University of Alberta

Quantity and Quality of Runoff Water from Freshly Manured Agricultural Soils

by

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ABSTRACT

Water quality concerns stemming from agricultural non-point source pollution of Alberta's surface waters prompted a study examining effects of freshly applied and incorporated manure on hydraulic characteristics and nutrients in runoff. Phosphorus and nitrogen in runoff increased with manure application rate although hydraulic characteristics remained unchanged. Nutrient fractions in runoff decreased or remained unchanged with manure incorporation, excluding nitrates, which increased. Hydraulic responses of the soil and landscape varied with manure incorporation between sites. Manure incorporation increased infiltration at the site with fine textured soils and decreased infiltration at the no-till managed site. Phosphorus fractions in runoff correlated to total phosphorus in manure and soil-test phosphorus with similar r^2 values while correlations to water extractable phosphorus in manure had lower r^2 values. Over thirty minutes of runoff, nitrogen concentrations decreased while phosphorus concentrations remained relatively constant. Nitrogen and phosphorus loads increased with time due to increasing runoff rates.

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LIST OF ACRONYMS

AAFRD	Alberta Agriculture, Food and Rural Development
AOPA	Agricultural Operation Practices Act
CAESA	Canada-Alberta Environmentally Sustainable Agriculture
Cl	chloride
DRP	dissolved reactive phosphorus
DURP	dissolved unreactive phosphorus
EC	electrical conductivity
EDI	effective depth of interaction
FWMC	flow-weighted mean concentration
KCl	potassium chloride
LRSAG	Livestock Regulations Stakeholder Advisory Group
NH_3-N	ammonia-nitrogen
NH_4-N	ammonium-nitrogen
NO_2-N	nitrite-nitrogen
NO_3-N	nitrate-nitrogen
PN	particulate nitrogen
PP	particulate phosphorus
SAR	sodium adsorption ratio
TDN	total dissolved nitrogen
TDP	total dissolved phosphorus
TN	total nitrogen
TP	total phosphorus
WEP	water extractable phosphorus

1. INTRODUCTION

Water quantity and quality have become global concerns in recent decades. With point source pollutants to surface waters being reduced by the development and enforcement of environmental standards in many countries, focus is being drawn to controlling non-point sources of pollutants (Daniel et al. 1998). Many countries have identified agricultural lands as a major contributor of nonpoint source pollution to surface waters. While nutrients such as phosphorus and nitrogen are necessary inputs to agricultural systems for maximized yields, excess nutrients can have adverse effects on surrounding surface waters. World wide, more nutrients are added to agricultural lands as fertilizers than are removed as produce (Carpenter et al. 1998). This buildup of nutrients in agricultural soils is the underlying cause of nonpoint source pollution from agriculture (Carpenter et al. 1998).

In Canada, changing trends in agriculture have prompted the need for greater environmental controls. While the total area of farmland in Canada has remained relatively constant, regional changes have occurred (Chambers et al. 2001). Historically, water quality concerns in Canada have been concentrated in the Great Lakes region. However, agricultural land has been decreasing in Eastern Canada while increasing in the prairie provinces (Chambers et al. 2001). Despite a decreasing number of farms in Canada, their individual sizes have grown and concentrated in economically advantageous locations. In areas of intense livestock production, large quantities of manure have become a concern for nutrient management. Significant transport costs would be incurred to land-apply this manure at nutrient rates based on crop requirements. Additionally, manure applied to agricultural land to meet nitrogen requirements generally results in application of phosphorus well above crop requirements.

Ninety-eight percent of Alberta's water use comes from surface water sources (Alberta Environment 2002). In 1998, the Canada-Alberta Environmentally Sustainable Agriculture (CAESA) Water Quality Committee published the results of a five-year study. The committee reported that total phosphorus (TP) and total nitrogen (TN) concentrations in Alberta streams increased with agriculture intensity (CAESA 1998). As well, the occurrences of total phosphorus and total nitrogen concentrations exceeding

Alberta Surface Water Quality Guidelines for the protection of aquatic life were higher in areas of higher agricultural intensity. At the time, the TP and TN guidelines were 0.15 mg L^{-1} and 1.0 mg L^{-1}, respectively (AEP 1993). The more recent Surface Water Quality Guideline for TP for the protection of aquatic life has been reduced to 0.05 mg L^{-1} (Alberta Environment 1999).

In Alberta, recent research initiatives have been developed to increase our understanding of nutrient transport from agricultural lands to surface waters. The Alberta Soil Phosphorus Limits Project was initiated by Alberta Agriculture, Food and Rural Development in 1999 in response to a request from the Technical Expert Committee of the Livestock Regulations Stakeholder Advisory Group (LRSAG). The committee requested that phosphorus guidelines be developed for manure application to agricultural land based on research conducted under Alberta conditions. The key objectives of the ongoing Soil Phosphorus Limits Project are to develop recommendations of phosphorus limits for agricultural land in Alberta and to determine implications and identify management options to implement such limits (Olson 2005).

This rainfall simulation study was initiated to provide a more in-depth look at the relationship of nutrients in soil, freshly applied manure and surface runoff. While watershed studies provide insight into natural conditions, large amounts of time and money are required to collect very small amounts of data. Small plot rain simulations can collect larger amounts of data using fewer resources. The purpose of this study was to determine the effects of varying rates of freshly applied manure, left unincorporated or incorporated into surface soils, on nutrient concentrations and loads in surface runoff as well as hydraulic characteristics of the runoff events.

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2. PROJECT CHARACTERIZATION AND METHODOLOGY

2.1 Project and Site Characterization

2.1.1 Project Background

This rainfall simulation experiment is a component of the Phosphorus Limits Project initiated in 1999 by Alberta Agriculture, Food and Rural Development (AAFRD) in response to recommendations from the Livestock Regulations Stakeholder Advisory Group (LRSAG) Technical Expert Committee (Olson 2005). LRSAG is involved with the development of regulations for the confined feeding livestock industry. While the most recent amendments to the Agricultural Operation Practices Act (Province of Alberta 2004) base manure applications on nitrogen content, LRSAG requested that phosphorus guidelines for manure application be developed once applicable research based in Alberta could be conducted. The purpose of the Soil Phosphorus Limits Project was to develop recommendations of phosphorus limits for agricultural lands in Alberta (Paterson et al. 2004). The objective of the rainfall simulation study was to determine the effects of manure application and incorporation into the soil on the hydrology and water quality of surface water runoff from cultivated agricultural soils in Alberta.

2.1.2 Experimental Design and Plot Layout

Three study sites were selected on cultivated agricultural lands near the towns of Beaverlodge, Lacombe and Raymond in Alberta (Figure 2.1). The sites were chosen to include a range of soils and natural regions within the province's agricultural areas (Table 2.1). The Beaverlodge and Lacombe rain simulations were conducted in October 2003, while the Raymond simulations were conducted over a two-week period in April and May 2004. Prior to simulations, all sites had been harvested and left uncultivated. At each site, furrows from previous field cultivation were orientated perpendicular to the slope.

A randomized block design was used, comprised of four replicates of eight treatments. The treatments were randomized separately for each site. Each treatment plot measured 7 m across by 10 m down slope. A 5-m buffer was left between replicates and a minimum 3-m buffer was provided around the plot area. At the Beaverlodge and Raymond sites, treatments of each replicate were orientated across the slope with Replicate 1 in the upper slope position through to Replicate 4 in the lower slope position. At the Lacombe site, treatments were orientated similarly. However, due to space restrictions, Replicate 1 was located in the upper slope position and Replicate 2 in the lower slope position. Replicates 3 and 4 were orientated beside Replicates 1 and 2, respectively.

2.1.3 Site Descriptions

2.1.3.1 Beaverlodge

The Beaverlodge simulations were conducted at the Agriculture and Agri-Food Canada Beaverlodge Research Station. The mean annual precipitation of this area, calculated from 1971 to 2000 data, lies in the 450 mm to 500 mm range (Chetner and the Agroclimatic Atlas Working Group 2003). The research station is located in the transition zone between the Central and Dry Mixedwood Subregions of the Boreal Forest Natural Region of Alberta (ANHIC 2005). These sub-regions are characterized by Aspen-dominated forests (*Populus tremuloides*) with common occurrences of *Populus balsamifera* (balsam poplar). Frequent fire prevents late succession tree species such as *Picea glauca* (White Spruce) and *Abies balsamea* (balsam fir) from occurring in great numbers in this area. A notable portion of the area has been cleared for agricultural use.

Soils of the area are dominantly of the Berwyn series with inclusions of the Esher Series (CAESA 1998). The Berwyn series is classified within the Canadian Soil Classification System (Soil Classification Working Group 1998) as a Dark Gray Luvisol. These soils have formed on gravelly and stony medium textured till. The Esher series tends to occur in lower landscape positions and is classified as a Gleyed Dark Gray Luvisol with Solonetzic B horizon tendencies developed on fine textured glaciolacustrine parent material. The landform is described as undulating with high relief. Soils classified on site appear similar to the Berwyn soil series description.

2.1.3.2 Lacombe

The Agriculture and Agri-Food Canada Lacombe Research Station, location of the Lacombe simulation site, lies in the Central Parkland Subregion of the Parkland Natural Region of Alberta (ANHIC 2005). Mean annual precipitation of this area, based on data from 1971 to 2000, is 500 mm to 550 mm (Chetner & the Agroclimatic Atlas Working Group 2003). Native vegetation of this subregion is composed of a gradation from grasslands with aspen groves (*Populus tremuloides*) in the south to aspen forest in the north. Common grasses include *Festuca scabrella* (rough fescue) and *Stipa curtiseta* (western porcupine grass). Due to the highly productive soils, a large portion of the area has been cultivated for agricultural use.

Soils of this area are co-dominated by the Sygnet series in upper slope landscape positions and the Lonepine series in mid to low positions (CAESA 1998). Smaller amounts of miscellaneous Orthic Humic Gleysols occur in depressional areas. The Sygnet soils are classified as Eluviated Black Chernozems developed on medium textured till. The Lonepine soils are Orthic Black Chernozems developed on medium textured materials overlying medium to fine textured till. The area's landforms are primarily ridged with low relief. On site soil classification is most similar in description to the Lonepine soil series.

2.1.3.3 Raymond

The Raymond site is located north of the town of Raymond on privately owned agricultural land and is situated in the Mixedgrass Subregion of the Grassland Natural Region of Alberta (ANHIC 2005). The mean annual precipitation (1971-2000) lies in the 400 mm to 450 mm range (Chetner & the Agroclimatic Atlas Working Group 2003). Common grasses of this area are *Stipa comata* (spear grass), *Stipa curtiseta* (western procupine grass), *Agropyron smithii* (western wheat grass) and *Agropyron dasystachyum* (northern wheat grass).

Soils in this area are dominated by the Readymade series, an Orthic Dark Brown Chernozem overlying a medium textured till, typically found in the upper slope landscape positions (CAESA 1998). Other soils include the Whitney and Chokio series. The Whitney series is classified as Orthic Dark Brown Chernozems developed on medium textured material overlying medium to fine textured till and resides in mid to lower slope landscape positions. The Chokio series is comprised of Calcareous Dark Brown Chernozems overlying medium to fine textured fluviolacustrine parent material and tend to be found in lower slope positions. Miscellaneous Orthic Humic Gleysols can also be found in depressional areas of the landscape. On site soil classification appears most similar to the Chokio series described above.

2.2 Rainfall Simulations

Four rainfall simulator frames were constructed for simultaneous use on four adjacent plots. These simulators were constructed using the specifications defined for rain simulation experiments of the United States National Phosphorus Project (Humphry et al. 2002). One of the simulators was aluminum-framed and previously used in the AAFRD Phosphorus Mobility Study (Wright et al. 2003). Three additional iron-framed simulators were constructed using the original simulator as a guide. The weight of the iron frames were most suitable for the windy conditions of the Lethbridge and Beaverlodge areas. Fitted tarps covered each simulator to isolate the plots from wind and sun exposure. The simulators were each equipped with a single Fulljet ½ SS HH WSQ nozzle centered over the runoff frame, 3 m above the soil surface. The simulators were calibrated to a nozzle pressure of approximately 28 kPa to generate continuous flow at an intensity of 70 mm h^{-1} onto the framed test plot areas within each treatment plot.

Runoff frame borders for the sides of the test plots were constructed from galvanized steel, while the top and front plates were constructed from steel and painted. The test plots measured 1.5 m across and 2.0 m down the slope. The top and side frame plates were driven into the soil to a depth of approximately 0.1 m. The front plate was driven into the ground so that the top of the plate was just below the soil surface. A triangular metal painted tray was fitted over the front frame plate and was adjusted level with the soil surface. Care was taken to disturb the soil at the front end of the frame as little as possible. The opposite corner of the tray was positioned lower than the soil surface to allow runoff water collection. A 0.3-m deep hole was excavated under the down-slope corner of the tray to accommodate the collector cups. A 1.2-m by 1.8-m sheet of clear plexiglass was then placed over each collector tray, supported approximately 0.1 m above the trays with wood stakes. This arrangement prevented water from spraying directly onto the collection tray from the simulator nozzle.

Source water used for application was stored on-site in a 3640-L water truck and a 5460-L fiberglass tank mounted on the back of the water truck. Additional water, as required, was transported to the site using two fiberglass tanks mounted on a flatbed trailer. Water was pumped from the water truck, through a header system, and to the simulators using an electric pump run by a gasoline-powered generator. Water flow for each simulator was controlled by four valves located on the header. Nozzle pressure for each simulator was checked at the beginning of every simulation to ensure an accurate application rate.

