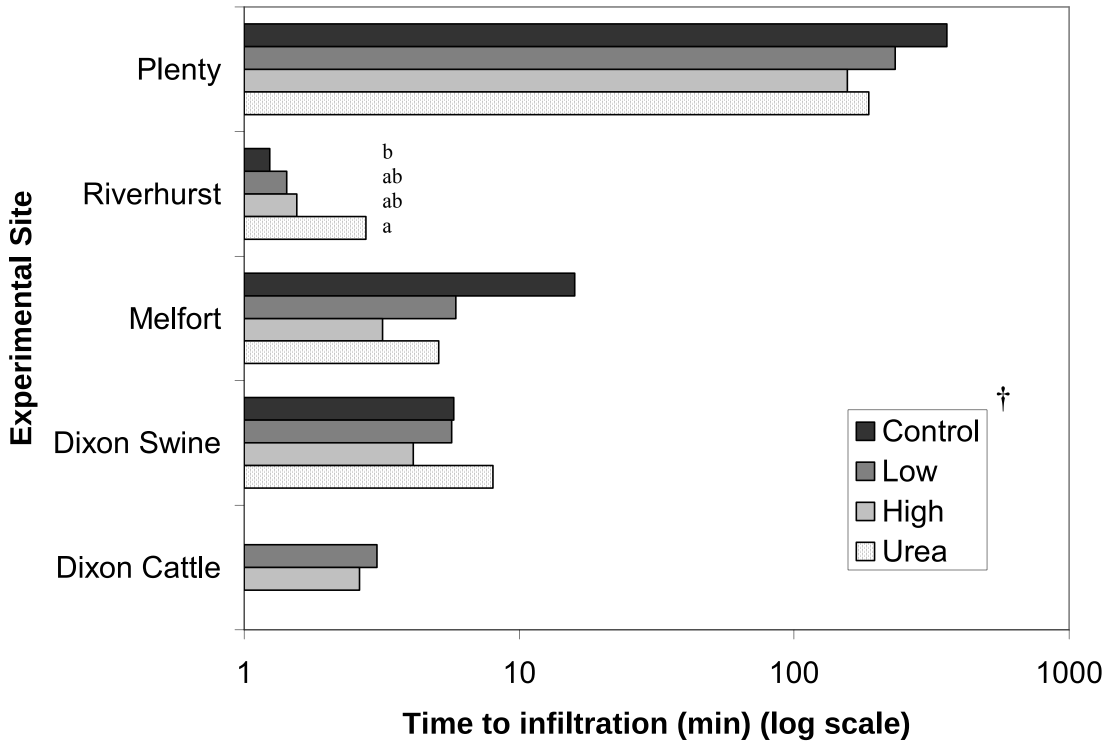


Figure 4.25 Time for the ponded water to completely infiltrate into the soil for four treatments at each of the four swine manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 90% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

The high rate of simulated rainfall used in this experiment, sets up the worst case scenario for the soils tested because salts will leach out, leaving Na behind. Numerous studies have found that increasing rainfall energy increases soil dispersivity (Tossell et al., 1990a; Tossell et al., 1990b; Shainberg et al., 1992).

4.3.4 Modulus of Rupture, COLE, EC, and ESP

The tendency at all sites is for the manure treatments to have slightly higher EC than the Control and Urea treatments (Figure 4.26). For the Plenty and Riverhurst sites, the High rate of swine manure has significantly higher ($P<0.05$) salinity than the Urea and Control treatments. At the Riverhurst site, both the Low and High rates of swine manure had significantly higher EC than the Control treatment. Zeleke (2003) found the high rate of hog manure significantly increased EC at Plenty in 2001, but found no significant difference at the Riverhurst site after manure application. Assefa (2002) found variable effects of manure on EC, as EC increased at one site and decreased at another. There were no significant differences at Dixon in 2000 (Assefa et al., 2004).

The High rate of cattle manure at the Dixon cattle manure site has an EC of over 0.2 dS m^{-1} greater than the low rate. The difference is not significant due to high variability, but the difference is larger than any other detected difference.

Despite increases in EC that were occasionally statistically significant, manure application has not resulted in soil salinity levels that approach threshold values for injury. The Agriculture Operations Practices Act in the Province of Alberta does not permit manure application to soils with an EC greater than 4 dS m^{-1}. The Act also stipulates that the manure cannot cause the EC to increase greater than 1 dS m^{-1} (Seiferling and Boehme, 2005). According to Henry (2003), 0-2 dS m^{-1} is considered non-saline and 2-4 dS m^{-1} is slightly saline where sensitive crops may be affected. Considering that the High rate of swine manure has caused an increase in salinity of less than 0.5 dS m^{-1} (approximately) after four to seven years of manure application at rates above what were recommended to meet a nutrient requirement, salinity does not appear to be an issue. Chang et al. (1991) observed a similar trend in Southern Alberta, where, both EC and SAR increased as cattle manure application rates increased. The researchers noted that EC increased in the surface 15 cm under irrigation. Nutrient demand of the crop and nutrient content of the manure should be observed when considering application rates and regular monitoring of salinity levels is recommended. A considerable amount of water was added to the soil during the infiltration study, which may impact the distribution of salts, and some salt may have been entirely removed from the core by leaching. Other research has shown irrigation to lower the depth at which salts become an issue (Chang et al., 1991). The researchers found that under non-irrigated conditions the salts did not leach beyond 120 cm.

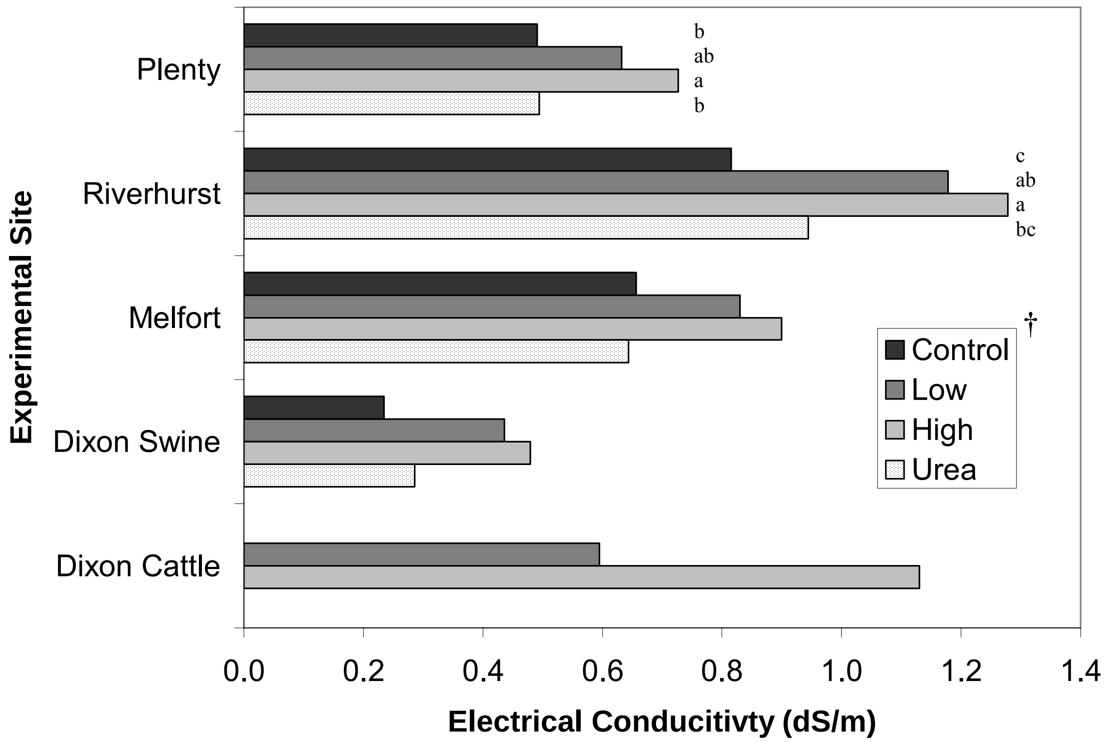


Figure 4.26 Electrical conductivity (EC) for four treatments at each of the four swine manure and one cattle manure experimental sites. Values presented are based on saturated extract values (Hogg and Henry, 1984).

* For a given measurement day, bars with different letters are significantly different at the 95% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

Similar to the EC, the ESP of the manure treatments at all sites tended to be slightly higher than the Control or Urea treatments (Figure 4.27), and the ESP increases with manure rate at all sites.

The Plenty soil had manure applied with an SAR of 14.07, higher than any other site. It appears that the clay content allows the soil to buffer the effect of the high SAR manure. Chang et al. (1991) observed that manure application with an SAR of 21.8 increased soil

SAR at the surface under non-irrigated conditions. Zeleke (2003) observed an increase of 0.14% in SAR value at Plenty in 2001. The magnitudes measured here were similar to Zeleke's findings, but not significant at $p<0.05$.

At the Melfort and Dixon sites, the ESP of the two manure treatments was significantly higher than the control and urea treatments. Again, the increase does not warrant management change, but simply monitoring. The threshold for a soil to be considered sodic is ESP > 15% (Henry et al., 1992) and ESP values at all sites are well below this threshold. However, other researchers found that a critical limit for ESP varies depending on the soil and conditions (Emerson and Bakker, 1973; Shainberg et al., 1980; So and Aylmore, 1993).

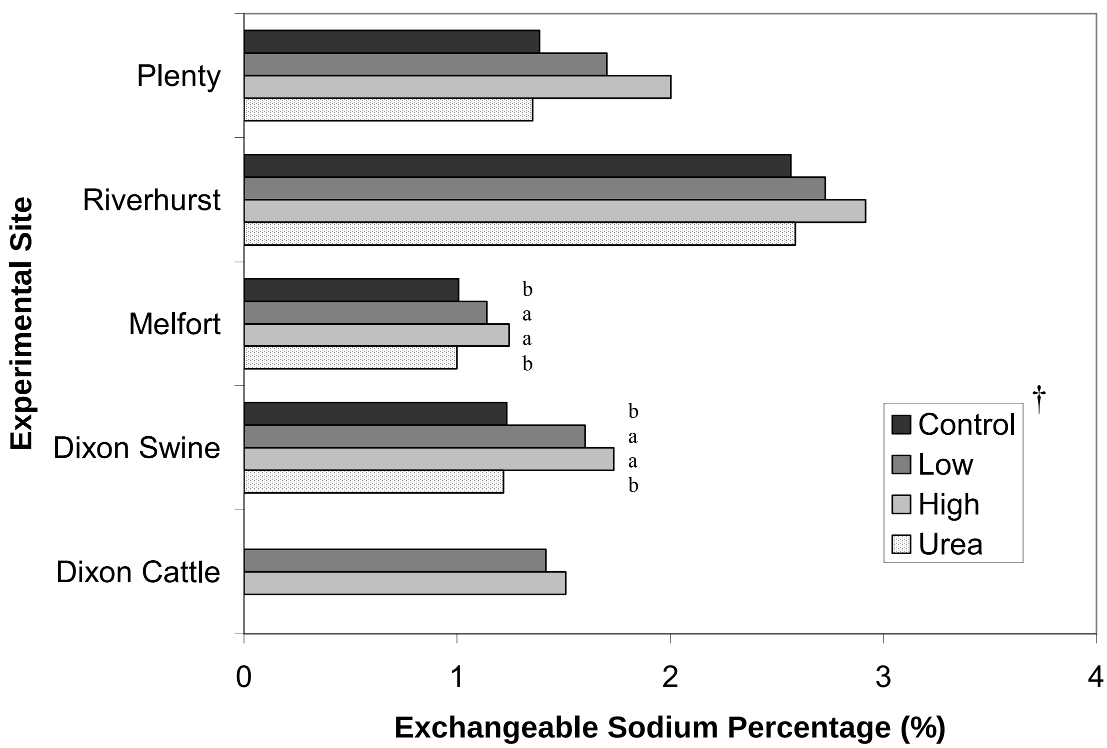


Figure 4.27 Exchangeable sodium percentage (ESP) for four treatments at each of the four swine manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 95% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.