2.3 Soil Sampling and Analysis

Baseline soil samples were collected from each plot using a frame-excavation method. A 50-cm long by 19-cm wide by 2.5-cm deep metal frame was inserted level with the soil surface. A 2.5-cm deep scoop was used to remove the soil from within the frame to the 2.5-cm sampling depth. For these pre-treatment samples, all aboveground crop residue material was removed prior to collection. The analysed sample was a composite of two sampling sites within each plot. Following manure application and tillage, a second, post-treatment sample, was collected using the same method except that the post-treatment sample included all incorporated and aboveground crop residue and freshly applied manure. All pre and post-treatment soil samples were passed through a 2-mm sieve and analysed for nitrate-nitrogen (NO_3-N) plus nitrite-nitrogen (NO_2-N), and ammonia-nitrogen (NH_3-N) using a 2 M KCl (potassium chloride) extraction method (Maynard and Kalra 1993). Soil-test phosphorus (STP) content was determined using the modified Kelowna extraction method (Quin et al. 1994). Despite differences in soil sampling procedures with respect to crop residue, no statistical differences were found between the pre-treatment samples and the unincorporated, nonmanured, post-treatment samples. Additional discrete soil samples were collected from each plot at the time of the simulations and were used to determine gravimetric soil moisture content.

Four to five soil cores were classified at each site according to the Canadian System of Soil Classification (Soil Classification Working Group 1998). Soil cores were taken from locations directly outside the 3-m plot area boundary and were sampled by horizon. Samples were air-dried and ground (< 2 mm) and analysed for percent saturation, pH, electrical conductivity (EC), and soluble ions using a saturated paste extract (Rhoades 1982) (Tables 2.2a, 2.2b, 2.3a, 2.3b, 2.4a and 2.4b). Sodium adsorption ratio (SAR) was calculated using sodium, calcium and magnesium ion concentrations. Available nutrient analysis was also conducted for NO_3-N, NH_3-N, and STP content using the methods described for the pre and post-treatment soil samples. Particle-size analysis was determined using the hydrometer method for all core samples (Gee and Bauder 1986).

2.4 Manure Application, Sampling and Analysis

Solid cattle manure was applied to all manure-amended plots. Plots at the Lacombe and Raymond sites received one of four manure rates: 0 (control), 50, 100, and 200 kg ha^{-1} total phosphorus (TP) target rates, and for both incorporated and unincorporated plots. At the Beaverlodge site, manure rates were reduced to half the above values due to low phosphorus content of the manure applied. The volume of manure required to achieve the planned phosphorus targets at the Beaverlodge site would have substantially exceeded typical manure application rates used by local producers.

Total phosphorus content was determined on ten samples of fresh manure from the manure source for each site (Peters 2003), approximately one week prior to application. Manure rates (wet-weight equivalent) applied to the plots were determined according to the mean phosphorus content of the source manure samples using the following equation:

$$\begin{array}{c}\text{Wet mass of}\\ \text{manure required}\\ (\text{kg plot}^{-1})\end{array} = \frac{\text{Target TP rate (kg ha}^{-1}\text{) x 0.007 ha plot}^{-1}\text{ x 1000 kg Mg}^{-1}}{\text{TP content of manure (kg Mg}^{-1}\text{)}} \qquad (2.1)$$

Manure samples were also collected at the time of application and analysed for TP and water extractable phosphorus (WEP) (Kleinman et al. 2002) and NO_3-N and ammonium-nitrogen (NH_4-N) (Hoskins 2003). From this analysis, actual rates of manure phosphorus applied to the plots were calculated for each plot using the following equation:

$$\begin{array}{c}\text{Actual}\\ \text{nutrient rate}\\ (\text{kg ha}^{-1})\end{array} = \frac{\begin{array}{c}\text{Nutrient content of manure (kg Mg}^{-1}\text{) x}\\ \text{Wet mass of manure applied (kg plot}^{-1}\text{)}\end{array}}{\text{0.007 ha plot}^{-1}\text{ x 1000 kg Mg}^{-1}} \qquad (2.2)$$

Actual nutrient manure values were then converted to units of g m^{-2} for reporting purposes to better represent the scale at which the experiment was conducted.

Manure was weighed and applied to the plots by hand, spread as uniformly as possible with rakes, and incorporated the same day. A 3.7-m wide double disk was used for incorporation at the Lacombe and Raymond sites, while a 1.8-m wide disk was used at the Beaverlodge site. All tilled plots were disked once with furrows orientated with the slope.

2.5 Hydrologic Measurements and Calculations

Times were recorded at the start of each simulation and also when runoff began. The difference between these times along with the rainfall intensity was used to calculate the initial abstraction for each simulation event. The initial abstraction was considered to be the amount of rainfall required to fill the surface soils to saturation before runoff began. The beginning of runoff (T = 0 minutes) was defined as being the point in time when runoff reached 200 mL min^{-1}, which was the approximate rate required to produce a steady stream of water. Total volumes of runoff were collected during each of four consecutive time intervals, starting when runoff began. The time intervals measured were 0-5, 5-10, 10-20 and 20-30 minutes. Simulations stopped after 30 minutes of runoff had occurred.

Runoff and infiltration rates (mm hr^{-1}) were calculated for each interval and averaged for the entire 30 minutes. Infiltration rate was considered to be the portion of rainfall that did not run off the plots. Evapotranspiration, interception and storage were considered negligible because the plots were protected from wind and sun exposure; had relatively small amounts of host-harvest plant residue on the surface; and had little surface ponding remaining immediately after the simulations stopped. Runoff coefficients were calculated for intervals and for the entire 30 minutes as a ratio of runoff collected (mm) to precipitation applied (mm). Initial abstraction was calculated as follows:

$$\begin{array}{c}\text{Initial}\\ \text{Abstraction}\\ \text{(mm)}\end{array} = [\text{Runoff start (hr)} - \text{Simulator start (hr)}] \times \text{Runoff rate (mm hr}^{-1}) \qquad (2.3)$$

2.6 Water Quality Sampling and Analysis

Treated water from the municipal supplies of Beaverlodge, Lacombe and Lethbridge was used as source water for this study. At Beaverlodge and Lacombe, a 1-L sample of source water was collected directly from the header system once per day during the rainfall simulations. For Raymond, a more intense sampling program was administered. Source water samples were collected at the municipal loading station for each load of water taken as well as on-site from the header system after each set of four simulations. Filtered and unfiltered samples were prepared similar to the runoff water samples described below.

The source water analysis values were generally low with respect to values from the runoff samples (Table 2.5). Some samples from Beaverlodge and Lacombe measured dissolved reactive phosphorus (DRP) concentrations greater than TP concentrations. It is believed that contamination may have been introduced to the samples during filtration because of less sterile field laboratory facilities. However, the amount of contamination possibly introduced to some filtered samples would have been considerably less than the concentration differences between treatments for these two sites. Proper laboratory facilities were available for filtrating samples from Raymond. The Raymond April 30th source water samples have total suspended solids (TSS) and phosphorus concentrations elevated above samples from the other days. However, runoff concentrations from simulations using this water were not notably elevated above other results.

Composite samples of runoff water were collected during consecutive intervals ending 5, 10, 20, and 30 min after the commencement of runoff. The total volume of water collected during each timed interval was recorded. A 1-L sample of water from the total volume of water collected during each time interval was transported to the lab in a cooler with ice packs. Approximately 200 mL of unfiltered water was removed from the 1-L bottles and refrigerated. An additional 200 mL was collected after filtration using either a Nalgene membrane 0.45-µm filter unit or a Gelman 0.45-µm high-capacity filter within 24 h of sampling. Filtered water samples were analysed for NO_3-N, NO_2-N, NH_3-N, total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), DRP and chloride (Cl), while unfiltered water samples were analysed for total nitrogen (TN), TP, and TSS (Greenberg et al. 1995). Samples were preserved with five percent sulphuric acid.

Particulate phosphorus and nitrogen (PP and PN) concentrations were calculated from the difference between total and total dissolved phosphorus and nitrogen concentrations.

2.7 Data Analysis

All significant differences have been determined at the $P \leq 0.05$ level unless otherwise stated. Analytical results reported below detection limits were adjusted to half the detection limit value for statistical comparison purposes. The data sets from each site were evaluated for outliers by identifying plots with volume measurements inconsistent within each replicate. All data collected from irregular plots were removed from the data set before analysis. Ten plots from the Raymond site received approximately 16 mm of rain over night, after manure was applied and before the rain simulations were conducted. These plots were also removed from the data set because the manure could no longer be considered freshly applied. Nutrient concentrations from these plots were consistently lower than runoff samples from remaining plots, confirming the decision to delete data for these ten plots.

Nutrient mass loads for each runoff interval were calculated as a product of the nutrient concentration and the runoff volume for the interval. Mass loads for the 30-minute runoff period were determined by summing the mass loads of the four runoff intervals. The flow-weighted mean concentrations (fwmcs) were then calculated by dividing the total mass load for the 30-minute interval by the total flow volume for the same period.

Regression analysis was used to regress nutrient concentrations in runoff against soil and manure nutrients variables for the different incorporation methods. The regressors for the analyses were the following manure and soil variables: STP, Manure TP, Manure WEP, Soil NO_3-N, Soil NH_3-N, Manure $N0_3$-N and Manure NH_4-N. The nutrient concentration and load response variables were as follows: TP, TDP, DRP, PP, NO_3-N, NH_3-N, TN, TDN, and PN. R-squared values were used to assess whether a nonlinear or linear model best represented the data. Linear relationships were modeled using the PROC MIXED procedure of SAS (Little et al. 1996). Nonlinear relationships were modeled using the PROC NLMIXED procedure in SAS (SAS Institute Inc. 2000). The nonlinear model used is explained as follows:

$$Y = \frac{a}{1+\exp[-(X - x_0)/b]} \qquad (2.4)$$

where, Y is the concentrations and loads of phosphorus and nitrogen fractions in runoff, a is the maximum runoff concentration or load attained, X is the soil and manure variables (regressor), b is the X of the first derivative (the maximum slope attained along the curve), and x_0 is the X level at the point of inflection. The runoff concentration or load at the inflection point (y_i) was estimated as follows:

$$y_i = \frac{a}{2} \qquad (2.5)$$

Linear and non-linear modeling included both incorporation methods, and coefficients for each incorporation method were compared. Combinations of linear and non-linear models were separately fit to the different incorporation method data when r-squared values differed markedly and/or convergences problems occurred particularly for the non-linear regression. For these instances, the models for the different incorporation methods were considered inherently different, thus negating the need for formal statistical tests.

An analysis was conducted to determine if the effect of target TP rate and incorporation method for runoff volume, runoff coefficient, runoff rate, infiltration rate, all phosphorus and nitrogen fraction concentrations and loads in runoff varied on the same plots over time. Repeated measures analysis was conducted using the PROC MIXED procedure of SAS (Little et al. 1996) with replicate and location assigned as random effects and the applied treatments assigned as fixed effects.

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Table 2.1. Characteristics of the three study sites

Characteristic	Beaverlodge Site	Lacombe Site	Raymond Site
Slope (%)	5%	10%	5%
Aspect	East	West	South
Soil[z]	Orthic Dark Gray Luvisol	Orthic Black Chernozem	Calcareous Dark Brown Chernozem
Natural Regions[y]	Boreal Forest	Parkland	Grassland
2003 Crop cover	Annual cereal (oat)	Annual cereal (barley)	Annual cereal (wheat)

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Table 2.2a. Physical characteristics and nutrient content of the Beaverlodge soils

Borehole Number	Depth Interval cm	Soil Horizon[z]	Sand %	Clay %	Silt %	Texture Class[y]	Saturation %	Nutrients[x] NO_3-N (mg kg^{-1})	NH_3-N (mg kg^{-1})	STP (mg kg^{-1})	K (mg kg^{-1})
1-W-03	0 - 12	Ap	24	39	37	CL-C	51.3	68.9	14.2	46.7	5.8
	12 - 48	Bt	18	63	19	HC	50.0	3.7	6.4	5.2	5.1
	48 - 65	BC	16	80	4	HC	83.3	2.4	4.1	2.0	5.6
	65 - 110	Cca	33	41	26	C-CL	50.7	6.1	5.2	1.2	3.3
2-W-03	0 - 12	Ap	28	40	32	CL-C	55.3	56.9	20.0	53.3	6.2
	12 - 38	Bt	17	61	22	HC-C	50.7	14.6	6.7	4.3	5.5
	60 - 80	Cca	15	58	27	C	69.7	8.5	4.1	2.0	4.9
	90 - 120	II Ck	14	73	13	HC	86.7	7.1	4.9	1.5	6.0
3-W-03	0 - 12	Ap	30	36	34	CL	86.7	36.4	17.4	41.4	6.9
	12 - 43	Bt	16	66	18	HC	60.0	10.1	4.7	2.6	4.9
	43 - 60	BC	15	62	23	HC	60.0	18.3	3.9	2.2	4.6
	60 - 85	II Cca	14	74	12	HC	86.7	17.1	5.8	1.9	6.4
	85 - 120	Ck	19	64	17	HC	86.7	13.4	5.8	1.6	5.1
4-W-03	0 - 20	Ap	32	35	33	CL	48.3	48.3	8.9	44.0	5.1
	51 - 90	Bt	31	48	21	C	50.0	14.7	4.4	2.6	3.5
	90 - 120	Cca	20	69	11	HC	75.2	25.5	2.7	2.1	4.6
5-W-03	0 - 16	Ap	30	38	32	CL	65.0	24.7	13.0	38.4	5.9
	20 - 50	Bt	21	60	19	C-HC	56.7	4.9	6.0	9.7	5.6
	60 - 80	II Cca	18	59	23	C-HC	56.7	13.9	4.5	2.5	5.0
	85 - 120	Ck	14	74	12	HC	68.3	15.5	9.8	2.3	5.9

z. Soil horizons classified according to the Canadian System of Soil Classification.

y. Clay (C), clay loam CL), heavy clay (HC)

x. nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), soil-test phosphorus (STP) and potassium (K)

Table 2.2b. pH, electrical conductivity (EC), sodium adsorption ration (SAR) and soluble ions of the Beaverlodge soils