For the COLE measurement, significant treatment effects were observed only at the Melfort and Dixon Swine manure sites. The High rate of swine manure at Melfort had significantly higher extensibility than the Urea treatment, while at Dixon, the Control treatment was significantly higher than the Urea treatment. Problems were encountered with breakage of the briquets prior to measurement. No significant differences were detected in modulus of rupture (Appendix A). Poor briquet formation is believed to be due to low Na concentration in the soils at the experimental sites. Better results were achieved using the survey soils (Appendix C).

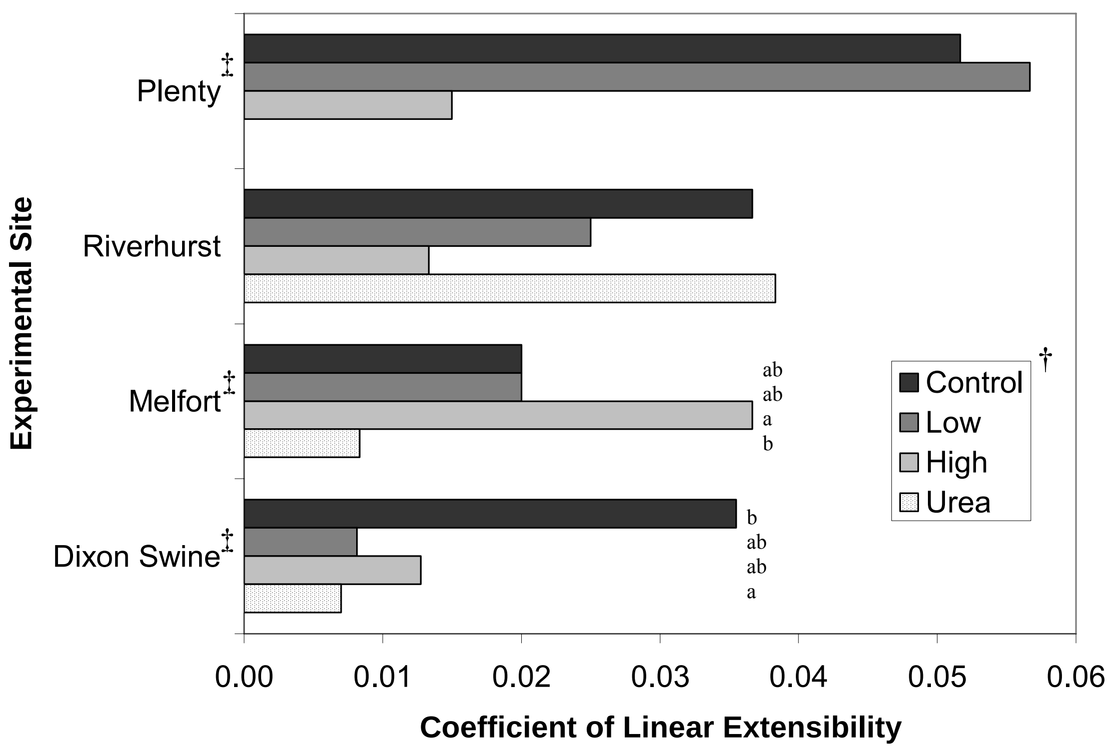


Figure 4.28 Coefficient of linear extensibility for four treatments at each of the four swine manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 95% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.
‡ Data does not conform to a normal distribution for this site.

None of the sites had soils that consistently formed briquets stable enough to test for modulus of rupture. It would seem that crusting is not a serious issue for these soils, regardless of whether manure is applied or not.

4.4 Comparison of Results from Manured Study to Soils with Known Structural Limitations

In accordance with recommendations from Prof. Henry, a small set of survey samples were also collected from southwest Saskatchewan where structural limitations are known to exist. These soils are more susceptible to deterioration because of the soil type and the water source used on the land, directly through irrigation or indirectly by manure or sewage sludge application. They provide a contrast to the experimental sites where manure is applied at agronomic rates on ideally suitable soils. All the experiments conducted on the five experimental sites were conducted on these soils as well, and are discussed in greater detail in Appendix C. Although some of the results were not as bad as anticipated, the productivity of some of these soils has been compromised.

The crust strengths of all soils from south of Swift Current were generally higher than those observed in the experimental sites. At the RM 17 sample sites, manure appeared to cause an increase in crust strength, but below published thresholds for emergence. An irrigation expansion near Cadillac, SK caused crust strengths to increase from 43 – 312% greater than the crust strengths found on soils at a nearby non-irrigated site. At another sample site near Climax, SK, irrigated with municipal effluent, the maximum crust strength of 0.46 MPa was noted on Day 9 of the canola experiment. This is much higher than any other soil sampled and near the 0.63 MPa threshold (Arndt, 1965). The aggregate size of this site was high as well – 17.2 mm.

Flax emergence was also poor on these soils, ranging from 30 to 70%. Emergence was poorest on the Climax municipal waste site and the irrigated soil.

Attempts to measure infiltration characteristics were limited due to large macropore development along the soil and core interface. Salinity was highest on the Irrigated site, but well below threshold limits. The ESP was near 30% at the Irrigated site, approximately 10% at Climax and 9% at the Forage site in RM17. Briquet formation was more consistent on these soils, but the results were difficult to interpret.

Comparison of the soils from the manure trials to these soils indicates that the techniques employed are capable of detecting physical and chemical limitations that relate to those observed and documented as real issues in the field.

4.5 Conclusion

The objectives of the research in this chapter were to observe the treatment effects of manure application on soil conditions in cores collected from the field and exposed to a simulated rainfall. This included evaluation of surface crusting, water infiltration characteristics, and changes in important structural indices (ESP, EC, COLE and modulus of rupture), as well as emergence of two small seeded crops: canola and flax. Two manure application rates (high and low – actual rates dependent on the site) were compared to an untreated control and a urea fertilizer treatment.

Repeated applications of liquid swine manure at either low or high rates decreased soil crust strength at the Plenty, Riverhurst and Melfort sites, and increased soil crust strength at the Dixon site. However, no treatments had crust strengths above published threshold values that would be considered a problem for emergence. Swine manure application caused canola emergence to decrease at Melfort, and flax emergence to decrease at Riverhurst compared to the control, and produced higher emergence of flax than urea fertilizer at the Dixon site. Overall, based on the results at these four swine manure sites, the surface soil crusting would not yet be a concern related to repeated manure application at agronomic rates.

After repeated applications of liquid swine manure, EC increased slightly at the Plenty and Riverhurst sites. Exchangeable sodium percentage also increased slightly at the Melfort and Dixon sites. However, the increases were small and well below published threshold values at which crop growth and physical soil condition are considered to be negatively affected.

This study evaluated the effect of repeated manure applications from four to six years. Longer term effects should be evaluated and it is recommended that salinity and sodicity be monitored over time.

4.6 References

Arndt, W. 1965. The nature of the mechanical impedance to seedlings by soil surface seals. Aust. J. Soil Res. **3**:45-54.

Assefa, B. 2002. Single and repeated applications of hog and cattle manure and their effects on soil conditions and plant growth in gray luvisolic and black chernozemic soils. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 131 p.

Assefa, B.A., J.J. Schoenau, and M.C.J. Grevers. **2004.** Effects of four annual applications of manure on Black Chernozemic soils. Canadian Biosystems Engineering **46**:6.39-6.46.

Chang, C., T.G. Sommerfeldt, and T. Entz. **1991.** Soil chemistry after eleven annual applications of cattle feedlot manure. J. Environ. Qual. **20**:475-480.

Cutforth, H.W., O.O. Akinremi, and S.M. McGinn. 2001. Precipitation trends on the Canadian Prairie. p.391-395. *In* (ed.). Soils and Crops, Extension Division, University of Saskatchewan, Saskatoon, SK. 22-23 Feb 2001.

Emerson, W.W., and A.C. Bakker. **1973.** The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. Aust. J. Soil Res. **11**:151-157.

Hendershot, W.H., H. Lalande, and M. Duquette. **1993a**. Soil reaction and exchangeable acidity. p. 141-146. *In* M. R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers, Anne Arbor, MI.

Hendershot, W.H., H. Lalande, and M. Duquette. **1993b**. Ion exchange and exchangeable cations. p. 167-176. *In* M. R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers, Anne Arbor, MI.

Henry, L. 2003. Henry's handbook of soil and water Houghton Boston, Saskatoon, SK. pp.218

Henry, L., B. Harron, and D. Flaten. **1992**. The nature and management of salt-affected land in Saskatchewan). Saskatchewan Agriculture.

Hogg, T.J., and J.L. Henry. **1984.** Comparison of 1:1 and 1:2 suspensions and extracts with the saturation extract in estimating salinity in Saskatchewan soils. Can. J. Soil Sci. **64**:699-704.

Mazurak, A.P., L. Chesnin, and A.E. Tiarks. **1975.** Detachment of soil aggregates by simulated rainfall from heavily manured soils in eastern Nebraska. Soil Sci. Soc. Am. Proc. **39**:732-736.

McInnis, T.A. 2001. The effect of tillage and cropping frequency on soil crusting in the Brown Soil Zone of Saskatchewan. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 126 p.

McIntyre, D.S. 1958. Permeability measurements of soil crusts formed by raindrop soil impact. Soil Sci. **85**:185-189.

Miller, J.J., N.J. Sweetland, and C. Chang. **2002.** Soil physical properties of a Chernozemic clay loam after 24 years of beef cattle manure application. Can. J. Soil Sci. **82**:287-296.

Richards, L.A. 1953. Modulus of rupture as an index of crusting of soil. Soil Sci. Soc. Am. Proc. **17**:321-323.

Seiferling, M., and P. Boehme. **2005**. Manure Management Regulations under the Agricultural Operation Practices Act (AOPA): Implications for Agricultural Operations [Online]. Available by Alberta Agriculture and Food http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/epw9908 (posted 31 May 2005; verified 4 Feb 2007, 2007).

Shainberg, I., J.D. Rhoades, and R.J. Prather. **1980.** Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. **45**:273-277.

Shainberg, I., D. Warrington, and J.M. Laflen. **1992.** Soil dispersibility, rain properties and slope interaction in rill formation and erosion. Soil Sci. Soc. Am. J. **56**:278-283.

Sheldrich, B.H. 1984. 43-032 Shrinkage of disturbed samples (COLE rod). p. 32/1-32/2. *In* B. H. Sheldrich (ed.) Analytical methods manual 1984. Land Resource Research Institute, Ottawa, ON.

So, H.B., and L.A.G. Aylmore. **1993.** How do sodic soils behave? The effects of sodicity on soil physical behaviour. Aust. J. Soil Res. **31**:761-777.

Tattleman, P., and P.T. Willis. **1985**. Model vertical profiles of extreme rainfall rate, liquid water content, and drop-size distribution. (Environmental Research Papers, No. 928). Air Force Geophysics Laboratory, Atmospheric Sciences Division.

Tossell, R.W., W.T. Dickinson, R.P. Rudra, and G.J. Wall. **1987.** A portable rainfall simulator. Can. Agric. Engin. **29**:155-162.

Tossell, R.W., G.J. Wall, W.T. Dickinson, R.P. Rudra, and P.H. Groenevelt. **1990a.** The Guelph rainfall simulator II: Part 1 - Simulated rainfall characteristics. Can. Agric. Engin. **32**:205-213.

Tossell, R.W., G.J. Wall, R.P. Rudra, W.T. Dickinson, and P.H. Groenevelt. **1990b.** The Guelph rainfall simulator II: Part 2 - A comparison of natural and simulated rainfall characteristics. Can. Agric. Engin. **32**:215-224.

Truman, C.C., J.M. Bradford, and J.E. Ferris. **1990.** Antecedent water content and rainfall energy influence on soil aggregate breakdown. Soil Sci. Soc. Am. J. **54**:1385-1392.

USA, R.S.L. 1954. Diagnosis and improvement of saline and alkali soils U.S. Govt. Print. Off., Washington. pp.160

Wace, S.A., and C.T. Hignett. **1991.** The effect of rainfall energy on tilled soils of different dispersion characteristics. Soil Tillage Res. **20**:57-67.

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The objectives of this thesis, as stated in Chapter 1 were to:

1) Quantify soil strength (penetrability) and crop emergence under field conditions as affected by repeated additions of liquid swine manure and solid cattle manure in four contrasting soils;

2) Determine the effect in the laboratory on crusting, emergence, aggregation, surface seal, infiltration, sodicity and salinity resulting from repeated applications of liquid swine manure and solid cattle manure in four contrasting soils.

Soil samples were collected from five different experimental sites, representing the Brown, Dark Brown, Black and Grey Soil Zones in Saskatchewan. The soil associations represented include: 1) Regina clay (Plenty), 2) Birsay sandy-loam (Riverhurst), 3) Kamsack clay-loam (Melfort), and 4) Cudworth loam (Dixon). Four of the experimental sites involve application of liquid swine manure from a nearby earthen lagoon, injected into the soil annually for four to seven years. The fifth experimental site had solid cattle manure from a feedlot applied and incorporated annually for seven years. At each site there was a control treatment, two rates of manure application (N based agronomic rate and high rate), and a urea fertilizer treatment. To achieve objective one, a recording cone penetrograph was used to measure soil strength in the surface 20 cm at Dixon, Saskatchewan in the spring of 2003. Measurements were taken 20, 39 and 123 days after seeding on treatments including a control, liquid swine manure applied at 37 and 148 kL ha^{-1}, and urea applied at 112 kg N ha^{-1}. The measurements were taken after seven annual applications of manure on a Cudworth loam (Dixon) in the Black Soil Zone. The results are as follows:

- Early in the growing season, repeated application of low and high rates of manure increased soil strength at the 5 cm depth compared to the control, but did not differ significantly from the urea fertilizer treatment. Increases were small, and well below the threshold limiting root proliferation.

- In mid-summer, the low rate of manure application increased soil strength at the 10 cm depth compared to the control. The high rate decreased soil strength compared to the urea fertilizer and low rate treatments at the 15 cm depth.

- In fall, the manure application treatments had decreased soil strength at the 5 cm depth and the high application rate decreased soil strength at the 10 cm depth compared to the control. However, manure application did not cause soil strength to differ from the soil strength of the urea treatment.

- Barley emergence was unaffected by manure application compared to the control. Barley emergence was reduced slightly on the high rate treatment, compared to the urea fertilizer treatment.

Objective two was achieved by evaluating soil samples taken from each experimental site. The results are as follows:

- After simulated rainfall, soil crust strength decreased with repeated applications of liquid swine manure compared with the control, at three of the four swine manure experimental sites. At the Cudworth loam (Dixon) site, soil crust strength increased after six applications of liquid swine manure compared to the unfertilized control. For the most part, there were no differences detected between manure application rates and the urea treatment.

- Flax emergence was reduced by the low rate of manure application at the Birsay sandy-loam (Riverhurst) site compared with the control. Flax emergence of the low manure rate treatment was greater compared to the urea fertilizer treatment at the Cudworth loam (Dixon) site. Overall, there were no conclusive trends in the data to indicate that flax emergence was affected by manure application.

- There were no important differences in surface seal properties.
- Manure application at any rate did not have significant effects on soil aggregation compared to the control or urea treatments at any of the sites
- Evaluation of modulus of rupture and COLE indicated that manure application did not result in crusting, as briquets were often too fragile to measure.
- Manure application caused an increase in soil salinity and sodicity at some sites. However, increases were small and levels in the soil were well below published thresholds for impacting soil productivity.

The underlying objective of this study was to evaluate soil physical and chemical properties that would have an important influence on emergence, seedling growth and early plant development, supported by evaluations of plant emergence and health. Overall, four to seven annual applications of liquid swine manure did not cause soil parameters to exceed published threshold values and cause plant harm. As there were no substantial differences in plant emergence or health compared to the control, or the urea fertilizer treatment, the application of liquid swine manure does not appear to have any negative impacts on soil physical or chemical properties after four to seven years of application.

This study showed that the application of liquid swine manure to four soils did not cause any measured parameters to exceed published thresholds that would cause plant harm. However, there were trends showing that repeated applications must be monitored for potential environmental harm. Two parameters that need to be monitored regularly are salinity (EC) and sodicity (SAR/ESP). The survey samples from southern Saskatchewan with known structural limitations serve as a warning of a worst case scenario. The variability of soils and manure sources was also apparent in the study, showing that each situation must be analyzed as unique due to inherent differences in manure composition and soil type. Although this study should not be applied directly to any soil or any manure source without analyzing manure composition and soil type, agronomic rates of liquid swine manure application were safe for the soils studied after four to seven years of application.

Nutrients that are removed in harvest should be replaced based on soil test results. Manure provides an alternative choice for farmers to replenish soil fertility, but plant available nutrients are not the only measurements that need to be taken regularly in manured soils. More work is needed to gain a more comprehensive understanding of the effects of manure application over many years on various soil types (associations) and with varied manure sources, including other types like dairy and poultry, as well as composts and digestates. Some specific measurements that will improve our understanding of soils fertilized with liquid swine manure include: salinity and sodicity measurements of the crust region (surface 5 mm), field infiltration rate throughout the season, analysis of runoff water quality, and water and wind stable aggregates.

CHAPTER 6

APPENDICES

6.1 Appendix A: Thesis Data

Table 6.1 The particle size distribution of the four experimental sites as determined by a Horiba particle size analyzer in 2006.

Experimental Site	Sand	Silt	Clay
	-----------%-----------		
Plenty	15.1	45.8	39.1
Riverhurst	56.7	34.4	8.8
Melfort	32.3	40.8	26.9
Dixon (Swine and Cattle)	46.9	44.9	8.1

Table 6.2 Crop rotations used at the four experimental sites since inception.

Site	Plenty	Riverhurst	Melfort	Dixon
Year		Crop		
2003	Wheat	Wheat	Canola	Barley
2002	Crop failure	Crop failure	Oat	Flax
2001	Wheat	Barley	Canola	Wheat
2000	Canary seed	Barley	Wheat	Canola
1999	Wheat	Pinto beans	--	Barley
1998	--	--	--	Wheat
1997	--	--	--	Canola

Table 6.3 Nutrient concentrations in manure applied for the 2003 growing season.

Experimental Site	Total N	NH_4	NO_3	Total P	Available P	K	Ca	Mg	Cu	Fe	Mn	Zn	S	Na
	ug/g wet manure													
Dixon Cattle (Spring 2003)	5330			1650		3433	9253	3638	17.5	739	67	33	1360	750

Experimental Site	Total N	NH4	NO3	Total P	Available P	K	Ca	Mg	Cu	Fe	Mn	Zn	B	Na
	ug/ml													
Dixon Swine (Spring 2003)				77		1113	447	89	1.2	28	3.1	4.5	1	510
Melfort (Fall 2002)	3119	2055		41	2.3	1053	388	124	0.54	10	1.23	0.4	1.5	414
Plenty (Fall 2002)	2758	1476		136	9.1	1148	218	61	0.87	25.7	1.39	2.9		912
Riverhurst (Fall 2002)	3354	2025		122	9	1320	184	62	1.3	17	1.6	4		422

Table 6.4 Mean gravimetric soil moisture contents measured in correspondence with soil penetrability 20, 39 and 123 days after seeding (DAS) at the Dixon site.

Manure	Rate	20 DAS†		39 DAS		123 DAS	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
				% (g g^{-1})			
Dixon Cattle	**Low**	22.6	0.017	13.0	0.018	18.5	0.014
	High	22.1	0.021	14.8	0.021	18.7	0.012
Dixon Hog	**Control**	18.3	0.036	13.8	0.022	15.7	0.016
	Low	19.6	0.026	11.9	0.027	16.9	0.013
	High	18.3	0.014	12.4	0.019	15.2	0.015
	Urea	17.5	0.024	12.2	0.022	15.2	0.017

† Days After Seeding

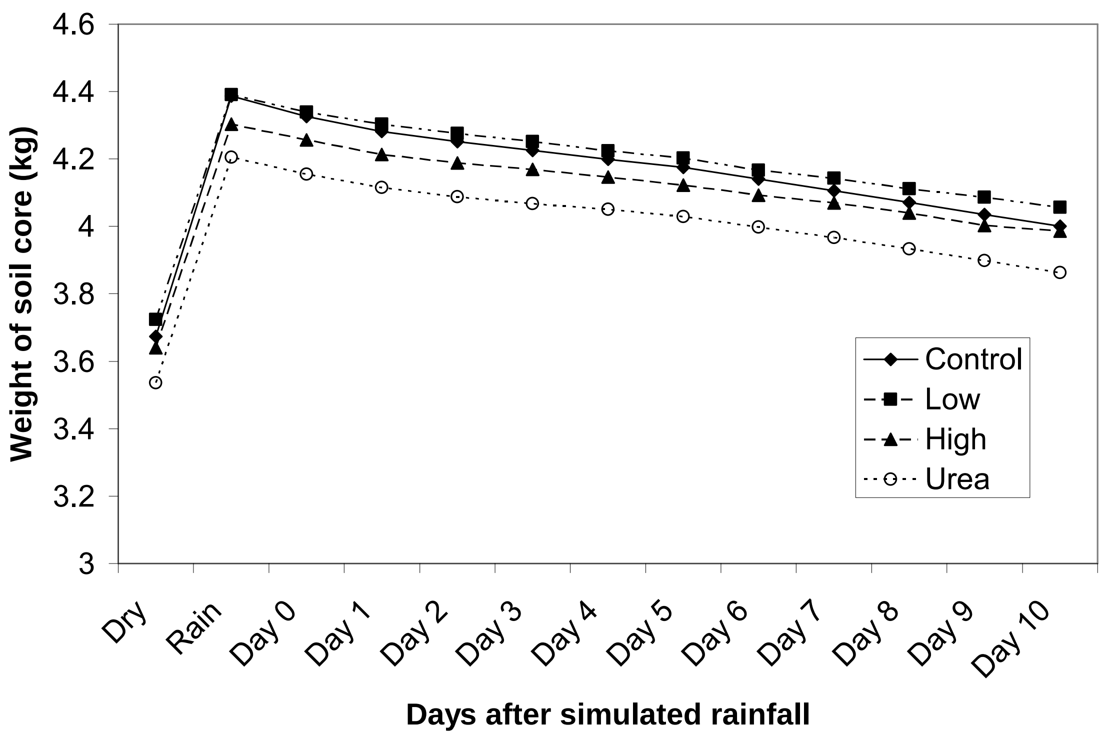


Figure 6.1 Weights of the soil cores before, and for 10 days after, the simulated rainfall event on the Plenty soils during the canola crust strength and emergence experiment.

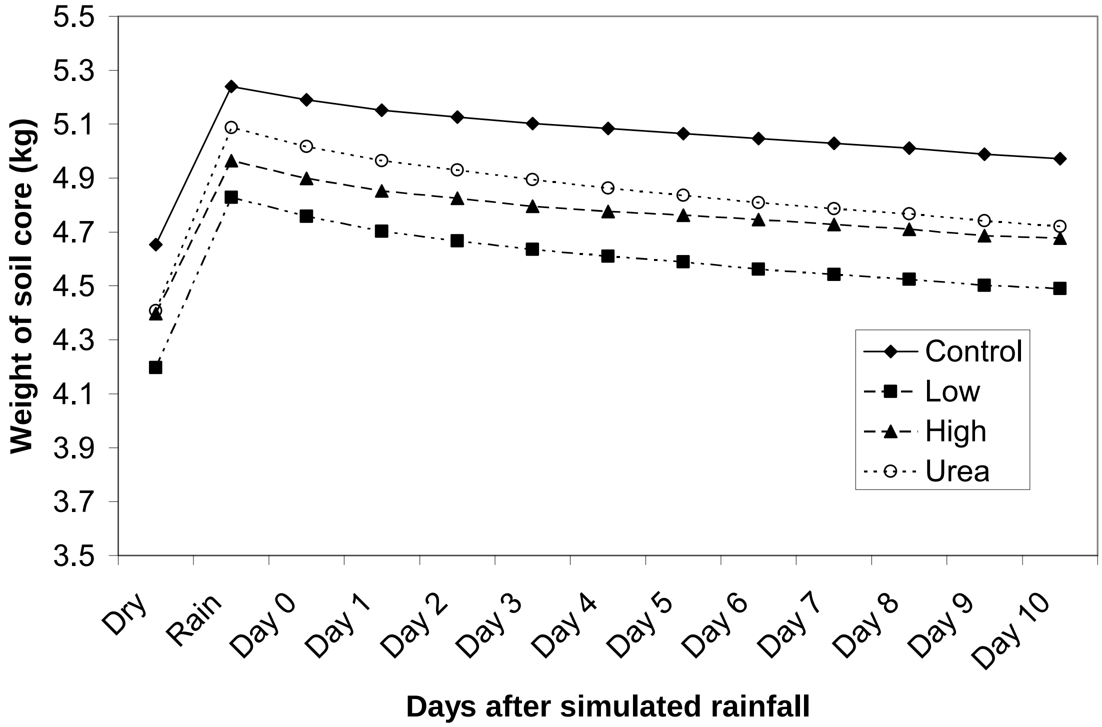


Figure 6.2 Weights of the soil cores before, and for 10 days after, the simulated rainfall event on the Riverhurst soils during the canola crust strength and emergence experiment.