Borehole Number	Depth Interval cm	Soil Horizon[z]	pH	EC $dS\ m^{-1}$	SAR	Soluble Ions[y] Ca (mmolc L^{-1})	Mg	Na	K	SO_4	HCO_3	CO_3	Cl
1-W-03	0 - 12	Ap	4.2	1.71	1.8	5.9	5.6	4.2	0.19	2.5	na	na	0.7
	12 - 48	Bt	6.2	0.98	4.0	1.8	2.6	6.0	0.04	4.9	na	na	0.3
	48 - 65	BC	7.4	5.48	4.8	24.2	29.7	25.0	0.31	67.0	3.5	0.0	0.3
	65 - 110	Cca	7.6	6.42	7.4	20.0	32.2	37.9	0.36	78.0	2.8	0.0	1.0
2-W-03	0 - 12	Ap	4.5	1.33	0.9	7.2	4.5	2.1	0.27	0.9	na	na	0.5
	12 - 38	Bt	5.7	1.19	3.1	3.6	2.9	5.6	0.07	5.6	3.4	0.0	0.2
	60 - 80	Cca	7.4	4.66	4.9	25.0	16.7	22.6	0.32	51.0	3.5	0.0	1.0
	90 - 120	II Ck	7.5	4.52	5.7	21.5	14.7	24.4	0.28	49.0	3.2	0.0	0.5
3-W-03	0 - 12	Ap	4.9	1.15	1.8	4.4	2.5	3.4	0.27	2.3	na	na	1.9
	12 - 43	Bt	6.7	1.79	5.9	4.7	4.0	12.3	0.04	7.5	na	na	0.3
	43 - 60	BC	7.3	4.07	8.0	11.4	10.5	26.4	0.13	23.0	4.5	0.0	13.1
	60 - 85	II Cca	7.6	6.22	7.7	25.6	26.2	39.1	0.26	72.0	4.1	0.0	0.8
	85 - 120	Ck	7.6	6.18	8.1	24.0	21.8	38.7	0.24	69.5	3.3	0.0	1.6
4-W-03	0 - 20	Ap	4.5	1.21	0.8	5.6	3.2	1.7	0.16	0.7	1.1	0.0	0.2
	51 - 90	Bt	6.8	5.20	5.6	28.6	18.0	26.9	0.16	56.5	4.6	1.9	0.6
	90 - 120	Cca	7.5	5.14	6.7	23.8	16.0	30.1	0.15	53.5	3.6	0.0	1.3
5-W-03	0 - 16	Ap	4.7	0.79	3.0	1.6	1.4	3.7	0.11	0.9	na	na	0.3
	20 - 50	Bt	6.4	1.48	5.9	3.7	2.9	10.8	0.07	10.6	na	na	0.3
	60 - 80	II Cca	7.6	6.34	8.0	25.9	23.5	39.8	0.36	71.3	3.9	0.0	2.6
	85 - 120	Ck	7.6	6.62	9.7	23.0	21.8	45.8	0.33	78.0	4.1	0.0	1.1

z. Soil horizons classified according to the Canadian System of Soil Classification.

y. Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl), not analyzed (na)

Table 2.3a. Physical characteristics and nutrient content of the Lacombe soils

Borehole Number	Depth Interval cm	Soil Horizon[z]	Sand %	Clay %	Silt %	Texture Class[y]	Saturation %	Nutrients[x] NO$_3$-N (mg kg^{-1})	NH$_3$-N (mg kg^{-1})	STP (mg kg^{-1})	K (mg kg^{-1})
1-W-04	0 - 20	Ap	51	22	27	SCL-L	49.5	41.0	11.5	51.9	na
	40 - 60	Bm	55	29	16	SCL	41.9	3.1	4.0	5.5	na
	100 - 120	Bm	55	31	14	SCL	39.4	1.4	3.9	2.8	na
	160 - 210	II Cca	53	36	11	SC-SCL	48.0	1.6	2.0	0.8	na
2-W-04	0 - 13	Ap	39	24	37	L	51.9	50.8	63.8	101.4	na
	13 - 35	Bm	45	39	16	CL-C-SC	43.3	11.7	3.9	18.7	na
	50 - 70	Bm	71	18	11	SL	35.6	2.6	2.6	7.8	na
	90 - 120	II Cca	43	37	20	CL	39.4	1.3	2.2	6.1	na
	125 - 210	III CCa	70	12	18	SL	31.3	1.8	2.9	1.3	na
3-W-04	0 - 20	Ap	50	24	26	SCL	52.3	22.7	7.2	41.1	na
	20 - 50	Bm	55	26	19	SCL	47.4	8.3	3.3	7.4	na
	70 - 90	II Cca	60	14	26	SL	44.5	2.2	2.7	2.7	na
	120 - 160	III Ck1	70	14	16	SL	31.3	3.3	2.5	0.5	na
	160 - 210	III Ck2	78	11	11	SL	27.3	1.4	2.3	0.4	na
4-W-04	0 - 20	Ap	53	23	24	SCL	53.7	27.9	4.9	90.3	na
	20 - 40	Ah	46	24	30	L	54.7	13.9	3.6	61.5	na
	50 - 70	Bm	66	22	12	SCL	39.3	1.4	2.9	14.8	na
	90 - 120	II CB	65	26	9	SCL	41.3	1.2	3.2	2.4	na
	150 - 180	II Cca	50	30	20	SCL	40.0	1.2	3.1	0.7	na

z. Soil horizons classified according to the Canadian System of Soil Classification.

y. Sandy clay loam (SCL), sandy clay (SC), loam (L) clay loam CL), sand loam (SL)

x. nitrate-nitrogen (NO$_3$-N), ammonia-nitrogen (NH$_3$-N), soil-test phosphorus (STP) and potassium (K)

Table 2.3b. pH, electrical conductivity (EC), sodium adsorption ration (SAR) and soluble ions of the Lacombe soils

Borehole Number	Depth Interval cm	Soil Horizon[z]	pH	EC $dS\ m^{-1}$	SAR	Soluble Ions[y] Ca	Mg	Na	K	SO_4	HCO_3	CO_3	Cl
						$mmolc\ L^{-1}$							
1-W-04	0 - 20	Ap	5.7	0.99	0.9	5.5	1.6	1.6	0.37	1.1	na	na	2.2
	40 - 60	Bm	6.8	0.20	0.7	1.1	0.4	0.6	0.05	0.7	na	na	0.1
	100 - 120	Bm	6.0	0.56	0.4	3.0	1.1	0.6	0.10	0.5	na	na	3.6
	160 - 210	II Cca	7.4	0.95	0.3	6.1	1.8	0.5	0.02	0.8	na	na	6.0
2-W-04	0 - 13	Ap	6.1	1.41	1.9	5.8	1.7	3.7	1.30	2.0	na	na	3.6
	13 - 35	Bm	6.8	0.54	0.4	3.2	1.0	0.6	0.09	0.5	na	na	1.5
	50 - 70	Bm	7.4	0.21	0.8	1.1	0.4	0.7	0.06	0.2	na	na	bd
	90 - 120	II Cca	6.0	0.31	0.6	1.4	0.7	0.6	0.02	0.7	na	na	1.6
	125 - 210	III CCa	6.9	1.31	0.3	8.0	3.0	0.6	0.06	0.5	na	na	8.6
3-W-04	0 - 20	Ap	6.2	0.51	0.3	3.6	1.0	0.4	0.09	0.5	na	na	0.2
	20 - 50	Bm	6.9	0.27	0.4	1.7	0.5	0.4	0.03	0.2	na	na	bd
	70 - 90	II Cca	6.5	1.59	0.4	9.8	3.2	0.9	0.10	0.2	na	na	12.9
	120 - 160	III Ckl	7.3	0.78	0.3	5.2	1.5	0.6	0.10	0.5	na	na	3.9
	160 - 210	III Ck2	7.8	0.83	0.3	5.3	1.7	0.6	0.11	0.4	na	na	5.0
4-W-04	0 - 20	Ap	7.1	0.63	0.4	5.0	1.4	0.7	0.17	0.7	na	na	0.5
	20 - 40	Ah	7.4	0.48	0.3	3.9	0.9	0.5	0.04	0.3	na	na	0.2
	50 - 70	Bm	7.3	0.58	0.3	3.5	1.1	0.5	0.10	0.4	na	na	3.4
	90 - 120	II CB	6.5	0.95	0.5	4.8	2.2	1.0	0.15	0.4	na	na	7.2
	150 - 180	II Cca	7.0	1.90	0.2	11.5	4.5	0.7	0.12	0.5	na	na	14.5

z. Soil horizons classified according to the Canadian System of Soil Classification.

y. Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl), not analyzed (na)

Table 2.4a. Physical characteristics and nutrient content of the Raymond soils

								Nutrients[x]			
Borehole Number	Depth Interval cm	Soil Horizon[z]	Sand %	Clay %	Silt %	Texture Class[y]	Saturation %	NO_3-N	NH_3-N	STP	K
								mg kg^{-1}			
9-W-04	0 - 15	Apk	30	40	30	CL-C	62.0	4.4	0.8	69.6	na
	20 - 40	Bmk	36	36	28	CL	47.5	1.7	bd	1.6	na
	70 - 90	Cca	26	55	19	C	59.0	1.0	2.9	1.4	na
	130 - 160	II Csk	13	58	29	C	75.0	21.0	0.7	2.0	na
10-W-04	0 - 15	Ap	29	38	33	CL	60.0	3.2	0.6	19.7	na
	15 - 27	Bmk	32	48	20	C	64.0	5.2	bd	2.5	na
	30 - 50	Cca	35	48	17	C	52.0	6.4	1.1	1.9	na
	100 - 120	Ck	44	38	18	CL	44.5	1.0	1.9	2.0	na
	160 - 190	Csk	36	50	14	C	66.5	3.7	3.1	2.5	na
11-W-04	0 - 20	Ap	27	38	35	CL	59.5	9.2	bd	46.6	na
	30 - 45	Bmk	26	45	29	C	60.0	3.4	0.7	2.0	na
	70 - 90	Ccasa	21	40	39	SiCL-C	51.0	1.7	bd	5.4	na
	120 - 140	Ck	25	52	23	C	55.5	3.8	bd	9.7	na
12-W-04	0 - 20	Ap	25	43	32	C	55.0	14.5	0.7	43.4	na
	20 - 38	Btjk	22	53	25	C	62.5	11.2	0.8	5.3	na
	60 - 80	Cca	27	41	32	C-CL	48.5	40.9	bd	24.7	na
	120 - 150	Ck	21	37	42	CL-SiCL	51.5	15.2	bd	9.3	na

z. Soil horizons classified according to the Canadian System of Soil Classification.

y. Clay (C), clay loam CL), silty clay load (SiCL)

x. nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), soil-test phosphorus (STP) and potassium (K), below detection limit (bd), not analyzed (na)

Table 2.4b. pH, electrical conductivity (EC), sodium adsorption ration (SAR) and soluble ions of the Raymond soils

Borehole	Depth Interval	Soil	pH	EC	SAR	Soluble Ions[y] Ca	Mg	Na	K	SO_4	HCO_3	CO_3	Cl
Number	cm	Horizon[z]		dS m^{-1}		mmolc L^{-1}							
9-W-04	0 - 15	Apk	7.2	1.08	7.6	2.5	1.4	0.94	0.6	na	na	na	na
	20 - 40	Bmk	8.1	0.57	3.3	1.5	0.6	0.03	0.4	na	na	na	na
	70 - 90	Cca	8.9	0.66	0.6	2.9	3.8	0.08	2.9	na	na	na	na
	130 - 160	IICsk	8.4	7.69	21.9	68.7	36.6	0.23	5.4	na	na	na	na
10-W-04	0 - 15	Ap	7.7	0.57	3.8	1.0	0.4	0.57	0.3	na	na	na	na
	15 - 27	Bmk	7.8	0.59	4.0	1.5	0.4	0.07	0.2	na	na	na	na
	30 - 50	Cca	8.4	0.38	1.8	1.8	0.4	0.06	0.3	na	na	na	na
	100 - 120	Ck	8.7	0.68	0.7	3.7	2.6	0.17	1.8	na	na	na	na
	160 - 190	Csk	8.0	4.62	23.6	33.0	15.6	0.44	2.9	na	na	na	na
11-W-04	0 - 20	Ap	7.2	0.85	4.8	2.1	1.1	0.92	0.6	na	na	na	na
	30 - 45	Bmk	8.0	0.69	3.3	2.8	1.0	0.08	0.6	na	na	na	na
	70 - 90	Ccasa	8.6	5.58	6.5	51.8	29.0	0.11	5.4	na	na	na	na
	120 - 140	Ck	8.7	9.33	7.0	88.9	55.4	0.25	8.0	na	na	na	na
12-W-04	0 - 20	Ap	6.4	0.71	2.8	3.2	1.0	0.25	0.6	na	na	na	na
	20 - 38	Btjk	8.2	0.78	2.3	4.0	1.4	0.04	0.8	na	na	na	na
	60 - 80	Cca	8.8	6.81	3.2	58.0	42.2	0.05	7.6	na	na	na	na
	120 - 150	Ck	8.6	2.54	2.3	13.1	16.3	0.06	5.9	na	na	na	na

z. Soil horizons classified according to the Canadian System of Soil Classification.

y. Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl), not analyzed (na)