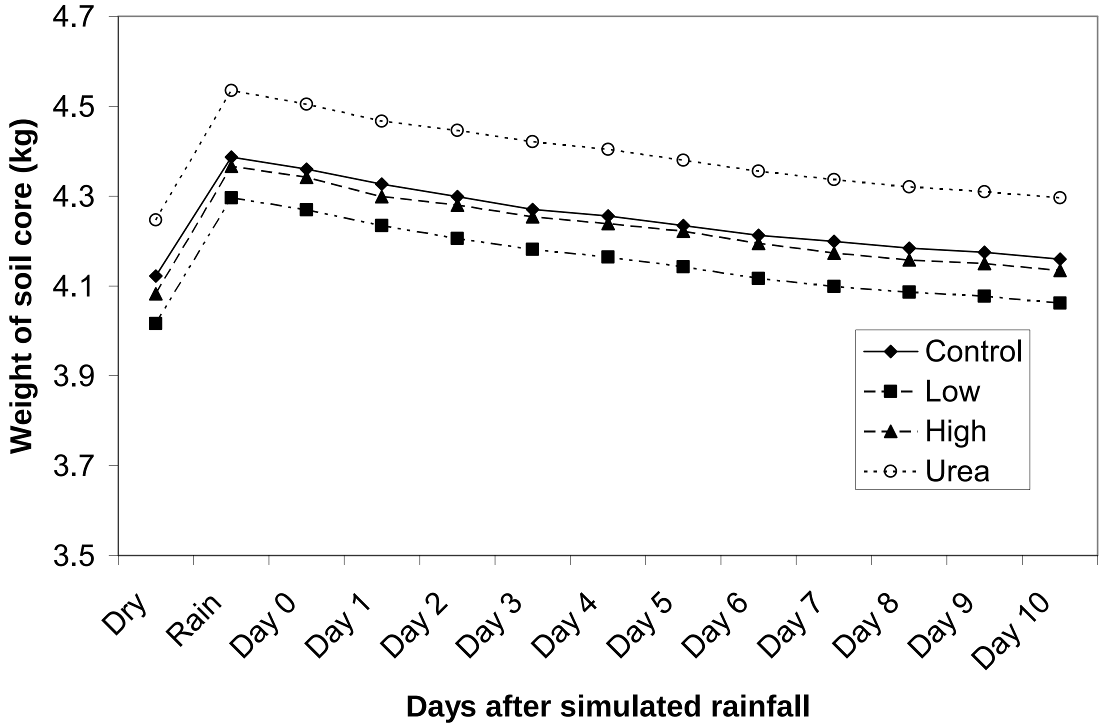


Figure 6.3 Weights of the soil cores before, and for 10 days after, the simulated rainfall event on the Melfort soils during the canola crust strength and emergence experiment.

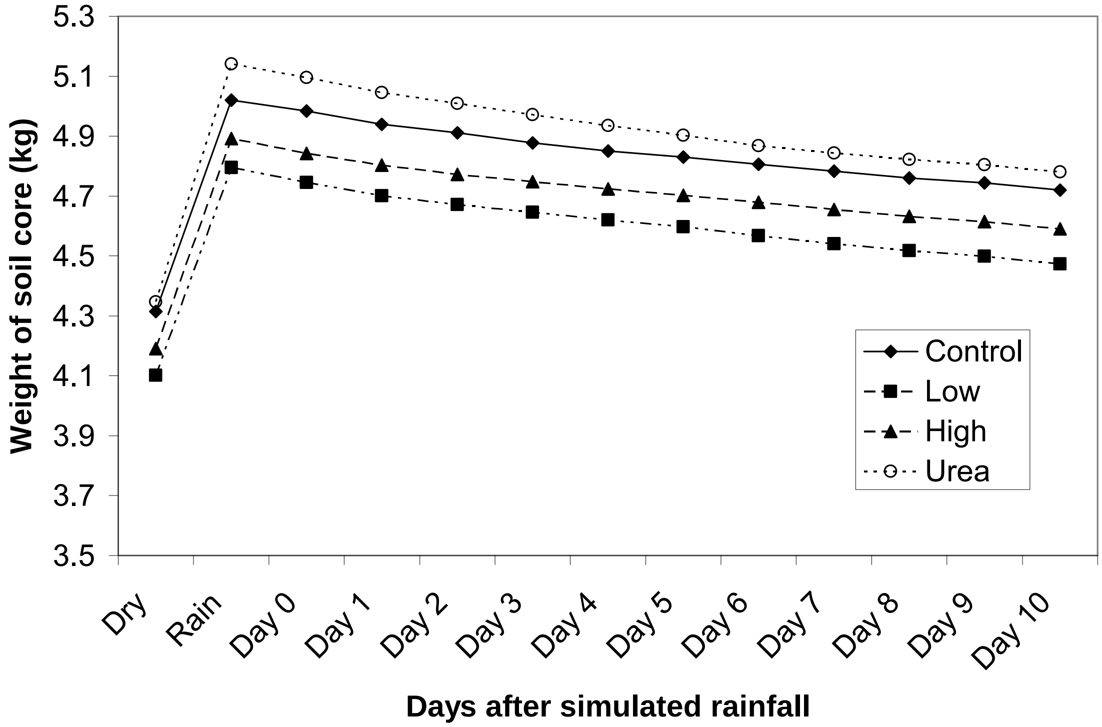


Figure 6.4 Weights of the soil cores before, and for 10 days after, the simulated rainfall event on the Dixon Swine manured soils during the canola crust strength and emergence experiment.

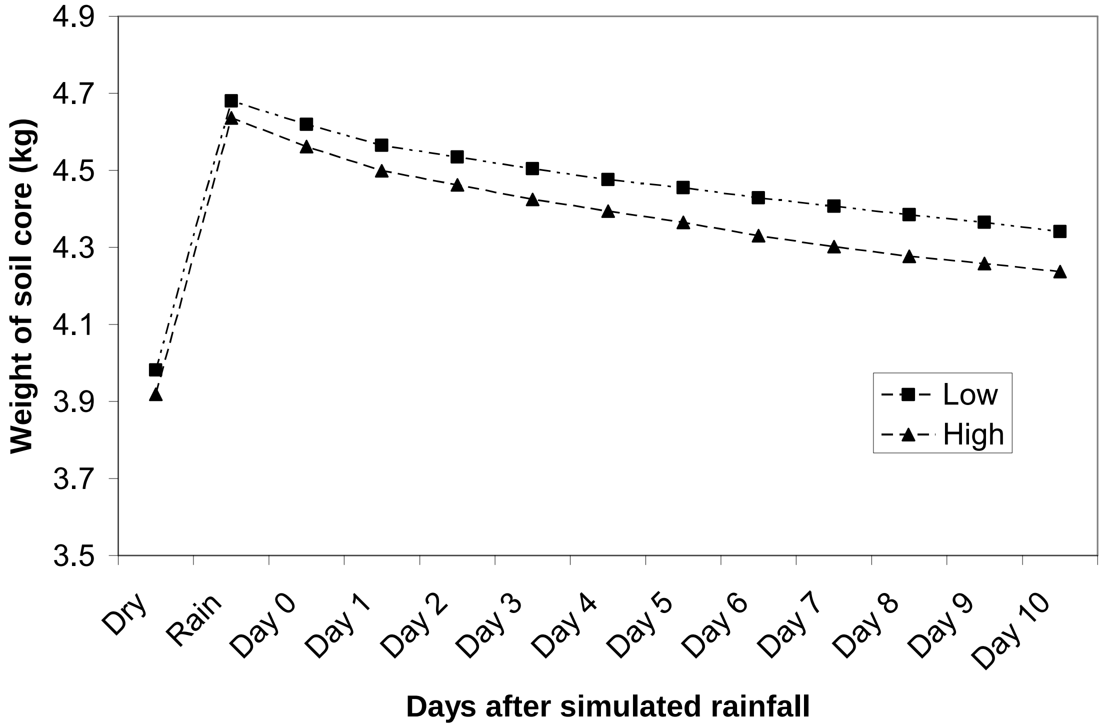


Figure 6.5 Weight of the soil core before, and for 10 days after, the simulated rainfall event on the Dixon Cattle manured soils during the canola crust strength and emergence experiment.

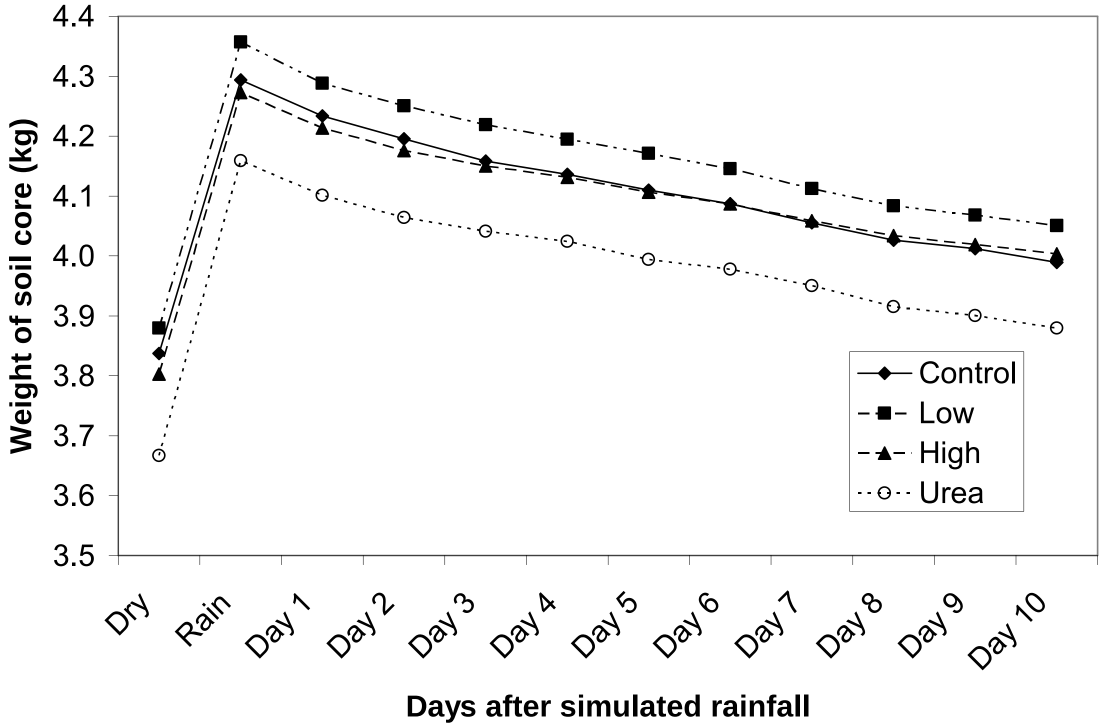


Figure 6.6 Weight of the soil core before, and for 10 days after, the simulated rainfall event on the Plenty soils during the flax crust strength and emergence experiment.

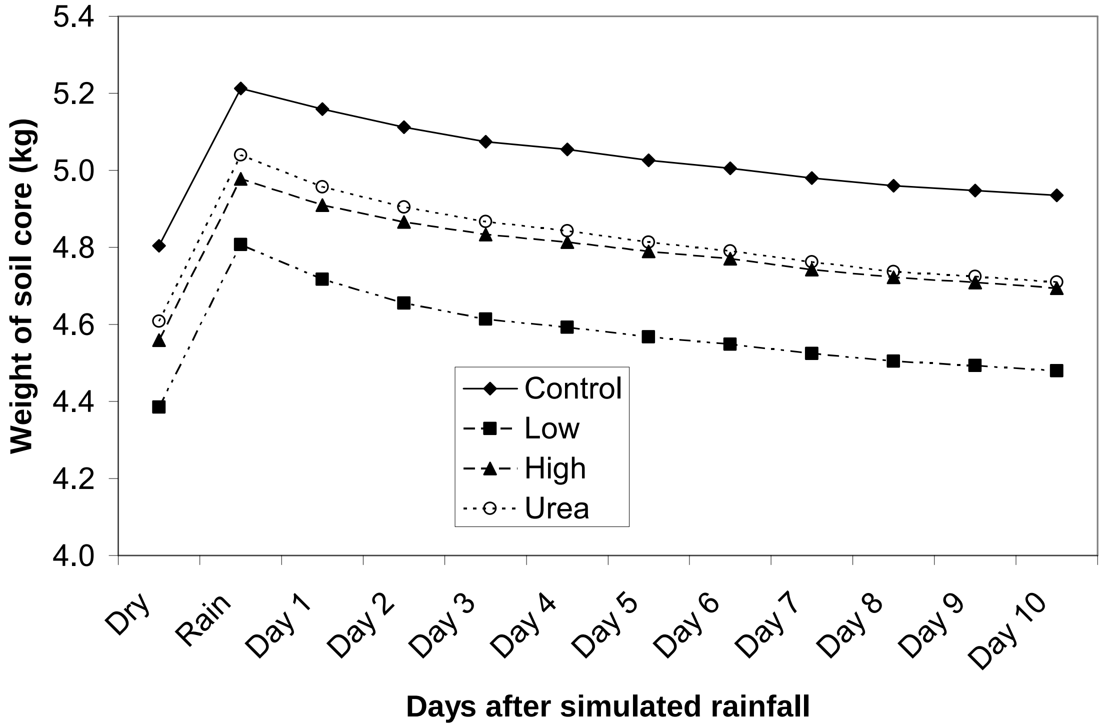


Figure 6.7 Weight of the soil core before, and for 10 days after, the simulated rainfall event on the Riverhurst soils during the flax crust strength and emergence experiment.

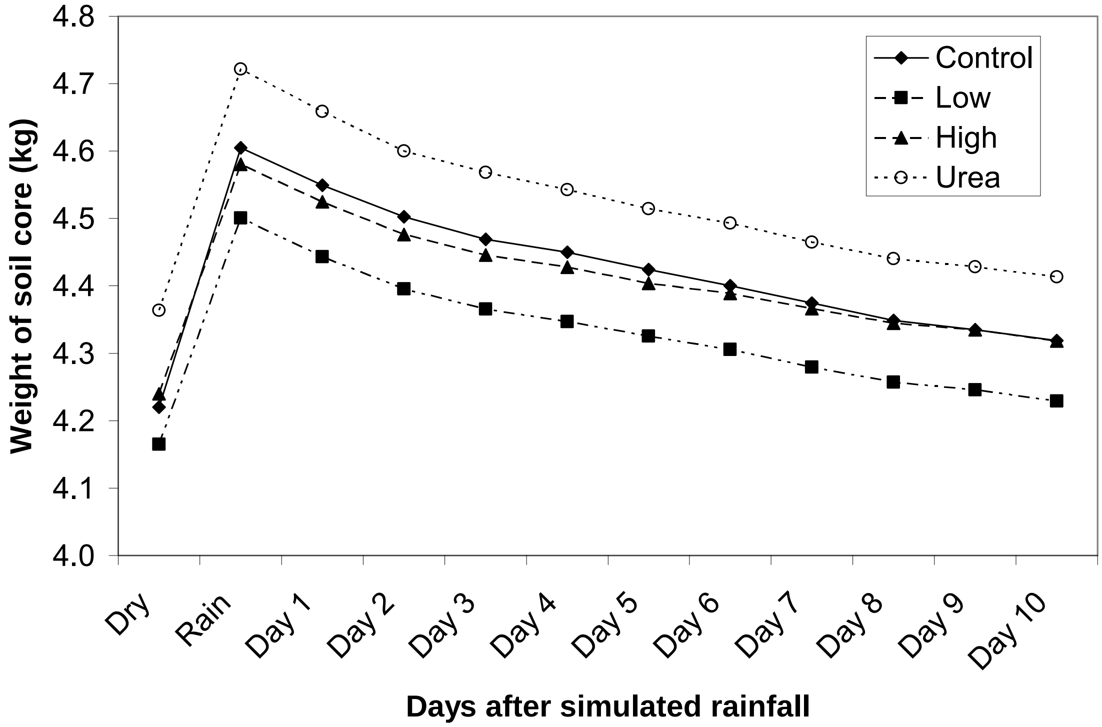


Figure 6.8 Weight of the soil core before, and for 10 days after, the simulated rainfall event on the Melfort soils during the flax crust strength and emergence experiment.

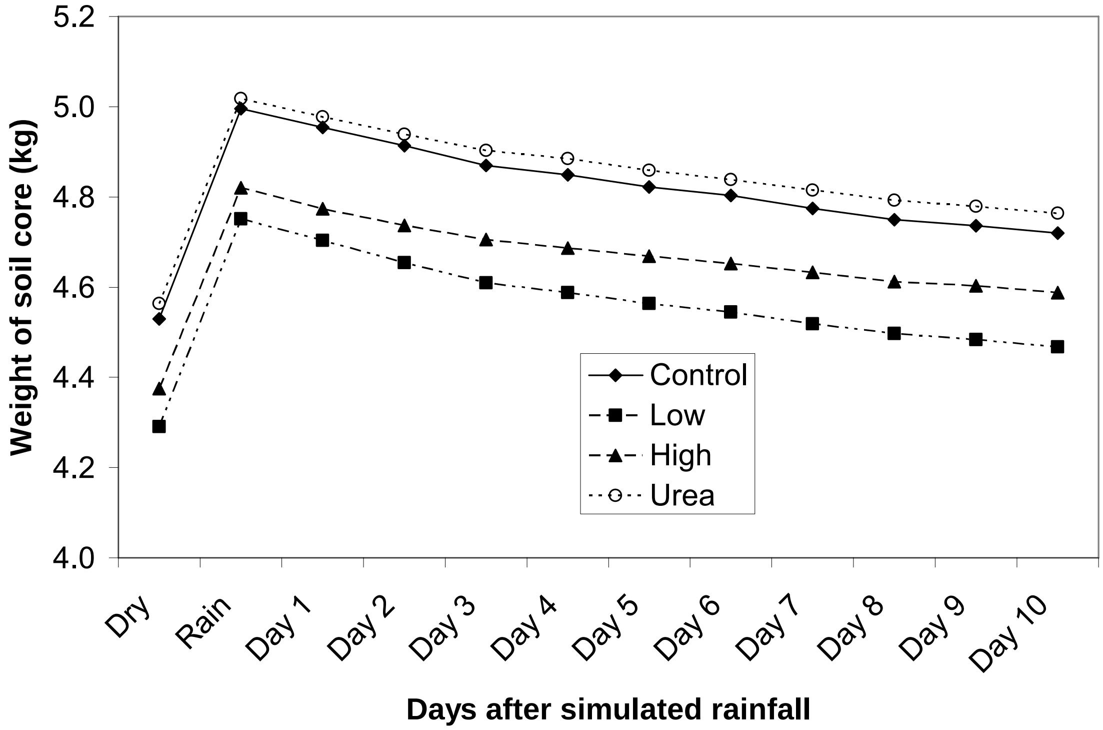


Figure 6.9 Weight of the soil core before, and for 10 days after, the simulated rainfall event on the Dixon Swine manured soils during the flax crust strength and emergence experiment.

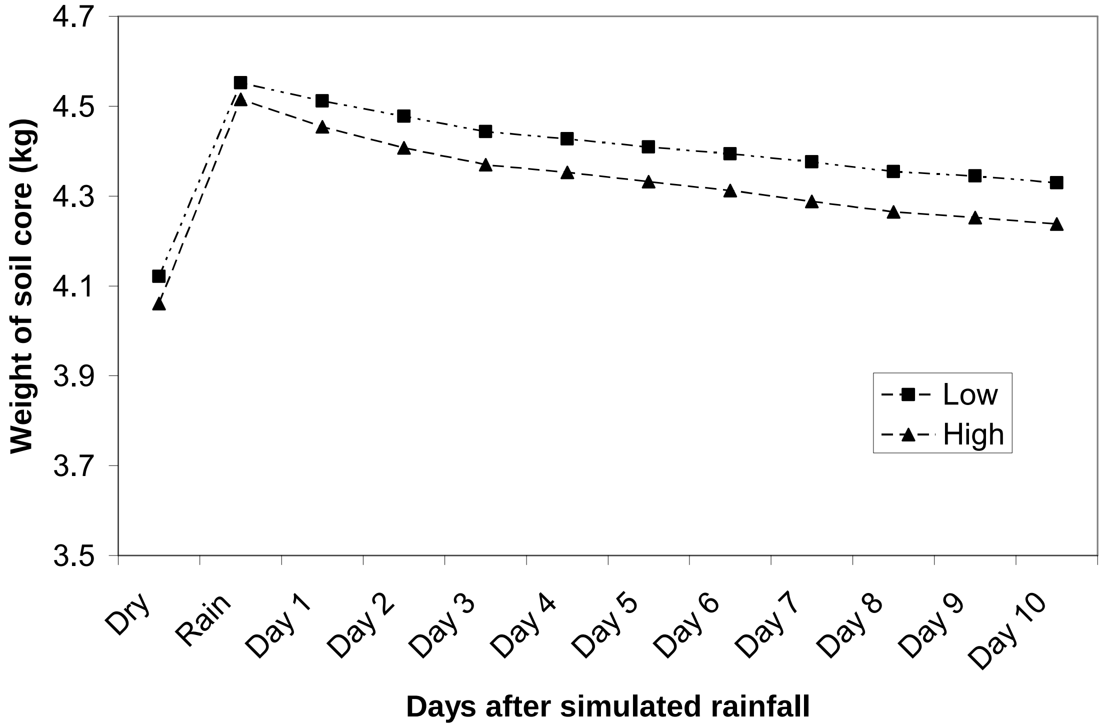


Figure 6.10 Weight of the soil core before, and for 10 days after, the simulated rainfall event on the Dixon Cattle manured soils during the flax crust strength and emergence experiment.

Table 6.5 Cation exchange capacity of the soil after four to six years of manure application at the five experimental sites.

	Plenty	Riverhurst	Melfort	Dixon Swine	Dixon Cattle
	---------------cmol(+) kg^{-1}---------------				
Control	43.47	14.63	29.34	27.23	n/a
Low	43.37	14.38	30.64	24.09	26.07
High	42.43	14.03	29.50	24.74	29.51
Urea	39.07	14.27	29.42	28.10	n/a

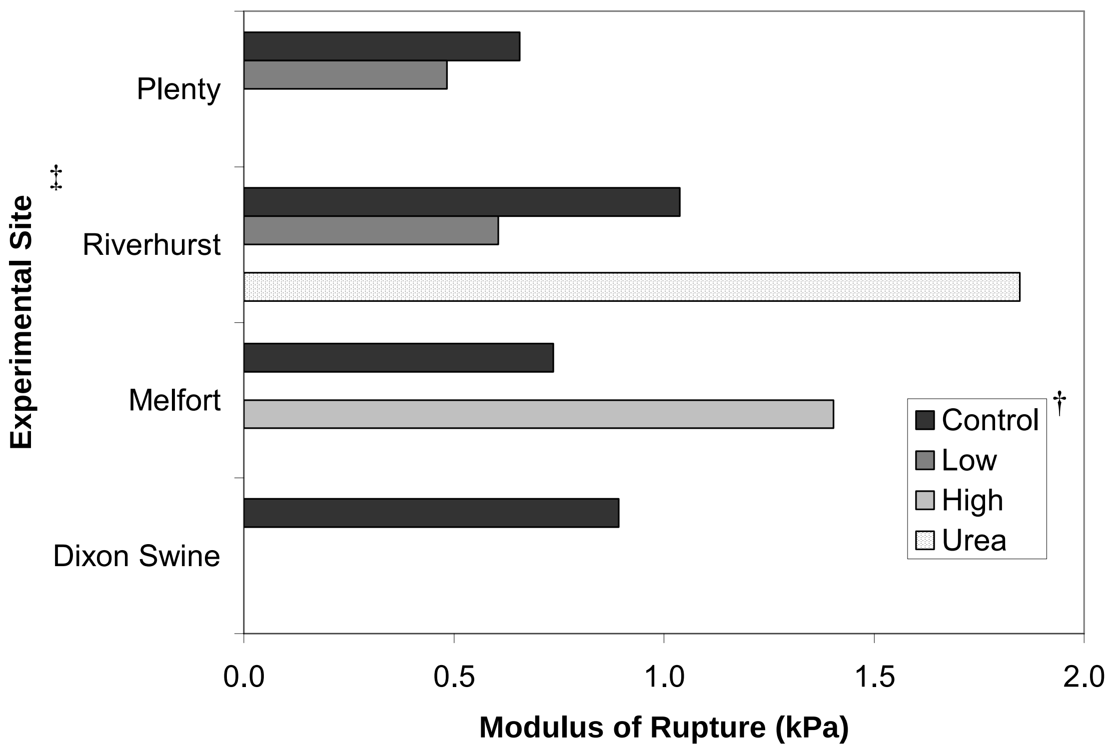


Figure 6.11 Modulus of rupture for four treatments at each of the four hog manure and one cattle manure experimental sites.