Table 2.5. Summary of source water analytical results

Site/Sample Name	DRP[z] mg L^{-1}	TDP[z] mg L^{-1}	TP[z] mg L^{-1}	NO_3-N[z] mg L^{-1}	NO_2-N[z] mg L^{-1}	NH_3-N[z] mg L^{-1}	Cl[z] mmolc L^{-1}	TSS[z] mg L^{-1}
Beaverlodge Site								
Source water-Oct 19/03	0.014	na	bd	0.17	bd	bd	0.20	10
Source water-Oct 20/03	0.010	na	bd	0.18	bd	bd	0.21	10
Source water-Oct 21/03	0.054	na	bd	0.19	bd	bd	0.27	0
Source water-Oct 22/03	bd	na	0.106	0.23	bd	bd	0.25	0
Lacombe Site								
Source water-Oct 02/03	bd	na	bd	bd	bd	bd	0.45	0
Source water-Oct 03/03	bd	na	bd	bd	bd	bd	0.39	0
Source water-Oct 04/03	0.148	na	0.068	0.07	bd	bd	0.43	20
Source water-Oct 05/03	0.002	na	0.088	0.06	bd	0.06	0.46	0
Raymond Site								
Source purchased-April 27/04	0.006	0.007	0.033	0.08	bd	bd	0.20	0
Source purchased-April 30/04	0.015	0.043	0.074	0.07	bd	bd	0.19	2200
Source purchased-May 03/04 am	bd	0.017	0.031	0.12	bd	bd	0.17	0
Source purchased-May 03/04 pm	bd	0.019	0.033	0.11	bd	bd	0.17	0
Source purchased-May 04/04 am	bd	0.020	0.022	0.10	bd	bd	0.17	0
Source purchased-May 04/04 pm	bd	0.016	0.042	0.10	bd	bd	0.19	0
Source onsite-April 27/04	0.006	0.015	0.039	0.13	bd	0.19	0.20	0
Source onsite-April 29/04	0.004	0.008	0.012	0.07	bd	bd	0.20	0
Source onsite-April 30/04	0.012	0.058	0.077	0.06	bd	bd	0.19	1600
Source onsite-May 03/04 am	bd	0.024	0.033	0.12	bd	0.22	0.18	0
Source onsite-May 03/04 pm	bd	0.018	0.027	0.11	bd	bd	0.17	0
Source onsite-May 04/04 am	bd	0.010	0.025	0.08	bd	bd	0.16	0
Source onsite-May 04/04 pm	bd	0.010	0.029	0.09	bd	bd	0.17	0
Source onsite-May 05/04	0.003	0.006	0.045	0.08	bd	0.12	0.18	0
Laboratory Detection Limit	*0.002*	*0.002*	*0.002*	*0.04*	*0.04*	*0.04*	*0.11*	*0*

z. Total phosphorus (TP), total dissolved phosphorus (TDP), dissolved reactive phosphorus (DRP), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), ammonia-nitrogen (NH_3-N), chloride (Cl), total suspended solids (TSS), below detection limit (bd), not analyzed (na)

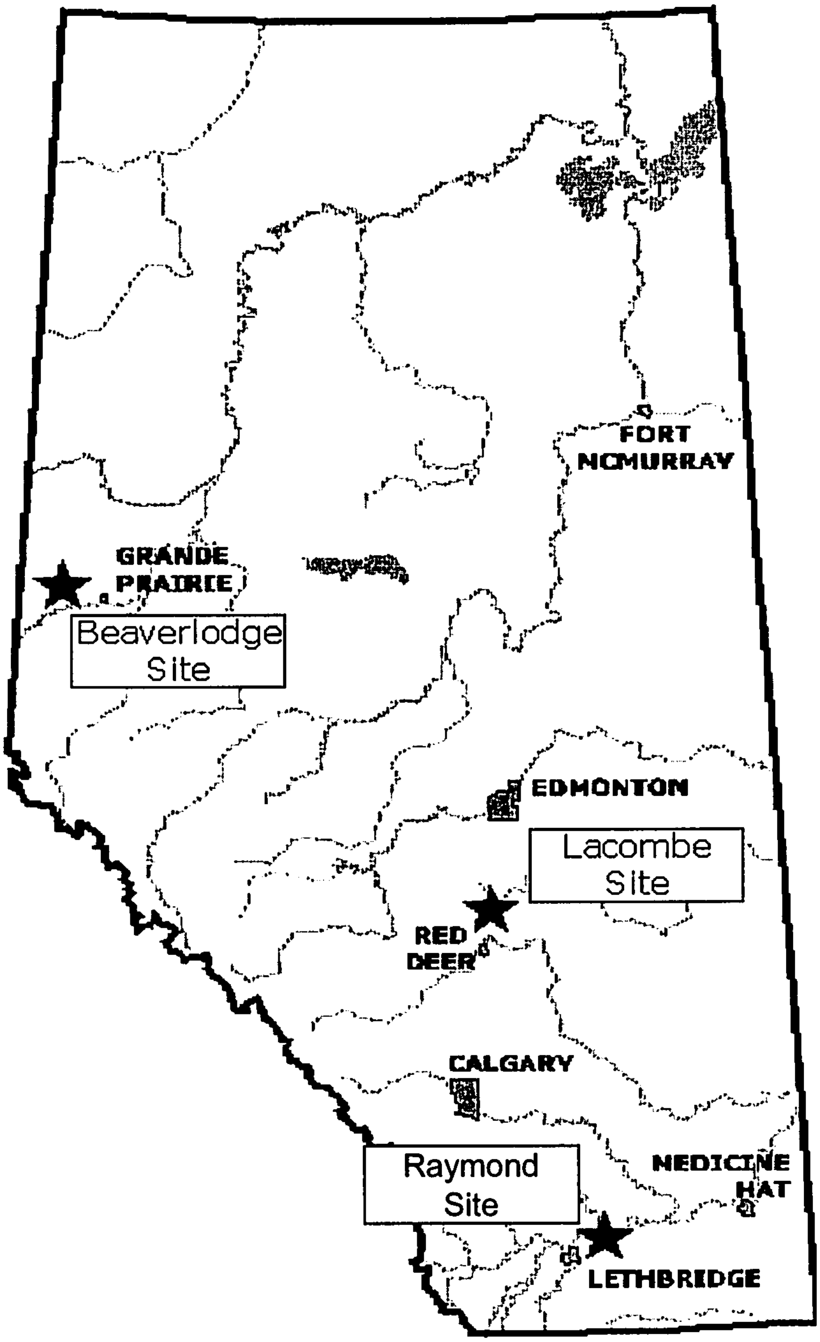

Figure 2.1. Location of the three study sites within the province of Alberta

3. SURFACE HYDROLOGY OF MANURED AGRICULTURAL LANDS

3.1 Introduction

To date, much research has focused on the effects of agricultural management practices on runoff and surface water quality with respect to nonpoint source nutrient pollution. Water quality plays an important role in determining nutrient loads exported from agricultural lands to surface water systems. For land managers to accurately assess the impact of these agricultural practices on water quality, their effects on surface hydrology need to be properly understood. While many studies investigating nutrients in runoff have been conducted, often they only briefly refer to the hydrologic processes of the runoff events.

3.1.1 Runoff

Runoff occurs when precipitation reaching the soil surface exceeds the soil's infiltration capacity and begins to flow across the soil surface. Factors affecting the occurrence and magnitude of runoff include storm intensity, evapotranspiration, surface storage, transmission losses, interception and infiltration capacity. Rainfall simulation experiments allow researchers to control some of these factors. In the case of a typical field rain simulation experiment where water application is held constant and plots are protected from the external climate, storm intensity and evapotranspiration are considered negligible. Surface storage under such conditions would primarily depend on management practices such as tillage and its orientation to the landscape slope. Transmission losses may be a factor in large-framed simulations where runoff travels a longer distance to the outlet. Interception is a function of the amount and type of vegetation present (Wolfe 2001). Soil infiltration capacity can be the most important factor affecting surface runoff in small-scale field rain simulations.

3.1.2 Infiltration

The process of infiltration at the start of a rainfall event begins with percolation of water downward under the influence of gravitational and capillary forces (Gray et al.

1970). As percolation penetrates deeper into the soil profile, infiltration slows because fewer channels are typically available for flow at depth.

Soil infiltration is ultimately affected by the amount of available soil pore space and the hydraulic gradient present. Antecedent soil moisture affects the portion of total pore space remaining for additional water and impacts hydraulic gradients of the soil profile. Lower antecedent soil moisture conditions result in higher infiltration rates and influence the infiltration rate most strongly at the beginning of a precipitation event (Wolfe 2001). Once the soil has been wetted, runoff is less affected by antecedent soil moisture conditions. As the surface soils reach saturation, infiltration rates tend to decrease with time (Gray et al. 1970).

Soil texture also governs available pore space and hydraulic gradients. Coarser textures create larger-sized pores with lower capillary forces, resulting in higher infiltration rates (ASCE 1996). Alternately, high bulk densities from mechanical soil compaction lower soil porosity and, therefore, lower infiltration (Ward and Trimble 2004). Compaction in an annually cropped field will be greatest after harvest, before cultivation occurs. Macroporosity can also influence infiltration. Macropores are created by processes such as worm activity, plant rooting and by soil cracking resulting from soil wetting and drying (ASCE 1996).

Surface sealing is another factor that can greatly decrease infiltration. Soil chemistry, kinetic energy and vegetative cover all play a role in the degree of surface sealing that takes place (Gray et al. 1970). High sodium content of a soil can increase its dispersiveness. As soil aggregates break down, surface soil pores become clogged with dispersed particles, creating a seal. The kinetic energy of rainfall can also cause a breakdown of soil aggregates. Therefore, higher intensity storms can create a greater degree of surface sealing. However, substantial vegetative cover can absorb much of this kinetic energy, reducing the extent of sealing.

Difficulties occur when comparing hydrologic results between runoff studies because of the wide array of conditions among them. Such factors as manure type and consistency, soil type, antecedent moisture conditions, management practices, hill slope and vegetation cover can all play an important role in the hydrologic characteristics of a runoff experiment. In field experiments, these factors can be difficult to control.

3.1.3 Measures of Hydrology

Gray et al. (1970) defined initial abstraction as the amount of water necessary to replace the soil moisture deficit plus fill the non-capillary pores to near saturation within the depth of soil required to establish the moisture profile. The American Society of Civil Engineers (ASCE 1996) defined initial abstraction as the total water losses during a precipitation event before runoff begins. This is a broader definition including canopy interception, evaporation, infiltration and retention in surface depressions. Regardless of the various definitions for specific applications, initial abstractions tend to give insight into the pre-existing conditions of the soil, vegetation and landscape.

Runoff rate is the depth of runoff from a given area flowing through an outlet over a given time period. Infiltration rate, inversely related to runoff rate, is defined as the rate at which soil absorbs water that has been applied to the surface by rainfall, snowmelt or surface water sources (ASCE 1996).

Runoff coefficients are calculated as ratios of the depth of runoff collected to the depth of rainfall during a specified time interval. Any parameter that increases the infiltration or surface storage will decrease the runoff coefficient. Inversely, greater storm intensities will increase an event's runoff coefficients because of the degree to which rainfall is exceeding infiltration rates.

3.1.4 Effects of Manure Application

Manure is generally considered a beneficial amendment to crop land. It replenishes soil nutrients through microbial mineralization, stabilizes soil structure and increases infiltration and soil water holding capacity (Havlin et al.1999). A recent study by Miller et al. (2002) reported significant increases in soil water retention, field soil water content, ponded infiltration, field-saturated hydraulic conductivity and number of soil pores with a 24 year history of annual manure applications compared to the unmanured control. Ginting et al. (1998) observed decreases in runoff for three consecutive years after a one-time manure application under moldboard plow and ridge tillage systems. This difference was attributed to improved soil structure that increased infiltration.

3.1.5 Effects of Tillage

Manure is often incorporated by various tillage practices to facilitate nutrient enhancement of the soil, to reduce odours and to reduce nutrient losses through volatilization and surface runoff. Contrary to these benefits, tillage can also increase the risk of soil loss by erosion. Many studies have shown that tillage reduces the volumes or rates of runoff (Daverede et al. 2003 and 2004, Mueller et al. 1984, Little et al. *In press*, Gupta et al. 1997, Freese et al. 1993, Myers and Wagger 1996) primarily because it increases soil infiltration. In some cases, under no-till management practices, infiltration is reduced with tillage compared to infiltration of the well-developed macropore system of the no-till soils (Seta et al. 1993).

3.1.6 Alberta Conditions

Annual mean runoff for typical agriculture areas across Alberta can range from 0.2 to 207 mm (Alberta Environment 2005), amounts tending to be lowest in southeastern Alberta, increasing northward and with elevation toward the Rocky Mountains and the Swan Hills. In addition to vast regional variability, runoff from Alberta watersheds varies largely between years. As would be expected, annual runoff trends coincide with annual precipitation trends across the province. Precipitation ranges from less than 350 mm in the province's southeast to greater than 600 mm west of Red Deer (Chetner et al. 2003). Agricultural areas of Alberta have a semiarid climate, meaning evapotranspiration exceeds precipitation on an annual basis (Chetner et al. 2003). These three factors, surface runoff, precipitation and evapotranspiration, tend to be the most dynamic components of the water balance because they are climate dependent.

3.1.7 Objectives

To date, the effect of recent one-time manure application and incorporation on water quantity variables have not been extensively studied in relation to Alberta soils. The objective of this study was to determine the effect of manure application, manure incorporation by tillage, and time on initial abstraction, runoff rate, infiltration rate and runoff coefficient from a simulated rainfall experiment conducted at three cultivated sites across Alberta. Interval means were compared over the 30 minutes of runoff from the rainfall \simulations to identify any hydrologic changes with time. Comparisons were also made between manure rates and incorporation methods for the 30-minute total means of each hydrologic parameter.

3.2 Materials and Methods

Materials and methods are described in Section 2.

3.3 Results and Discussion

3.3.1 Initial Abstraction

Initial abstraction values from the Beaverlodge, Lacombe and Raymond sites showed no discernible trend with the target wet manure application rate (Table 3.1). Findings of the Daverede et al. (2004) liquid swine manure study agree with these results. However, Michaud and Laverdière (2004) and Little et al. (*In press*) had higher initial abstractions for plots receiving liquid swine and solid beef manure, respectively, than unmanured treatments. Field observations from the Beaverlodge site indicate that incorporation may have increased infiltration by disturbing previously formed surface sealing.

At Beaverlodge, the mean initial abstraction values were significantly greater for incorporated than for unincorporated treatments (Table 3.1). These results agree with those of Daverede et al. (2003 and 2004) where tillage resulted in greater times required to produce runoff and therefore greater initial abstractions at a constant rainfall intensity. Daverede et al. (2003) concluded that greater surface roughness of the tilled plots encouraged surface retention and infiltration of the rainfall.

Incorporation had no significant effect on initial abstraction for the Lacombe or Raymond sites (Table 3.1). Though the Raymond values did not differ statistically with incorporation, they were distinctly grouped. Opposite to Beaverlodge, initial abstractions of the Raymond unincorporated means for all target manure rates were greater, ranging between 112 to 180 mm, than for the incorporated means ranging from 50 and 92 mm. From a rain simulation experiment located on three hay fields, Michaud and Laverdière (2004) also reported higher initial abstractions for untilled treatments, citing less surface sealing of the untilled relative to the tilled soils as a possible cause. Seta et al. (1993) concluded that greater initial abstraction values for untilled soils were a result of less surface sealing and more undisturbed macropores. The Raymond site differed from the Beaverlodge and Lacombe sites in that the soils were extremely dry, had a full year between the last tillage event and the simulations and had been managed using no-till practices for several years. Beaverlodge and Lacombe were simulated in the fall, four to five months after the last tillage event. Macropores may have been more developed at the Raymond site due to soil shrinking with dry condition, freeze/thaw cycles of the winter season and long-term no-till management practices. Once rainfall exceeded infiltration, the unincorporated treatment appeared to behave similarly to the Lacombe treatments and the incorporated treatments of Raymond and Beaverlodge, as further discussed in Section 3.3.2.