* For a given measurement day, bars with different letters are significantly different at the 95% confidence level according to Least Significant Differences. n = 3 (Plenty, Riverhurst, Melfort and Dixon Cattle); n = 4 (Dixon Swine). Bars without letters are not significantly different. There are no statistical comparisons drawn between sites.
† Low and High refer to the application rate of manure. Urea refers to the treatment that had N applied as urea. Control had no fertilizer or disturbance. For further detail, refer to Table 3.1.
‡ Data does not conform to a normal distribution for this test.

6.2 Appendix B: Soil Temperature at Dixon

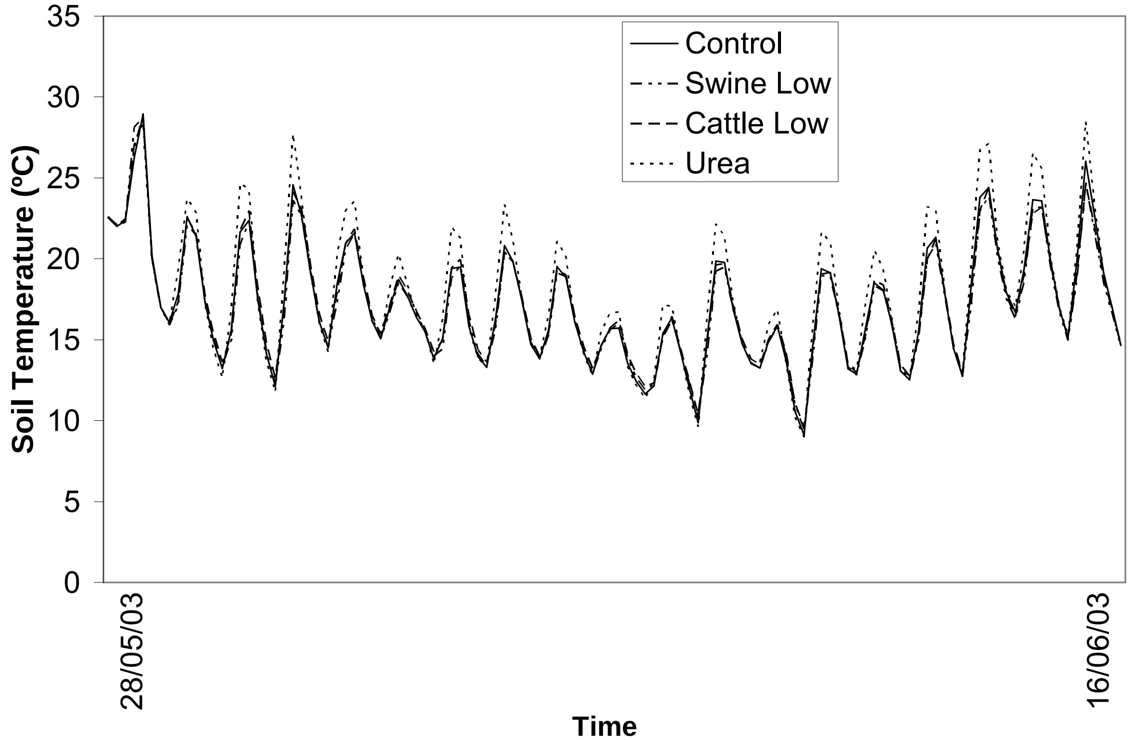


Figure 6.12 Soil temperature logged on four different treatments from May 28, 2003 to June 16, 2003. Data loggers were placed 6-7 cm below the soil surface.

6.3 Appendix C: Soils Damaged by Sodic Water Sources in Southwest Saskatchewan

In accordance with recommendations from Prof. Henry, a small set of survey samples were collected from southwest Saskatchewan in May 2003. These soils are more susceptible to deterioration from liquid swine manure application, or have already been damaged by an amendment of either manure, sewage sludge or poor quality water to the soil. Part of the reason for increased potential for damage is that the Judith River formation is a common source of water for swine barns. The high Na concentration in water from the Judith River formation results in a high Na concentration in the manure, increasing the potential for sodification.

The soils collected in this survey sample provide a contrast to the experimental sites. All the measurements and tests conducted on the five experimental sites were conducted on these soils as well. If analytical methods are sensitive in revealing physical and chemical limitations as they are actually manifested in the field, the value for parameters should approach or exceed thresholds for these soils. Although some of the results were not as bad as anticipated, the productivity of some of these soils has been severely compromised. There were three areas sampled (Table 6.4).

Near Cadillac, SK (Irrigated / Non-Irrigated) we sampled a site that had been irrigated from 1980 to 1986 with water from the Bull Creek. Since 1986, the irrigated portion of the land has been unproductive. We also sampled soil that had not received irrigation. In the 1980's, when the land started losing productivity, and water was not infiltrating, the investigation found that the actual Na levels in Bull Creek were very high. In the spring, snowmelt runoff diluted the water in the creek and when sampled it was found to be suitable for irrigation. In 1980, the SAR in the 0-30 cm depth was 1.3 and in 1986 it was 15.0 in the 0-15 cm depth and 20.9 in the 15-30cm depth. We also tried to measure soil resistance in the field, but the penetrometer would not enter beyond 10cm.

Near Climax, SK we sampled a site that had been irrigated with municipal sewage sludge. The area the sludge had been applied to in the mid to late 1980's had been abandoned, but there was some grass growing. At this site, the SAR in the 0-30cm depth was 16.3 in 1988, with an EC of 6.6. The town drinking water has a SAR of 5.1, with an EC of 2.9. There was also reportedly lots of water softening, where NaCl is cheaper than the alternative KCl, but potentially more damaging when the sewage is used in this way. As a result, sodium levels were elevated in the sewage sludge and ultimately the soil it was applied to.

Table 6.6 Soil associations and textures from soils sampled in southwest Saskatchewan (Survey, 1989; Survey, 1992a; Survey, 1992b).

Site†	Soil Zone	Soil Association Dominant (Significant)	Texture
Irr / Non-Irr	Brown	Ardill (Valor)	Clay Loam – Silt Loam
Climax	Brown	Frontier (Robsart)	Clay Loam
RM 17	Brown	Frontier (Chaplin & Robsart)	Clay Loam - Loam‡

† RM 17 is located near Bracken, SK and Irr / Non-Irr are the irrigated and non-irrigated soils collected from the Cadillac, SK area.

‡ The *RM 17 No Manure* location is clay loam to a silt loam (the other two RM 17 sites are clay loam to loam).

Near Bracken, SK (RM 17) we sampled three fields where manure applied was combined from swine, dairy and poultry sources into a primary and secondary cell system. The SAR of the water source was 50.8, resulting in a SAR in the combined effluent of 25.3, with an EC of 12.5. The SAR and EC of the primary and secondary cells were believed to be equivalent. The EC was believed to be high due to high Cl levels in the feed source. None of the land has received excessive amounts of manure as none was applied prior to 1990 and there is a large land base to distribute the manure application. The manure is currently applied using a dragline system with low-disturbance coulters. An enzyme was being added to the lagoons to control the smell, which may have an influence on the nutrient availability of the manure. One field was sampled that had received manure for the first time in the fall of 2002. We sampled a nearby forage field that was in smooth and meadow brome grass for 10 years. The field has received manure every year since 1990 from the secondary cell. This soil appeared to have superb tilth and had very low penetration resistance. The third field has never had manure applied. The stubble field had deposition of soil on the surface resulting in a deep profile, including a secondary A horizon.

The crust strengths of all soils from southwest Saskatchewan were generally higher than those observed in the experimental sites (Figure 6.12 and Figure 6.13). At the RM 17 sample sites, manure appeared to cause an increase in crust strength, but sound agronomic practises resulted in crust strengths below published thresholds that would hinder plant emergence. An irrigation expansion near Cadillac, SK caused crust strengths to increase from 43 – 312% greater than crust strengths found on soils at a nearby non-irrigated site. At another sample site near Climax, SK, irrigated from municipal effluent, the soil had a maximum crust strength of 0.46 MPa on Day 9 of the canola experiment. This is much higher than any other soil sampled and near 0.63 MPa threshold (Arndt, 1965). The aggregate size of this site was high as well: 17.2 mm (Table 6.5).

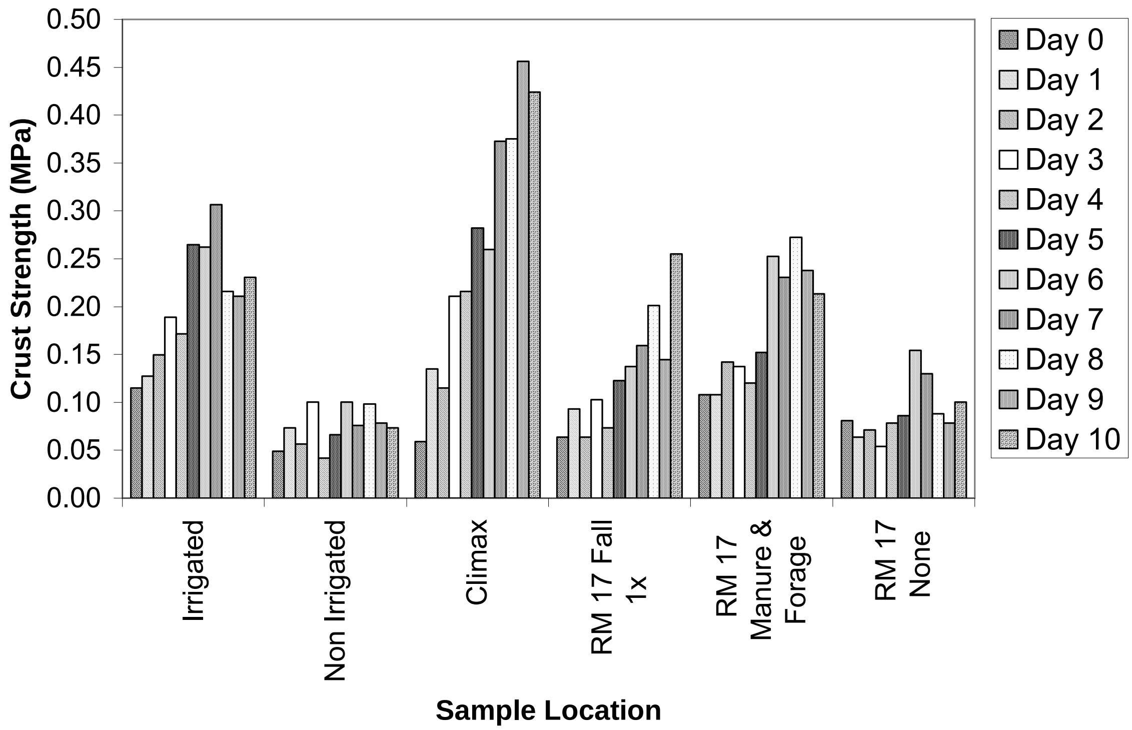


Figure 6.13 Soil crust strength for the southwest Saskatchewan survey samples for the canola emergence and crusting experiment.

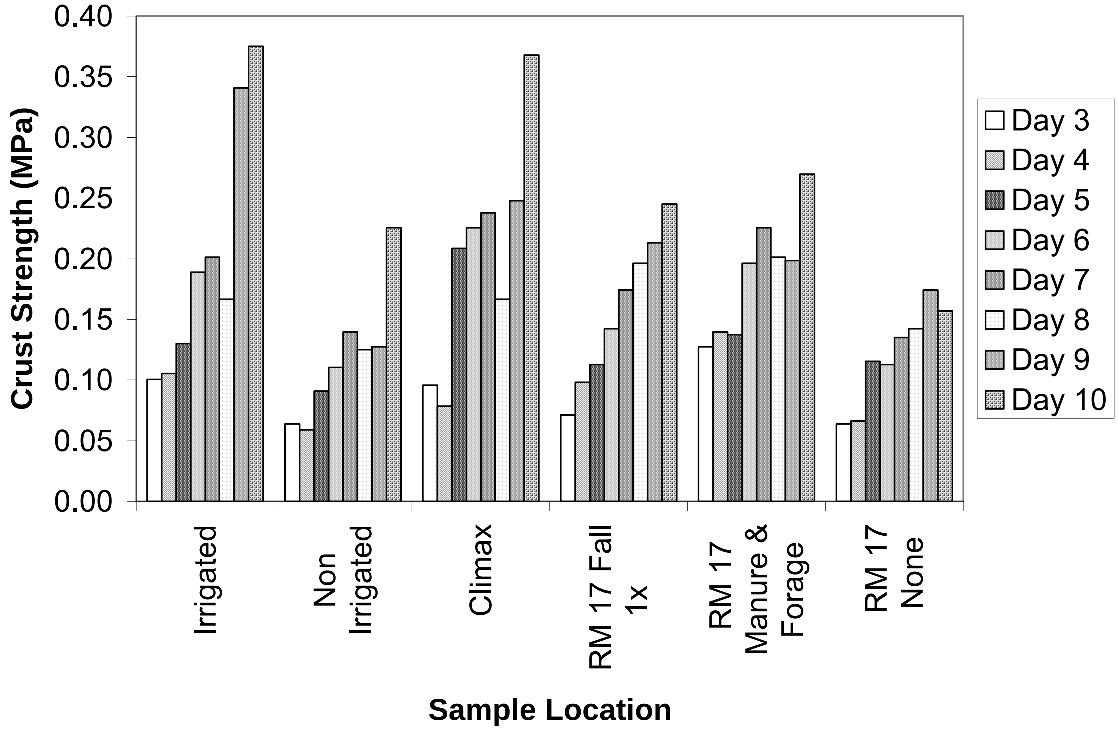


Figure 6.14 Soil crust strength for the southwest Saskatchewan survey samples for the flax emergence and crusting experiment.

Overall, the plant health during the canola experiment was poor at all locations (Table 6.5). Flax emergence was poor on these soils, ranging from 30 to 70%. Emergence was poorest on the Climax municipal waste site and the irrigated soil. Emergence was better where either no manure was received.

Table 6.7 Emergence, plant health quality and aggregate size for the southwest Saskatchewan survey samples.

	Canola ratings	Flax Emergence	Flax Weight	MWD
			g	mm
Irrigated	1.00	3.00	0.01	8.41
Non Irrigated	1.00	7.50	0.03	6.77
Climax	0.50	3.00	0.01	17.21
RM 17 Fall 1x	2.00	6.00	0.03	10.63
RM 17 Manure & Forage	2.00	4.50	0.02	7.35
RM 17 None	2.50	7.00	0.03	10.77

Attempts to measure infiltration characteristics were limited due to large macropore development along the soil and core interface (Figure 6.14, Figure 6.15 and Figure 6.16).

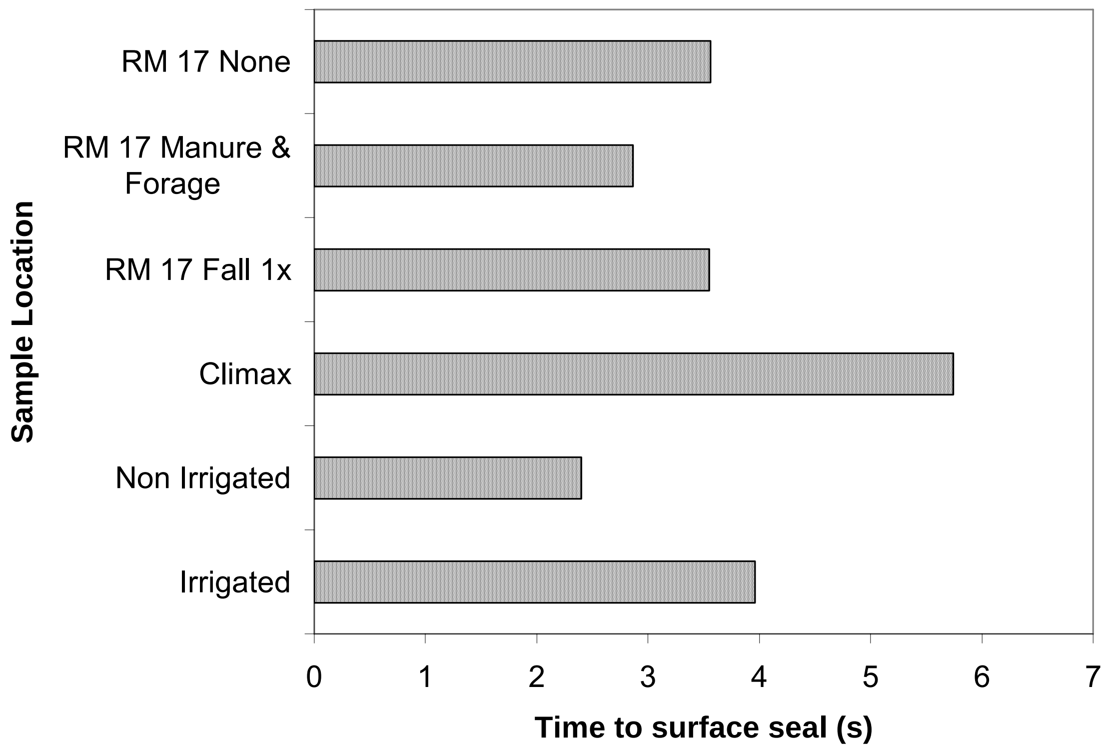


Figure 6.15 Time for the soil surface to seal and allow water to start ponding on the surface for the soils collected for survey.

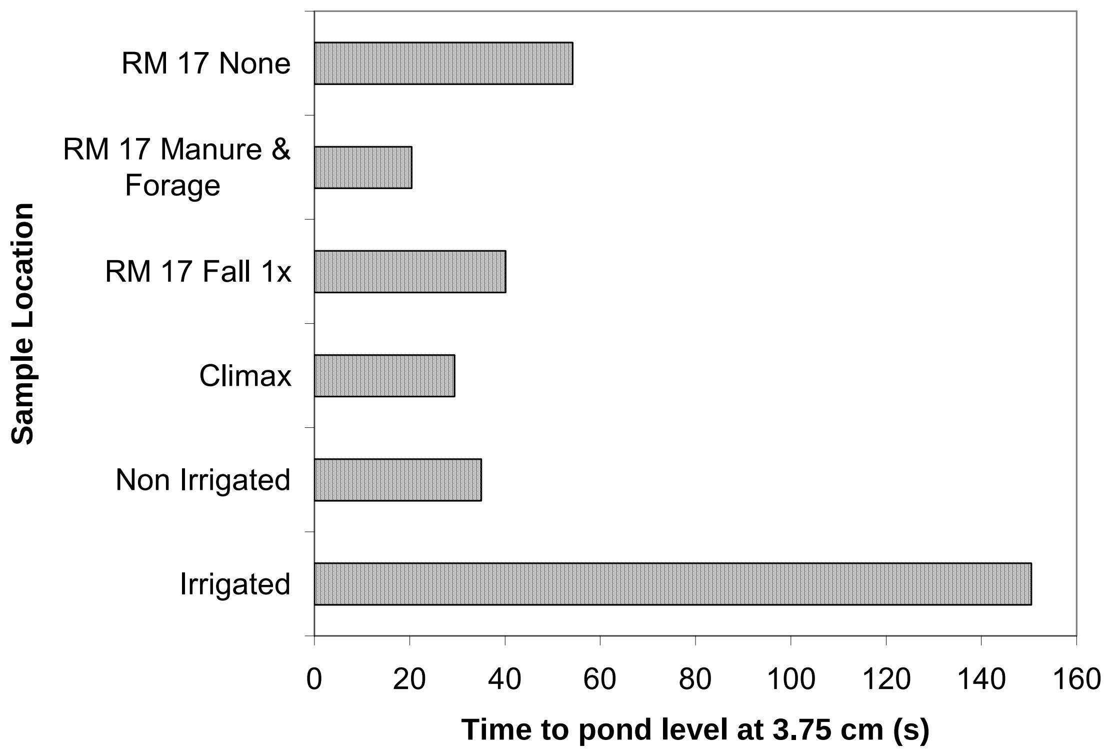


Figure 6.16 Time for the ponded water to reach 3.75 cm above the soil surface for the soils collected for survey.

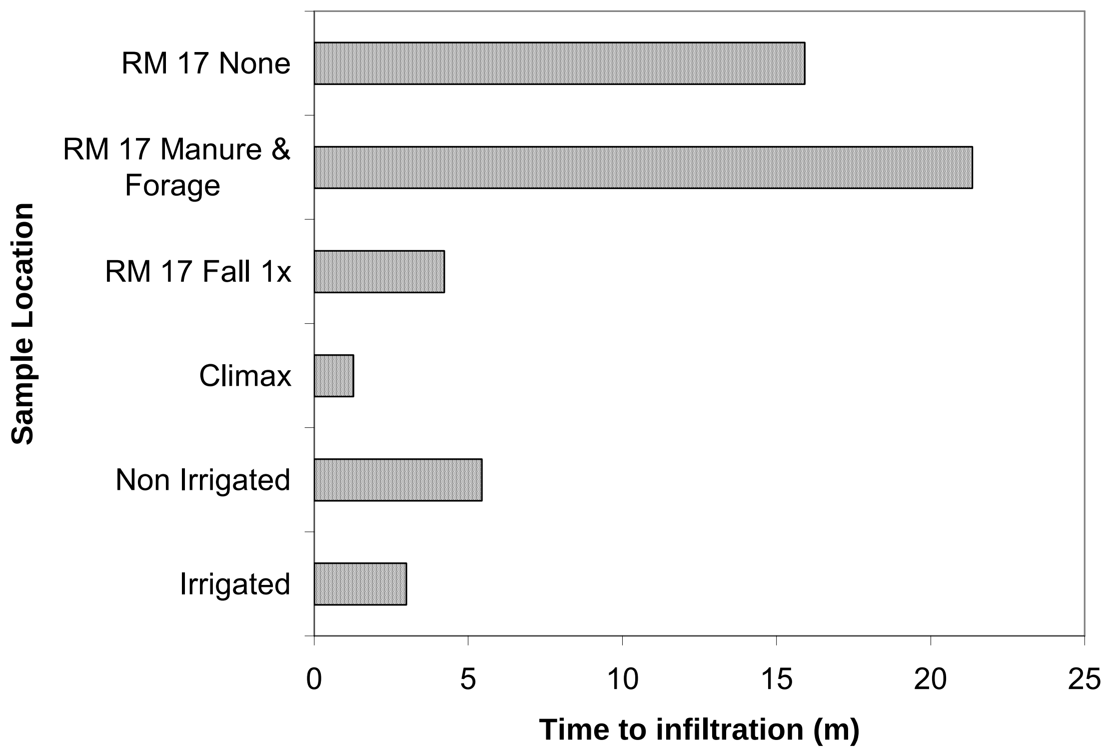


Figure 6.17 Time for the ponded water to completely infiltrate into the soil for the soils collected for survey.

To convert the EC measurements to the standard saturated extract values, all soils were considered medium textured (Hogg and Henry, 1984). Salinity was highest on the Irrigated site, but well below threshold limits. There appears to be a small increase in salinity after manuring soils in RM 17 (Figure 6.17). Exchangeable sodium percentage at the Irrigated site was 29.6%, 9.4% at Climax and 6.7% at the Forage site in RM17. As ESP increases from 2% to 4% with one manure application and to nearly 7% with several manure applications on forage, sodification is occurring at the RM 17 site. All levels are still below thresholds.