3.3.2 Runoff Coefficient, Runoff Rate & Infiltration Rate

For all three sites, runoff coefficient, runoff rate and infiltration rate from the 30 minutes of runoff did not change significantly from unmanured to manured treatments or within increasing target manure rates for incorporated or unincorporated treatments (Table 3.1). Gilley and Eghball (1998) found no change in runoff between manured and unmanured treatments for both broadcasted and incorporated treatments from long-term no-till managed land. Ginting et al. (1998) reported significantly lower runoff rates from manured than unmanured treatments with moldboard plow and ridge tillage incorporation methods. Mueller et al. (1984) and Little et al. (*In press*) observed similar, though not significant, differences with broadcasted and incorporated manure using various tillage methods. Kleinman et al. (2002) reported greater runoff rates for manured incorporated treatments and lower runoff rates from manured surface applied treatments than their unmanured counterparts. With such variable results reported in the literature, it is apparent that other factors tend to influence the effect of manure applications on runoff rates, more prevalently.

At Beaverlodge, there was an incorporation effect on runoff coefficient, runoff rate and infiltration rate (Table 3.1). The unincorporated means for both the runoff coefficient and runoff rate were double the incorporated means. Inversely, mean infiltration rates of the incorporated treatments were greater than unincorporated. Manure incorporation at Lacombe and Raymond did not have an effect on these three hydrologic measures (Table 3.1). Soils at the Beaverlodge site were of a much higher subsurface clay content and had an observably increased infiltration capacity when tilled. The unincorporated Beaverlodge treatments had the lowest infiltration rates and consequently achieved runoff quicker and yielded more runoff than any other site or treatment. As with the initial abstraction, other studies have found an array of differing runoff rate results. Similar to the Beaverlodge site, many other studies reported greater runoff from untilled treatments compared to various types of tilled treatments (Daverede et al. 2003 and 2004, Mueller et al. 1984, Little et al. *In press*, Gupta et al. 1997, Freese et al. 1993, Myers and Wagger 1996). In step with the Lacombe and Raymond sites, Gilley and Eghball (1998) reported no change in runoff volume between tilled and untilled treatments from their long-term no-till managed site. However, Kleinman et al. (2002), Michaud and Laverdière (2004) and Seta et al. (1993) found less runoff collected from untilled than tilled treatments. While manure application and incorporation may affect the hydrologic variables of a runoff event, pre-existing soil conditions tend to dictate the degree and nature of these effects relative to unmanured, untilled soils.

3.3.3 Infiltration Curves

Infiltration curves for the 30 minutes of runoff (Figures 3.1, 3.2 and 3.3) were constructed for incorporation methods separately or combined according to the statistical results described in Section 3.3.2. Infiltration curves from all three sites decreased slightly over this time period. Mean infiltration rates of the Beaverlodge incorporated data closely resemble the Lacombe and Raymond values in magnitude while the Beaverlodge unincorporated data were comprised of notably lower infiltration rates. These lower infiltration rates are likely a reflection of lower porosity and a higher degree of surface sealing common to finer textured soils such as these.

Interestingly, the lowest mean infiltration rate among the sites, the Beaverlodge unincorporated, 20-30 minute interval, still accounted for two-thirds the rainfall rate. In most cases, less than one third of the rainfall from the three sites exited the plots as runoff.

3.3.4 Hydrologic Trends Over Time

The effects of site, incorporation method, target manure application rate and time on runoff coefficients, runoff rate and infiltration rate were assessed using analysis of variance. No significant treatment effects or interactions were detected for the three hydrologic parameters (Table 3.2). However, variance of the site by incorporation method (SxIn) interaction accounted for 68 % of the total variance for each of runoff coefficient, runoff rate and infiltration rate indicating that an incorporation effect may have been found had there been data collected from more than three sites. This variance appears most likely caused by the Beaverlodge incorporation differences as described in the precious section.

When the same analysis was conducted for the complete data set without site as a variable, a time interval effect and a time interval by incorporation method by target manure rate (TxInxR) interaction were detected for runoff rate, runoff coefficient and infiltration rate (Table 3.3). Means across the four time intervals were all significantly different from one another (Table 3.4). Little et al. (*In press*) and Seta et al. (1993) reported similar trends of increasing runoff over the duration of runoff events from their rain simulation studies. The significant TxInxR interaction was observable in the contrasting curvilinear responses to manure rate between incorporation methods with more pronounced differences developing in the latter two time intervals (Figures 3.4, 3.5 and 3.6). For runoff rate and coefficient, unincorporated results consistently showed a convex-curved relationship with increasing manure rate, whereas the incorporated results had a concave curve (Figures 3.4 and 3.5). Infiltration rate results showed the opposite trend (Figure 3.6). When the data were separated by site, these trends were noted most strongly for Beaverlodge, moderately for Lacombe and were essentially non-existent for Raymond (data not shown). Reasons for these trends are not intuitively obvious and no similar observations were found in published works reviewed during this project.

When analyzed independently, the Beaverlodge data revealed a significant time interval effect and incorporation method by target manure rate (InxR) interaction for runoff rate runoff coefficient and infiltration rate (Table 3.3). Mean values across time intervals were all significantly different from each other with runoff rate and coefficient increasing and infiltration rate decreasing over time (Table 3.4). The InxR interaction was a concave/convex relationship for unincorporated/incorporated treatments across manure rates, as observed for the combined sites. The unincorporated runoff rate and coefficient means within each time interval were consistently greater than the incorporated means. Once again, the reverse was observed for infiltration rate.

For Lacombe, a manure rate effect and a time interval by incorporation method (TxIn) interaction were significant (Table 3.3). Runoff rate and coefficient means increased steadily but insignificantly with manure rate with the exception of a significant decrease in the 5 g TP m^{-2} manure rate (Table 3.4). The opposite effect occurred among the infiltration means with the 5 g TP m^{-2} rate being greater than the control and significantly greater than the higher manure rates. The TxIn interaction was composed of a positive relationship between time interval and runoff rate or coefficient for both incorporation methods with the incorporated means greater than the unincorporated means at comparable intervals. Inversely, infiltration rate was negatively correlated with time intervals and the unincorporated means were greater than the incorporated means.

The Raymond site had only a significant time interval effect (Table 3.3). Runoff rate and coefficient increased significantly and infiltration rate decreased over time (Table 3.4). No other effects or interactions were significant.

3.4 Conclusions

Results of this experiment indicate that:

- Manure application rate had a statistically significant effect on the hydrologic characteristics of the Beaverlodge and Lacombe rain simulations but the opposing nonlinear trends between incorporation methods were largely inexplicable.
- No significant manure rate effects were observed for the Raymond simulations.
- Manure incorporation had no significant effect on hydrologic characteristics of the Lacombe and Raymond simulations, but did affect the initial abstraction, runoff coefficients, runoff rates and infiltration rates of the Beaverlodge simulations.
- The Raymond site had a notably greater, although not significant, mean initial abstraction from the unincorporated treatment than the incorporated treatment and treatments from the other two sites.

- Runoff rates and coefficients increased over the 30 minutes of measured runoff while infiltration rates decreased.

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Table 3.1. Mean initial abstractions, runoff coefficients, runoff rates and infiltration rates from rain simulations at the three study sites

Site	Incorporation Method[z]	Target Manure Total Phosphorus Rate	Wet Manure Application Rate	Mean Initial Abstraction[y]	Mean Runoff Coefficient (0-30 min)[y]	Mean Flow Rate (0-30 min)[y]	Mean Infiltration Rate (0-30 min)[y]
		g m^{-2}	kg m^{-2}	mm		mm hr^{-1}	mm hr^{-1}
Beaverlodge	UI	0	0	15 b	0.36 a b	17 a	53 b
	UI	2.5	2.9	11 b	0.45 a	21 a	49 b
	UI	5	5.7	15 b	0.51 a	24 a	46 b
	UI	10	11.4	20 b	0.38 a b	18 a	52 b
			Unincorporated Mean	*15*	*0.42*	*20*	*50*
	I	0	0	86 a	0.26 b c	12 b	58 a
	I	2.5	2.9	76 a	0.18 c	8 b	62 a
	I	5	5.7	64 a	0.13 c	6 b	64 a
	I	10	11.4	50 a	0.18 c	9 b	61 a
			Incorporated Mean	*69*	*0.19*	*9*	*61*
Lacombe	UI	0	0	70 h	0.19 h	5 h	65 h
	UI	5	3.1	65 h	0.16 h	4 h	66 h
	UI	10	6.6	55 h	0.27 h	10 h	60 h
	UI	20	13.1	49 h	0.31 h	8 h	62 h
			Unincorporated Mean	*60*	*0.23*	*7*	*63*
	I	0	0	34 h	0.33 h	11 h	59 h
	I	5	3.1	58 h	0.17 h	6 h	64 h
	I	10	6.6	53 h	0.28 h	7 h	63 h
	I	20	13.1	66 h	0.25 h	12 h	58 h
			Incorporated Mean	*53*	*0.26*	*9*	*61*
Raymond	UI	0	0	131 m	0.10 m	7 m	63 m
	UI	5	2.6	180 m	0.17 m	12 m	58 m
	UI	10	5.2	180 m	0.10 m	7 m	63 m
	UI	20	10.3	122 m	0.10 m	7 m	63 m
			Unincorporated Mean	*153*	*0.12*	*8*	*62*
	I	0	0	50 m	0.13 m	9 m	61 m
	I	5	2.6	92 m	0.14 m	10 m	60 m
	I	10	5.2	59 m	0.13 m	9 m	61 m
	I	20	10.3	61 m	0.13 m	9 m	61 m
			Incorporated Mean	*65*	*0.13*	*9*	*61*

z. Unincorporated (UI) and incorporated (I) treatments
y. Mean values followed by the same letter within each site are not significantly different

Table 3.2. Four-factor analysis of variance results for runoff coefficient, runoff rate and infiltration rate

Effect/Interaction[z]	Runoff Coefficient	Runoff Rate	Infiltration Rate
		(Variance Estimate)	
Site (S)	0.00247	5.4	5.4
S x Time Interval (T)	0.00008	0.2	0.2
S x Manure Rate (R)	0.00041	0.9	0.9
S x T x R	0.00000	0.0	0.0
S x Incorporation (In)	0.00984	21.4	21.4
S x T x In	0.00001	0.0	0.0
S x In x R	0.00171	3.7	3.7
S x T x In x R	0.00000	0.0	0.0
		(% Total Variance)[y]	
S	17	17	17
S x T	1	1	1
S x R	3	3	3
S x T x R	0	0	0
S x In	68	68	68
S x T x In	0	0	0
S x In x R	12	12	12
S x T x In x R	0	0	0

z. The symbol "x" refers to an interaction between terms.

y. Percent total variance is calculated as the variance for a given effect, divided by the sum of the variance estimate for the four effects associated with site, all multiplied by 100.

Table 3.3. Repeated measures analysis of variance results for runoff coefficient, runoff rate and infiltration rate

Site	Effect/Interaction[z]	Runoff Coefficient[y]	Runoff Rate[y] mm hr^{-1}	Infiltration Rate[y] mm hr^{-1}
All Sites	Time Interval (T)	**	**	**
	Target Manure Rate (R)	ns	ns	ns
	T x R	ns	ns	ns
	Incorporation (In)	ns	ns	ns
	T x In	ns	ns	ns
	R x In	ns	ns	ns
	T x In x R	*	*	*
Beaverlodge	T	**	**	**
	R	ns	ns	ns
	T x R	ns	ns	ns
	In	**	**	**
	T x In	ns	ns	ns
	R x In	*	*	*
	T x In x R	ns	ns	ns
Lacombe	T	**	**	**
	R	*	*	*
	T x R	ns	ns	ns
	In	*	*	*
	T x In	*	*	*
	R x In	ns	ns	ns
	T x In x R	ns	ns	ns
Raymond	T	**	**	**
	R x In	ns	ns	ns
	T x R	ns	ns	ns
	In	ns	ns	ns
	T x In	ns	ns	ns
	R x In	ns	ns	ns
	T x In x R	ns	ns	ns

z. The symbol "x" refers to an interaction between terms.
y. ** is $P < 0.001$, * is $P < 0.05$, ns is not significant

Table 3.4. Mean runoff coefficients, runoff rates and infiltration rates for significant treatment effects and interactions for sites combined and individually

Site	Treatment Effects & Interactions[z,y]	Runoff Coefficient[x]	Runoff Rate[x] mm hr^{-1}	Infiltration Rate[x] mm hr^{-1}
All Sites	Time Interval			
	0-5 min	0.15 d	6.8 d	63.2 a
	5-10 min	0.19 c	8.9 c	61.1 b
	10-20 min	0.23 b	10.7 b	59.3 c
	20-30 min	0.27 a	12.6 a	57.4 d
Beaverlodge	Time Interval			
	0-5 min	0.22 d	10.2 d	59.8 a
	5-10 min	0.27 c	12.4 c	57.6 b
	10-20 min	0.32 b	14.8 b	55.2 c
	20-30 min	0.36 a	16.9 a	53.1 d
	Incorporation x Rate			
	UI 0 g TP m^{-2}	0.34 bc	15.9 bc	54.1 cd
	UI 2.5 g TP m^{-2}	0.43 ab	19.9 ab	50.1 de
	UI 5 g TP m^{-2}	0.50 a	23.3 a	46.7 e
	UI 10 g TP m^{-2}	0.37 b	17.3 b	52.7 d
	I 0 g TP m^{-2}	0.24 cd	11.2 cd	58.8 bc
	I 2.5 g TP m^{-2}	0.16 de	7.6 de	62.4 ab
	I 5 g TP m^{-2}	0.12 e	5.7 e	64.3 a
	I 10 g TP m^{-2}	0.17 de	7.8 de	62.2 ab
Lacombe	Target Rate			
	0 g TP m^{-2}	0.22 ab	10.1 ab	59.9 ab
	5 g TP m^{-2}	0.13 b	5.9 b	64.1 a
	10 g TP m^{-2}	0.23 a	10.6 a	59.4 b
	20 g TP m^{-2}	0.27 a	12.5 a	57.5 b
	Incorporation x Time Interval			
	UI 0-5 min	0.13 e	5.9 e	64.1 a
	UI 5-10 min	0.16 e	7.3 de	62.7 ab
	UI 10-20 min	0.19 cde	9.0 cde	61.0 abc
	UI 20-30 min	0.23 bc	10.9 bc	59.1 cd
	I 0-5 min	0.16 de	7.4 de	62.6 ab
	I 5-10 min	0.23 bcd	10.5 bcd	59.5 bcd
	I 10-20 min	0.28 ab	13.0 ab	57.0 de
	I 20-30 min	0.31 a	14.4 a	55.6 e
Raymond	Time Interval			
	0-5 min	0.08 d	3.8 d	66.2 a
	5-10 min	0.10 c	4.7 c	65.3 b
	10-20 min	0.13 b	6.1 b	63.9 c
	20-30 min	0.16 a	7.4 a	62.6 d

z. Unincorporated (UI) and incorporated (I) treatments and Target manure total phosphorus (TP) rates
y. The symbol "x" refers to an interaction between terms.
x. Mean values followed by the same letter for each treatment effect or interaction within each site are not significantly different.