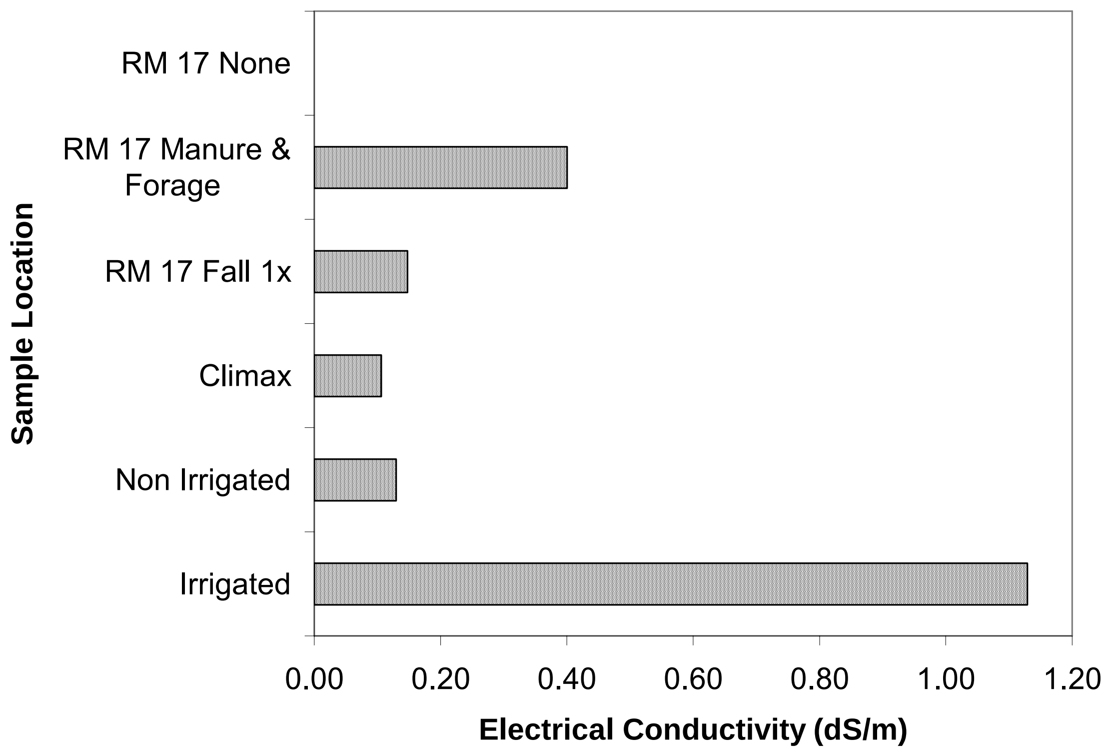


Figure 6.18 Electrical conductivity (EC) for the southwest Saskatchewan survey soils. Values presented are based on saturated extract values (Hogg and Henry, 1984).

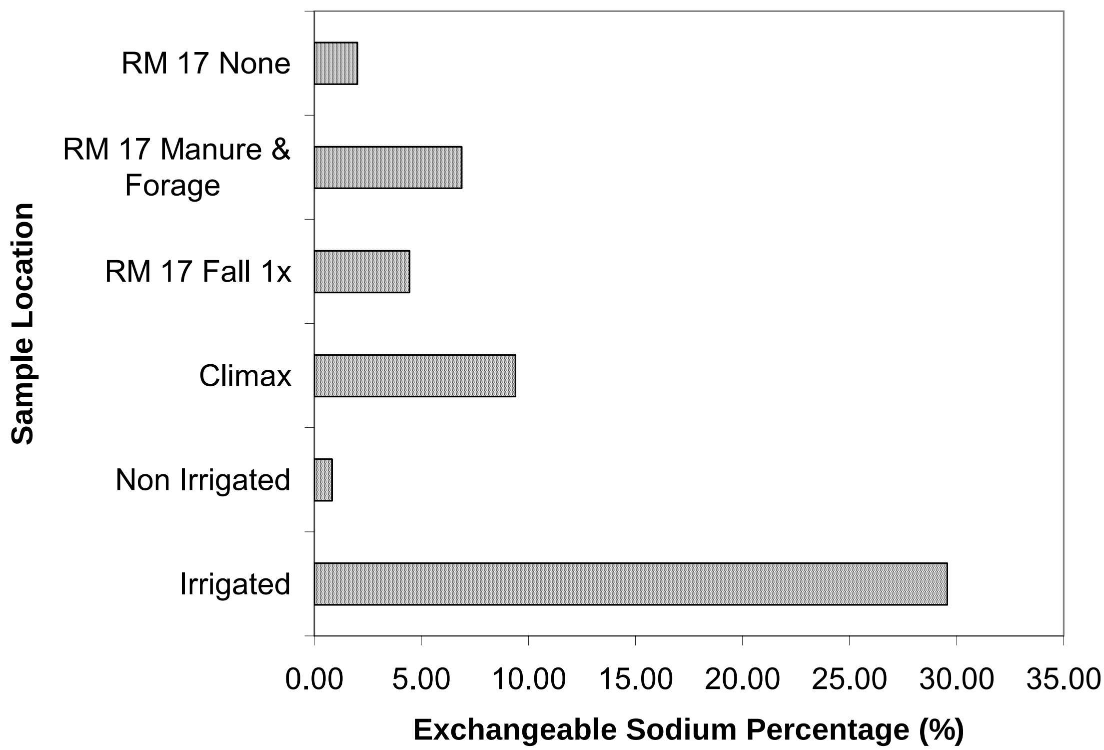


Figure 6.19 Exchangeable sodium percentage (ESP) for the southwest Saskatchewan survey soils.

Briquet formation was more consistent on these soils, but the results of the modulus of rupture and COLE experiments were difficult to interpret due to lack of replication and proper controls (Figure 6.19 and Figure 6.20). It is clear that the Irrigated site has increased rupture strength over the Non-Irrigated soil by approximately four times. There were no clear differences in linear extensibility.

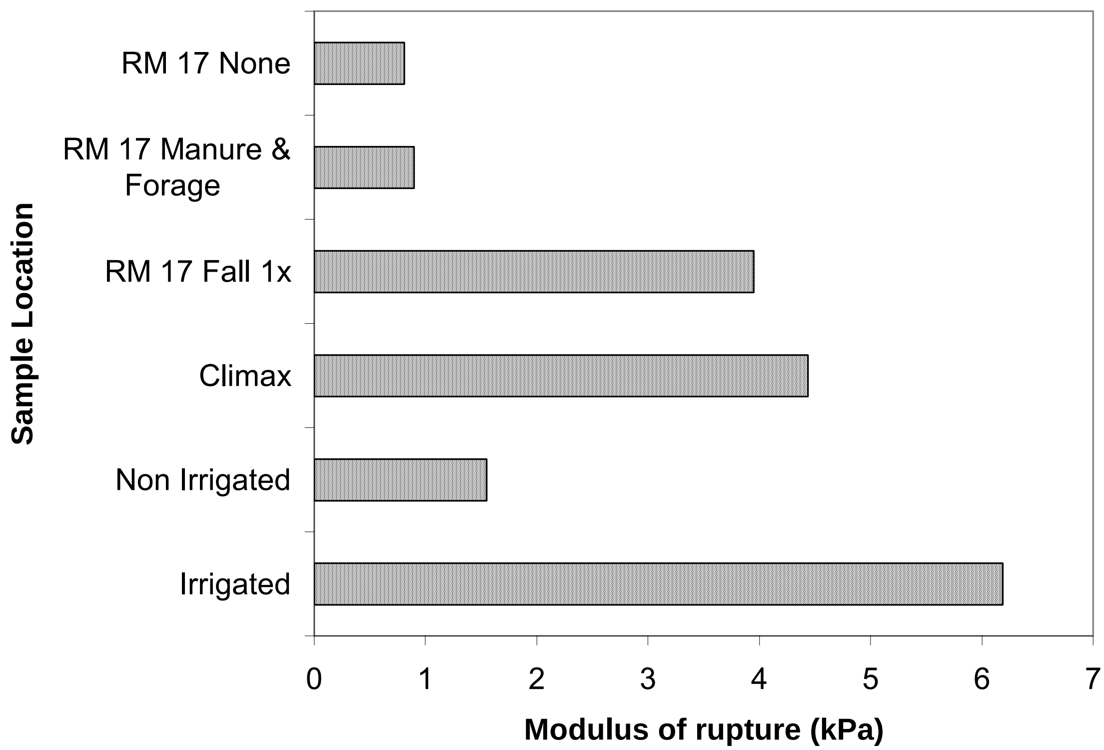


Figure 6.20 Modulus of rupture for the southwest Saskatchewan survey soils.

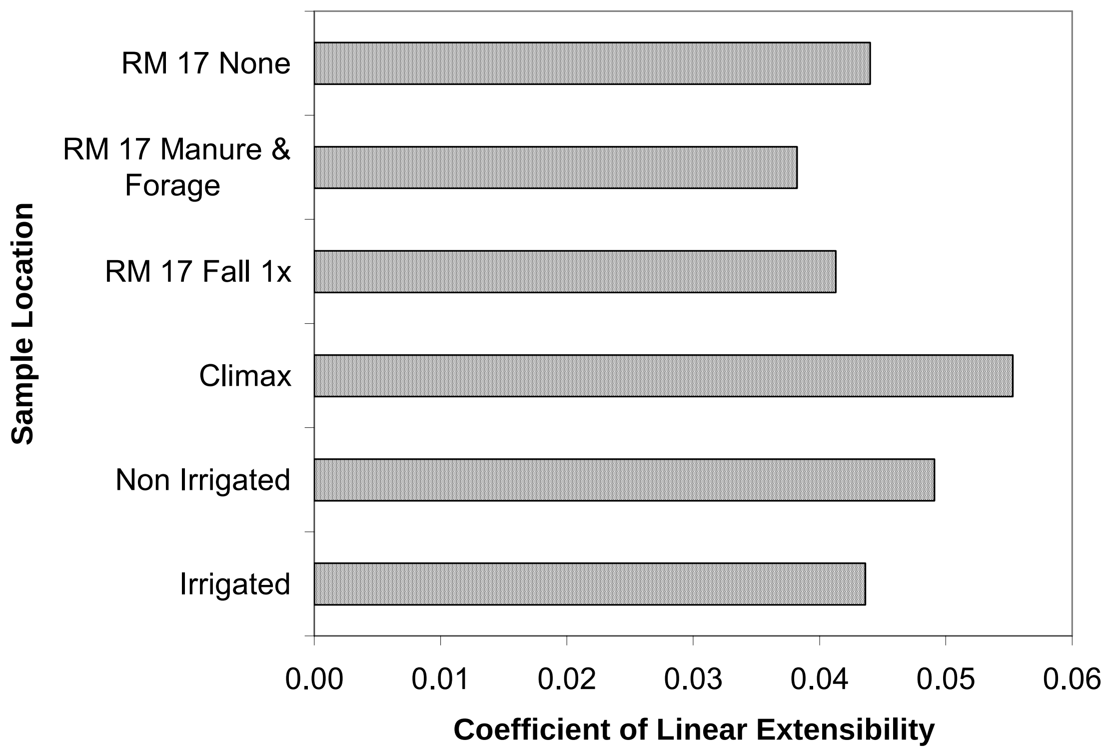


Figure 6.21 Coefficient of linear extensibility for the southwest Saskatchewan survey soils.

6.4 References

Hogg, T.J., and J.L. Henry. **1984.** Comparison of 1:1 and 1:2 suspensions and extracts with the saturation extract in estimating salinity in Saskatchewan soils. Can. J. Soil Sci. **64**:699-704.

Saskatchewan Soil Survey. 1989. Rural Municipality of Wise Creek Number 77: Preliminary soil map and report (SK77). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sk77/index.html

Saskatchewan Soil Survey. 1992a. Rural Municipality of Val Marie Number 17: Preliminary soil map and report (SK17). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sk17/index.html

Saskatchewan Soil Survey. 1992b. Rural Municipality of Lone Tree Number 18: Preliminary soil map and report (SK18). Saskatchewan Institute of Pedology: University of Saskatchewan, Saskatoon, Saskatchewan. http://sis.agr.gc.ca/cansis/publications/sk/sk18/index.html