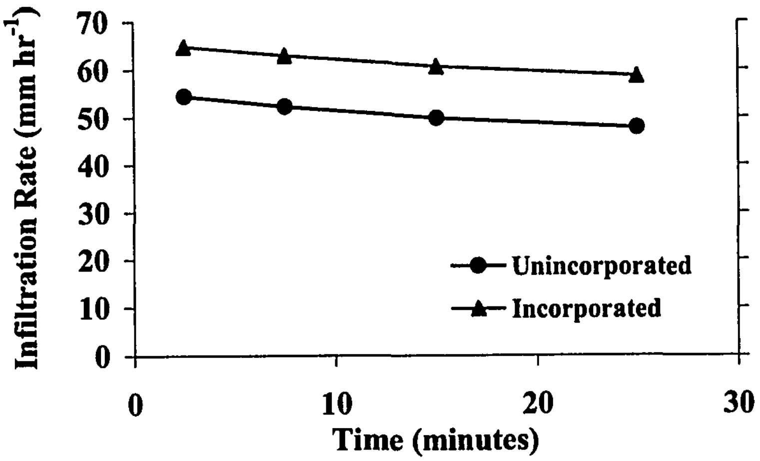

Figure 3.1. Infiltration curves of the Beaverlodge rainfall simulations

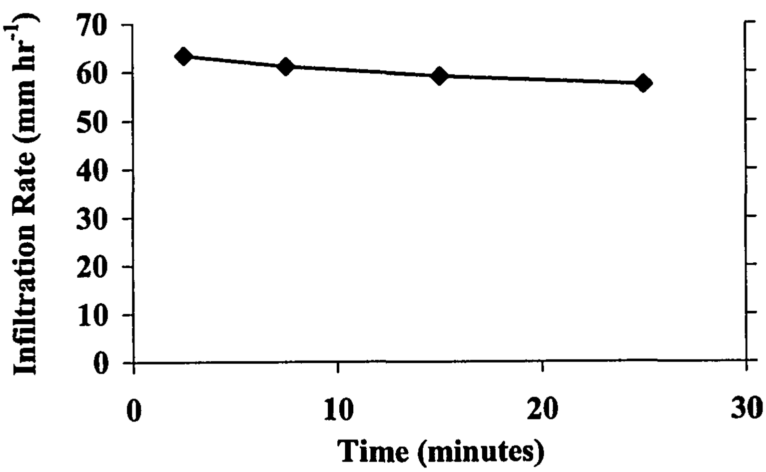

Figure 3.2. Infiltration curve of the Lacombe rainfall simulations

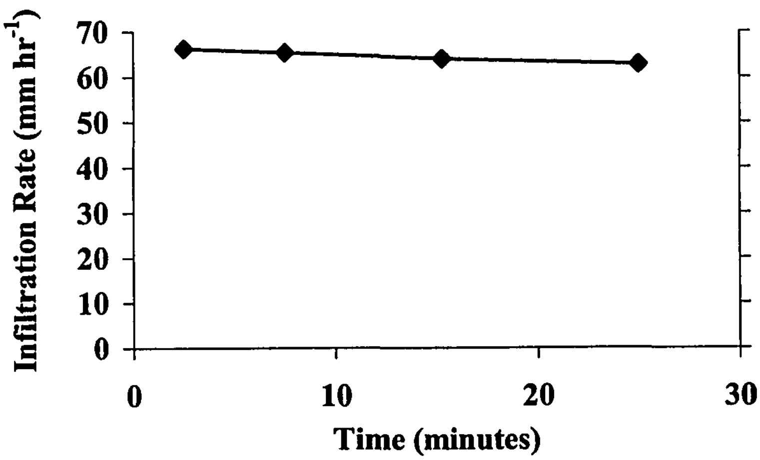

Figure 3.3. Infiltration curve of the Raymond rainfall simulations

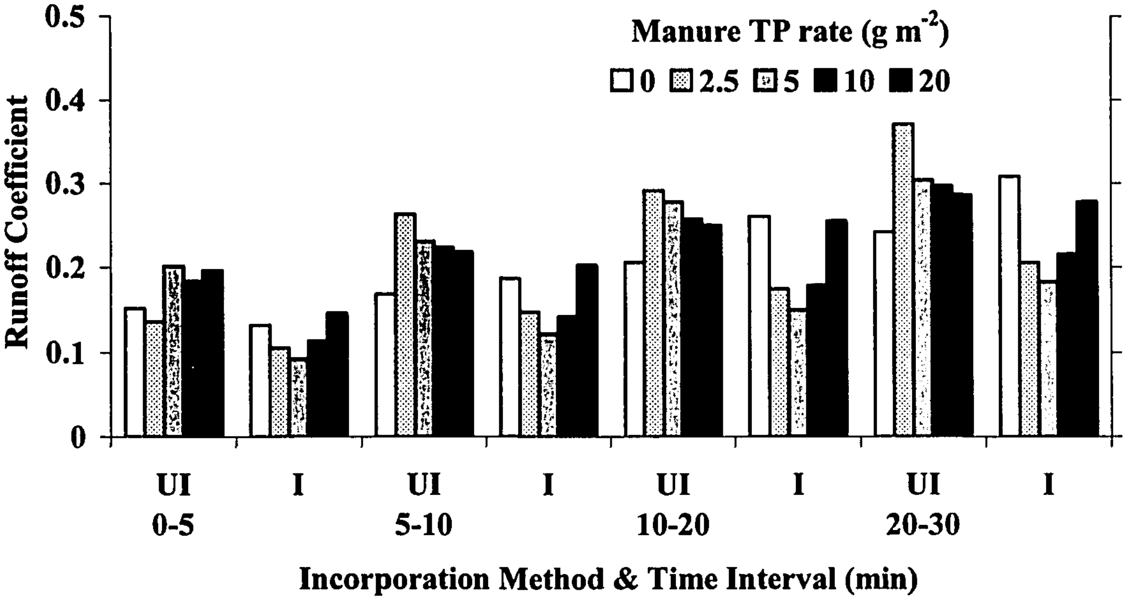

Figure 3.4. Mean runoff coefficients by time interval and manure total phosphorus (TP) rate for incorporated (I) and unincorporated (UI) treatments from all sites combined

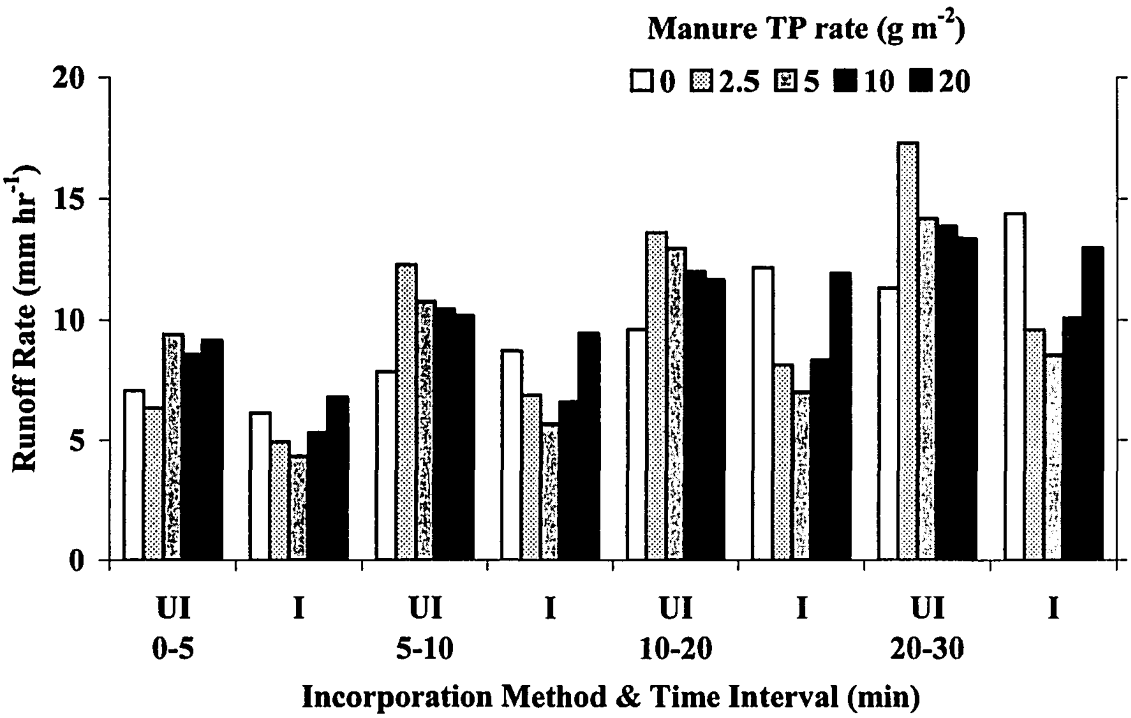

Figure 3.5. Mean runoff rates by time interval and manure total phosphorus (TP) rate for incorporated (I) and unincorporated (UI) treatments from all sites combined

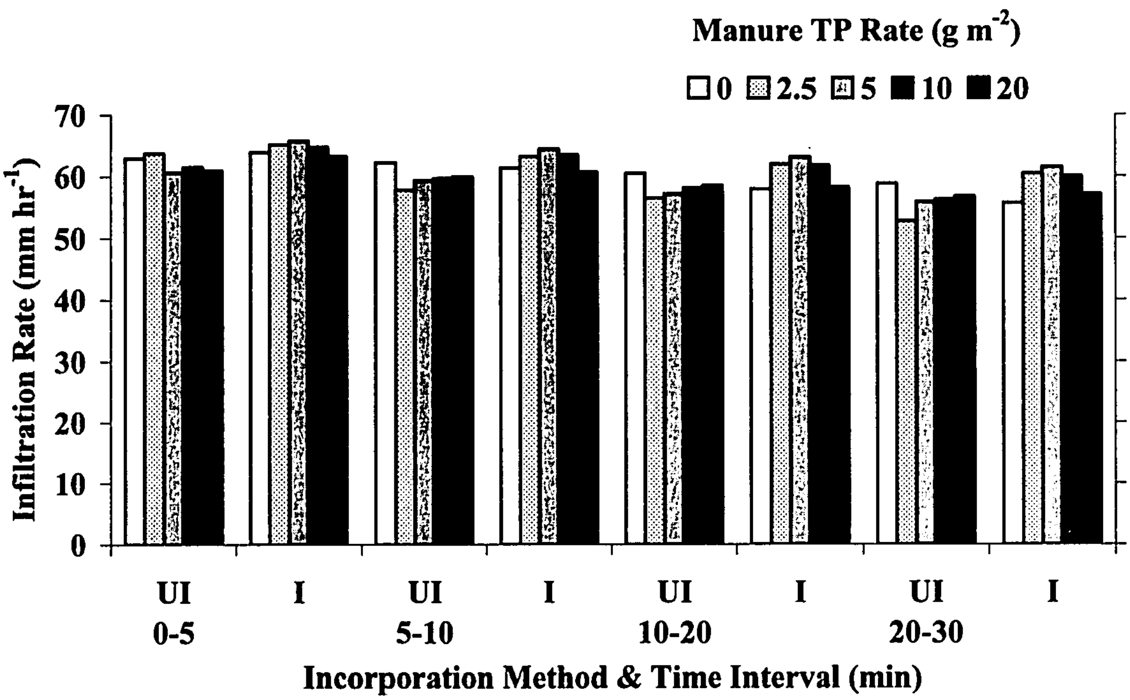

Figure 3.6. Mean infiltration rates by time interval and manure total phosphorus (TP) rate for incorporated (I) and unincorporated (UI) treatments from all sites combined

4. PHOSPHORUS IN SURFACE RUNOFF FROM MANURED AGRICULTURAL LANDS

4.1 Introduction

Phosphorus is an essential nutrient for agricultural crop and livestock production. Though soils can contain high amounts of total phosphorus, they are often limited in their amount of plant available phosphorus (Havlin et al. 1999). As a result, phosphorus additions to agronomic systems have become a common management practice for producers. It was previously believed that phosphorus was not mobile in soil, however, we now understand that phosphorus in surface soils and recently applied inorganic fertilizer or manure can be transported by leaching and surface runoff (Hart et al. 2004 and McDowell et al. 2000). If leachate and surface runoff water can move in appreciable amounts to surface water bodies, eutrophication of these bodies of water can occur. Surface runoff is considered the larger concern of the two transport pathways (Hansen et al. 2002, Sharpley and Reikolainen 1997 and Vadas et al. 2004).

Eutrophication is the process of nutrient enrichment in surface water bodies. Phosphorus tends to exert the limiting control on the degree of eutrophication that occurs (Sharpley and Halvorson 1994). Carbon and nitrogen are also involved in eutrophication but freely exchanged between the atmosphere and surface water, making them more abundant than phosphorus. Elevated levels of phosphorus in water promote aquatic plant and algal growth. Decomposition of these organisms leads to depleted oxygen, fish mortality and the production of toxic substances. These processes impair water use for recreational, domestic, agricultural, fishery and industrial purposes (Sharpley and Halvorson 1994).

Nutrients in runoff from urban and agricultural lands have been identified as the leading source of surface water impairment in the United States (U.S. EPA 2002). In Canada, eutrophication due to phosphorus enrichment of wetlands, rivers and lakes has been linked to municipal, agricultural and industrial sources (Environment Canada 2001). An assessment of water quality in Alberta found that phosphorus concentrations in lakes and streams increased with increasing intensity of agricultural activity (CAESA 1998). Alberta has some of the most eutrophic surface waters in North America which means they are highly sensitive to phosphorus additions from natural and anthropogenically induced sources (Howard et al. 1999).

Many countries have begun regulating nutrient inputs to aquatic ecosystems as they realize the crucial role nutrients play in accelerated eutrophication (Chambers et al. 2001). For example, the Alberta Surface Water Quality Guidelines for total phosphorus (TP) is 0.05 mg L^{-1}, which is a chronic guideline for the protection of freshwater aquatic life (Alberta Environment 1999). Alberta Environment, formerly Alberta Environmental Protection, also requires treated municipal wastewater to contain 1.0 mg L^{-1} total phosphorus (TP) or less before it is released to surface waters (Alberta Environmental Protection 1997). These types of guidelines are easily applied to point sources of phosphorus such as release of treated wastewater from municipal and industrial sources. However, non-point sources of phosphorus such as runoff from agricultural land and urban areas are not as simple to identify, measure or control. Several provincial governments in Canada have limited manure applications to soils based on nitrogen application rates in the attempt to reduce nutrient transfers from soil to surface waters (Environment Canada 2001). However, manure applications based on crop requirements for nitrogen typically contain phosphorus amounts well beyond crop needs.

4.1.1 Phosphorus in Soil

Natural sources of phosphorus present in soil and water originate from the weathering of phosphorus-containing rock such as apatite (Chambers et al. 2001). Phosphorus is an unstable element and, as a result, is naturally found with oxygen in the form of orthophosphate. As mineral weathering, plant uptake and microbial activity occur, phosphorus disperses through soil in various inorganic and organic forms. Organic phosphorus is derived from microbial degradation of plant and animal residue (Campbell and Edwards 2001).

Phosphorus in soil can be separated into three pools. Nonlabile phosphorus is a very stable form of orthophosphate ($H_2PO_4^{2-}$) adsorbed to mineral surfaces (Havlin et al. 1999) and occurring as complex organic molecules. The labile pool exists as orthophosphate ($H_2PO_4^{2-}$ or $H_2PO_4^{-}$) adsorbed to soil particles and organic matter, desorbing or mineralizing more readily than the nonlabile pool (Havlin et al. 1999). The third portion, solution phosphorus, is freely dissolved in soil solution. Phosphorus in soil solution is absorbed by plants and used in energy transfer and storage for plant growth and reproductive processes (Havlin et al. 1999).

As solution phosphorus is removed from the soil by plant uptake, inorganic labile phosphorus desorbs into solution. Nonlabile phosphorus is then transferred to the labile pool in order to maintain equilibrium (Havlin et al. 1999). When plant uptake occurs, inorganic labile phosphorus is also replenished by mineralization of phosphorus from organic forms (Sharpley and Halvorson 1994). Release of nonlabile phosphorus from mineral surfaces occurs slowly and thus is the controlling factor of phosphorus concentrations in solution (Havlin et al. 1999).

Factors such as type of soil minerals affect phosphorus concentrations in soil solution. Highly weathered acidic soils containing iron and aluminum oxides can adsorb large amounts of phosphorus (Havlin et al. 1999). As well, more phosphorus is adsorbed in soils of high clay content than sandy soils (Sharpley and Halvorson 1994). These factors will lessen the amount of phosphorus in soil solution relative to the labile and nonlabile pools.

Phosphorus solubility is also controlled by soil pH. Calcium present in the soil under highly basic conditions and iron and aluminum present under highly acidic conditions will decrease phosphorus solubility (Hausenbuiller 1985). A neutral soil pH tends to create the most soluble atmosphere for phosphorus at which calcium, iron and aluminum tend to lose their effectiveness in precipitating phosphorus (Hausenbuiller 1985).

Organic matter in soil will tend to increase phosphorus in soil solution. Organophosphate complexes, derived from decomposing organic material, compete with inorganic phosphorus for adsorption sites on soil particles and iron and aluminum oxides shifting more phosphorus to soluble forms (Havlin et al. 1999). Organic matter also provides additional inorganic phosphorus through mineralization. Recent additions of manure increase the amount of phosphorus available to plants in soil solution. Over time, these phosphorus additions tend to migrate toward more stable forms in the labile and nonlabile pools (Hausenbuiller 1985).

Higher temperatures can decrease or increase solution phosphorus. Higher air temperatures increase adsorption of phosphorus to soil and absorption of phosphorus by plants, both of which reduce phosphorus in solution (Havlin et al. 1999). Also, soils in warmer climates tend to be more weathered and thus have greater amounts of iron and aluminum oxides available to bind with phosphorus (Havlin et al. 1999). Alternately, microbial activity is enhanced by higher soil temperatures, which increase phosphorus mineralization from organic sources to the labile and soluble pools (Havlin et al. 1999).

Available phosphorus is an agronomic term referring to phosphorus that is readily available for plant absorption. This includes phosphorus in soil solution as well as a portion of labile phosphorus that is very easily transferred to solution phosphorus. Several soil tests have been developed to approximate plant available phosphorus. Common tests in North America include the Olson P, Mehlich-3 P, Bray P1 and modified Kelowna phosphorus tests. The Olson phosphorus test was developed for use on high pH soils while the Bray P1 test is more suitable for low pH soils (Howard et al. 1999). The Mehlich-3 and modified Kelowna tests are suitable for a wide range of soil pH levels and are most commonly used in the United States and the Canadian prairie provinces, respectively (Howard et al. 1999). Phosphorus results attained from these tests are often referred to as soil test phosphorus (STP) values.

Crops with sufficient phosphorus in soils have good root growth, proper seed formation and mature earlier (Havlin et al. 1999). The addition of phosphorus to soils is also known to increase straw strength in cereals and to increase the quality and disease resistance of fruits, vegetables, forages and cereal crops (Havlin et al. 1999).

4.1.2 Phosphorus Transport

Phosphorus is transported from soil to surface water in particulate and dissolved forms. Particulate forms of phosphorus are those attached to soil and organic particles eroded from the soil surface with runoff. These phosphorus laden particles tend to settle to the bottom of lakes and streams becoming a long-term, slowly released source of phosphorus in aquatic systems. Dissolved phosphorus tends to be more immediately available for biologic uptake. Dissolved reactive phosphorus (DRP) is a fraction of phosphorus determined by photometric analysis that is intended to represent orthophosphate, the dissolved inorganic fraction. Dissolved unreactive phosphorus (DURP) is calculated as the difference between total dissolved phosphorus (TDP) and

DRP, intended to represent the dissolved organic fraction. Relative portions of particulate and dissolved phosphorus in surface runoff depend on the terrestrial environment from which they were generated. Soils with a highly erosive nature will produce surface runoff with the particulate portion outweighing the dissolved portion of phosphorus. Soil erosivity is affected by such factors as clay content, infiltration capacity, surface roughness, litter cover, slope and rainfall intensity. Greater dissolved phosphorus concentrations in runoff are generally attributed to high amounts of soluble phosphorus in surface soils, surface residue and inorganic and organic fertilizer applications.

4.1.3 Phosphorus and Manure

When readily available, livestock manure can be an inexpensive source of nutrients for agricultural crops. Manure increases soil fertility; improves physical properties such as water infiltration and retention; and can reduce erosion by improving ground cover (Sharpley and Halvorson 1994). However, phosphorus in manure is highly variable (Sharpley and Halvorson 1994). Because of this, it can be difficult to apply manure at a constant phosphorus rate across large areas of land.

Several studies have linked increased phosphorus in runoff with increased STP. A large portion of these studies has identified a linear relationship with STP values less than 500 mg kg^{-1} (Aase et al. 2001, Andraski and Bundy 2003, Cox and Hendricks 2000, Pote et al. 1996, Pote et al. 1999, Sharpley 1995, and Wright et al. 2003). A study conducted on Danish soils with a large range of phosphorus reported an exponential relationship between soil phosphorus and dissolved phosphorus in runoff (Sibbsen and Sharpley 1997). Daverede et al. (2003) reported an S-curve relationship between phosphorus in runoff and STP (levels as high as 1300 mg kg^{-1}). Andraski and Bundy (2003) concluded that factors such as high residue surface cover, recent manure additions and low soil permeability could alter the relationship between available phosphorus in soil and dissolved phosphorus concentrations in runoff. Bundy et al. (2001) stated that the relationship between STP and phosphorus loss in runoff could be masked if manure had recently been applied to soil. While extensive research has been completed in the area of phosphorus transfer from soil to water, few studies have discussed the effects recently applied fertilizers and manures on phosphorus loss (Hart et al. 2004).

In many studies, manure incorporation has reduced DRP concentrations and loads in runoff compared to surface applied manure (Cox and Hendricks 2000, Daverede et al. 2004, Eghball and Gilley 1999, Kleinman et al. 2002, Meuller et al. 1984, Tabbara 2003, Tarkalson and Mikkelsen 2004 and Withers et al. 2001). However, in some cases, incorporation increased particulate phosphorus (PP) concentrations and loads due to greater erosivity (Cox and Hendricks 2000, and Eghball and Gilley 1999). These studies did not have reduced TP levels with incorporation due to the greater particulate portion of phosphorus in runoff. In some of the studies where DRP was the dominant fraction, TP concentrations and loads from incorporated manured treatments were similar to the controls (Daverede et al. 2004, Kleinman et al. 2002, Tabbara 2003 and Tarkalson and Mikkelsen 2004).

Findings differ in the literature with respect to the effect of time on phosphorus concentrations. Daverede et al. (2003) did not observe changes in phosphorus concentrations over the 30-minute duration of runoff of their rain simulation study. However, other studies have observed phosphorus concentrations in runoff declining over the duration of 30 to 90-minute runoff events (Laflen and Tabatabai 1984, Tabbara 2003, and Wright et al. 2003). Laflen and Tabatabai (1984) and Tabbara (2003) found this decreasing trend to be more pronounced for treatments of higher initial phosphorus concentrations where manure was surface applied rather than incorporated.

4.1.4 Objectives

The objective of this chapter was to determine the effect of phosphorus in soil, recently applied manure and incorporation of manure on particulate and dissolved forms of phosphorus in runoff from cultivated land. Also examined was the effect of time on particulate and dissolved forms of phosphorus in runoff over the course of a 30-minute runoff event. Manure TP and water extractable phosphorus (WEP) application rates were evaluated relative to plant available soil phosphorus in regards to their ability to estimate phosphorus concentrations and loads in runoff.

4.2 Materials and Methods

Materials and methods are described in Section 2.

4.3 Results and Discussion

4.3.1 Soil and Manure Characteristics

Pre-treatment STP values at all three sites were relatively uniform with no significant differences among target TP manure rate and incorporation method treatments within each site (data not shown). The Beaverlodge and Raymond sites had mean pre-treatment STP values ranging from 33 to 38 mg kg^{-1} and 40 to 57 mg kg^{-1}, respectively, while the Lacombe site had higher mean STP values ranging from 92 to 108 mg kg^{-1}. The Beaverlodge and Raymond STP values were consistent with values found elsewhere in Alberta for non-manured soils (Wright et al. 2003), while the Lacombe STP values ranged from slightly above to double the values observed in non-manured soils.

Post-treatment STP, including the incorporated or surface applied manure, for the three sites had a positive relationship with target TP manure rate (Table 4.1), but no significant differences were found between the incorporated and unincorporated treatments. Because the phosphorus added by manure greatly exceeded the original levels of phosphorus in the soil, similar STP levels between incorporation treatments suggests that the majority of phosphorus applied remained in the upper 2.5 cm of the soil profile after tillage. This is supported by observations in the field that much of the manure applied was still visible on the soil surface after one pass with a double disc.

Target TP application rates for Beaverlodge were reduced to half those used for the other sites because of the low TP content of manure used. Also, manure applied at full rates could not have been practically incorporated and would have been contrary to typical producer management practices. The Lacombe manure samples collected from each plot at the time of application had a mean moisture content of 69 percent and TP content of 4.7 g kg^{-1} (dry basis) with 25 percent of TP being water extractable (data not shown). Raymond manure samples had a mean moisture content of 47 percent and TP content of 7.4 g kg^{-1}, with 26 percent of TP being water extractable. Beaverlodge manure samples had a mean moisture content of 65 percent and TP content of only 2.8 g kg^{-1}, of which, 17 percent, was water extractable.

Actual rates of phosphorus applied were calculated from TP and WEP content of manure samples collected from each plot and the measured weight of manure applied (Table 4.1). This calculation was further explained in Section 2.4 (Equation 2.2). Despite the variable nature of manure and differences in moisture content with time, the actual rates of TP applied to the Beaverlodge and Lacombe plots were close to the target values. The actual rates tended to be slightly greater than target rates at the Beaverlodge site, whereas the opposite occurred at the Lacombe site. Due to significant drying of the Raymond manure between the times of source pile sampling and application to plots, the measured manure TP rates were approximately twice the target TP rates.

4.3.2 Overview of Relationships to Phosphorus in Runoff

Where not specified in this text, STP refers to results analyzed from post-treatment samples including the surface applied or incorporated manure. Strong correlations between STP and phosphorus flow-weighted mean concentrations (fwmcs) in runoff occurred at Lacombe and Raymond (r^2 from 0.67 to 0.97) with the exception of PP fwmc from the Raymond incorporated treatment (Table 4.2). Similar correlations between STP and phosphorus loads were consistently lower (r^2 from 0.57 to 0.89). Beaverlodge STP/phosphorus fwmc relationships were moderately correlated (r^2 from 0.49 to 0.64) while phosphorus load relationships were poorly to well correlated (r^2 from 0.28 to 0.82). The trend of higher variability for loads than concentrations is likely due to the effects of runoff rate, unaccounted for in these comparisons. Other studies also observed higher variability of phosphorus loads than concentrations in relation to soil phosphorus, attributed to runoff rate variability (Daverede et al. 2003, Daverede et al. 2004, Pote et al. 1999). Mueller et al. (1984) and Schroeder et al. (2004) also observed phosphorus loads differing from phosphorus concentrations due to treatment or extraneous effects on runoff volume or rate.

Raymond PP fwmcs and loads were poorly correlated to Manure TP and Manure WEP application rates and STP relative to other phosphorus fractions in runoff. The PP fraction in runoff collected from Raymond comprised a relatively small portion of TP. Particulate phosphorus could not be calculated from the phosphorus fractions analyzed from Beaverlodge and Lacombe samples. However, we can assume a similar trend for

Lacombe occurred because DRP concentrations from this site comprise a large portion of TP concentrations. Beaverlodge had lower DRP concentrations in the range of one half to one quarter the TP concentrations. The remaining portion would have been comprised of PP and DURP. Other studies have found varying portions of dissolved and particulate forms of phosphorus as well. For experiments involving recently applied manure, DRP concentrations making up a large portion of TP were found by Daverede et al. (2004), Kleinman et al. (2002) and Schroeder et al. (2004). Alternately, Tabbara (2003) found extremely high PP concentrations, approximately 90% of TP, and DRP concentrations less than one tenth of TP. Kleinman and Sharpley (2003) found high DRP concentrations relative to TP at one test site and low DRP concentration from another. Tillage also made a difference in some of these studies. These trends are most likely determined by a number of factors influencing erosivity of the soil.

Across all three sites, Manure TP application rate tended to have a stronger relationship than Manure WEP application rate with all fractions of phosphorus fwmcs and loads in runoff (Table 4.2). Under unincorporated conditions, phosphorus fwmcs and loads tended to be almost as well, or better, correlated to Manure TP as to STP. With incorporation, phosphorus in runoff was not as consistently well correlated to Manure TP as to STP. Beaverlodge DRP fwmcs and loads correlated reasonably well to Manure WEP when manure was not incorporated but no correlation was found under incorporated conditions. At Lacombe, DRP fwmc correlated reasonably well to Manure WEP and even better than Manure TP when manure was incorporated but Manure WEP and DRP load had only a moderately strong relationship (r^2 of 0.45 to 0.50). Raymond TDP and DRP fwmcs and loads related poorly to Manure WEP ($r^2 < 0.30$) with the exception of TDP load (r^2 of 0.65). Similar studies have found a strong linear relationship between water-soluble phosphorus concentration in manure and DRP concentration in runoff (Kleinman et al. 2002) and even better correlation than TP concentration in manure (DeLaune et al. 2004). Kleinman and Sharpley (2003) found similar results to these studies but noted that DRP concentrations did not correlate well with application rate of WEP in dairy manure, poultry manure and swine slurry.

The poor relationship between Manure WEP application rate and phosphorus in runoff may be attributed to the high variability of WEP in manure relative to TP. Manure WEP may be the intuitive choice for stronger relationships to phosphorus in runoff under conditions where TDP comprises the largest portion of TP in runoff. However, sampling methodology used in this study may not have adequately captured WEP present in the manure applied to the rain simulation area. Results discussed in subsequent sections do not include comparisons of phosphorus in runoff to Manure WEP because results tended to be less conclusive and did not contribute a further understanding of the subject than did the results using Manure TP alone.

4.3.3 Flow-weighted Mean Concentrations in Runoff

4.3.3.1 Total Phosphorus Flow-weighted Mean Concentrations

Total phosphorus fwmc values were regressed against Manure TP application rate and post-treatment STP values using linear and non-linear models. The linear relationship between STP and TP fwmc at Beaverlodge had a better fit for both incorporation treatments (Table 4.2). The unincorporated model had significantly greater TP fwmc estimates at comparable STP values above 50 mg kg^{-1} and the difference increased with increasing STP (Table 4.3, Figure 4.1). The Manure TP/TP fwmc regressions were best represented by an S-curve relationship for unincorporated treatments and a linear relationship for incorporated treatments (Table 4.2). A similar trend was observed between incorporation treatments for Manure TP as for STP. This site had the lowest STP and Manure TP values of all three sites.

TP fwmc relationships with STP and Manure TP from Beaverlodge had the weakest correlations of all three sites with r^2 values from 0.42 to 0.60 (Table 4.2). Beaverlodge also had the smallest portion of DRP within the TP fwmc and the highest total suspended solids (TSS) concentrations (data not shown) indicating a potential for greater PP concentrations relative to the dissolved portion. The actual PP concentration is unknown because the difference between TP and DRP concentrations would also include a DURP portion. In studies with high PP concentration, sediment phosphorus concentration accounted for a portion of the runoff TP variation (Aase et al. 2001, Andraski and Bundy 2003, Cox and Hendricks 2000, and Tabbara 2003). Additionally, Daverede et al. (2003) and Daverede et al. (2004) found sediment concentrations accounted for ten and three times the variation of TP concentration than Bray P1 extraction values from soil, respectively. The high clay content and low infiltration capacity of the Beaverlodge soils may have increased erosion and thus had lower DRP concentrations relative to the other sites. In this case, STP or Manure TP alone would not adequately explain concentrations of TP present in runoff.

At Lacombe, relationships between STP and TP fwmc were nonlinear for both incorporation treatments (Table 4.2). Data points were well correlated to S-curve models (r^2 0.88 and 0.90). The x_0 value (x-value at the inflection point) for the unincorporated curve was significantly greater than for the incorporated curve (Table 4.3). For Manure TP/TP fwmc regressions, S-curve and linear relationships best fit the unincorporated and incorporated results, respectively. The two models overlapped each other with similar TP fwmcs at the lower and upper Manure TP values (Figure 4.2). Larger unincorporated TP fwmc estimates occurred between 6 and 8 g m^{-2} Manure TP relative to the incorporated model. TP fwmc relationships from Lacombe were moderately well to very well correlated with r^2 values from 0.68 to 0.91 (Table 4.2). This site measured four times the STP and almost two times the maximum Manure TP of Beaverlodge.

The Raymond STP and Manure TP to TP fwmc relationships were similar to Lacombe and best fit to S-curve models. With STP, the unincorporated TP fwmc had significantly greater y-values at the inflection point (y_i) and the curve maximum (a) than the incorporated model (Table 4.3). No significant differences occurred between incorporated treatments of the Manure TP to TP fwmc regressions (Table 4.3). TP fwmc relationships from Raymond had the strongest correlations of all three sites with r^2 values from 0.90 to 0.97 (Table 4.2). This site measured 17 times the STP and 3 times the Manure TP of Beaverlodge.

TP fwmc showed increasing trends when related to STP and Manure TP application rate from all three sites. Maximum TP concentrations were identified by the models for nonlinear relationships where STP values greater than 200 mg kg^{-1} were measured. The TP fwmc relationships identified as linear tended to have less variability explained by the independent variable than the nonlinear relationships. Three of the four linear relationships found were at Beaverlodge, representing a smaller range of the independent variable. Generally, a nonlinear relationship best represented TP concentrations from the unincorporated treatments over a large range of STP values and Manure TP application rates. Though evidence was less conclusive, a similar trend of nonlinearity could be seen for incorporated treatments. Daverede et al. (2003) found a nonlinear relationship between Bray P1 extraction values in soil and TP in runoff from no-till and chisel plow treatments combined. No differences were observed between the two tillage treatments in their study.

Though differences between incorporation methods varied in magnitude, unincorporated treatments tended to have greater TP fwmcs at a given STP value. Unincorporated TP fwmcs were also greater than incorporated for all Beaverlodge Manure TP application rates, Lacombe Manure TP rates greater than 5 g m^{-2} and Raymond Manure TP rates greater than 12 g m^{-2}. Other studies reported similar differences in TP runoff concentrations with respect to surface-applied and incorporated manure (Daverede et al. 2004, Tabbara 2003, Tarkalson and Mikkelsen 2004, Withers et al. 2001).

4.3.3.2 Particulate Phosphorus Flow-weighted Mean Concentrations

Particulate phosphorus concentrations were calculated for the Raymond site only. The unincorporated relationship between STP and PP fwmc fit best to an S-curve model (r^2 of 0.68) but was determined from data points mostly grouped near the origin with three points scattered widely between the extreme edges of the x and y axis (Table 4.2). PP fwmc had no relationship with STP under incorporated conditions. Similarly, PP fwmc showed no relationship to Manure TP under either incorporation treatment (Table 4.2). As discussed previously in this chapter, the Raymond PP fraction in runoff was relatively insignificant, ranging between 0 and 3 mg L^{-1}.

4.3.3.3 Total Dissolved Phosphorus Flow-weighted Mean Concentrations

Total dissolved phosphorus concentrations were analyzed from samples of the Raymond site only. The relationship between STP and TDP fwmc is best fit to a linear model for the incorporated treatment (Table 4.2). For the unincorporated treatment, this relationship is best fit to an S-curve model (r^2 of 0.83, Table 4.2) though the linear model correlation strength was similar (r^2 of 0.78, data not shown). No observable differences between incorporation treatments were noted below 1000 mg kg^{-1} STP, above which, the incorporated plots did not have STP values (data not shown). TDP fwmc regressed against Manure TP fit best to an S-curve model for both incorporation treatments (Table 4.2). No significant differences occurred between coefficients of the incorporated and unincorporated curves (Table 4.3). These relationships were similar to comparable relationships with TP fwmc and the dependant variable. Tabbara (2003) did find greater dissolved phosphorus concentrations for surface-applied manure treatments relative to incorporated manure. However, this effect was attributed to phosphorus buried below the soil zone of interaction with surface water runoff.

4.3.3.4 Dissolved Reactive Phosphorus Flow-weighted Mean Concentrations

For Beaverlodge, DRP fwmc regressed against STP and Manure TP best fit an S-curve model for the unincorporated treatment and a linear model for the incorporated treatment (Table 4.2). The S-curve for the STP/DRP fwmc unincorporated relationship did not reach a curve maximum (data not shown). Based on observed results for the other phosphorus fractions and the other sites, it is possible that a curve maximum may have been reached under these condition had plots with greater STP values been used. With both STP and Manure TP, DRP fwmc estimates of the unincorporated model are notably greater than estimates of the incorporated model and differences increase with increasing STP and Manure TP values (Figure 4.3). Several other studies also found greater DRP concentrations in runoff from unincorporated manure treatments (Daverede et al. 2004, Eghball and Gilley 1999, Kleinman et al. 2002, Meuller et al. 1984, Tabbara 2003, and Withers et al. 2001).

The Lacombe STP to DRP fwmc relationship fit best to an S-curve model for both incorporation treatments (Table 4.2). No significant differences between curve coefficients of the incorporation treatments occurred (Table 4.3). When DRP fwmc was regressed against Manure TP, the unincorporated treatment best fit an S-curve model and the incorporated treatment was a linear model (Table 4.2). The unincorporated DRP fwmcs at the lower and upper Manure TP values appear similar to the incorporated DRP fwmcs while the unincorporated DRP fwmc estimates at Manure TP values between 6 and 12 g m^{-2} were greater than the incorporated DRP fwmcs (Figure 4.4).

At Raymond, DRP fwmcs regressed against STP and Manure TP fit best to an S-curve for both incorporation treatments (Table 4.2). With STP, DRP fwmc estimates for the inflection point (y_i) and the curve maximum (a) from the unincorporated model were significantly greater than estimates from the incorporated model (Table 4.3). Though, similar to TDP fwmc, DRP fwmc from the incorporated treatment did not measure STP values greater than 1000 mg kg^{-1}. With only three data points residing between 300 and 1000 mg kg^{-1} STP, conclusions based on the estimated curve maximum are limited. No significant differences occurred between curve coefficients of the incorporated and unincorporated models of the Manure TP/DRP fwmc regressions (Table 4.3). Though, the DRP fwmc estimates of the unincorporated model were greater than the incorporated model above 9 g m^{-2} Manure TP. Magnitudes of DRP fwmc at Raymond (0 to 20 mg L^{-1}) tended to be slightly greater than Lacombe (0 to 15 mg L^{-1}).

Generally, relationships between STP or Manure TP application rate and DRP fwmc were best described by a nonlinear relationship. Daverede et al. (2003) found an S-curve relationship between soil Bray P1 extractions and runoff DRP concentrations under non-tilled, unmanured conditions. McDowell and Sharpley (2001) found a split-plot model best represented the soil P/runoff DRP concentration relationship generated by their lab simulations with DRP concentrations increasing more dramatically beyond a critical soil Mehlich-3 phosphorus value of 193 mg kg^{-1}. Daverede et al. (2003) applied a split-plot model to their data below 360 mg kg^{-1} and identified the change point as a Bray P1 soil extraction value of 126 mg kg^{-1}. McDowell and Sharpley's split-plot model, with soil phosphorus values below 700 mg kg^{-1} is, in fact, similar to the lower end of the S-curve relationships found in Daverede et al. (2003) and this study. Many studies finding linear relationships between soil phosphorus and DRP concentrations in runoff have soil phosphorus values less than 500 mg kg^{-1} (Aase et al 2004, Andraski and Bundy 2003, Pote et al. 1996, Pote et al. 1999, Sharpley 1995). Other studies have also linked Manure TP application rate and DRP linearly but at TP application rates of less than 14 g m^{-2} (Cox and Hendricks 2000, DeLaune et al. 2004, Tarkalson and Mikkelsen 2004).

4.3.4 Phosphorus Concentrations over Time

4.3.4.1 Total Phosphorus Concentrations over Time

A significant three-way interaction (time interval by incorporation method by target TP manure rate) as well as a rate by incorporation interaction and singular effects for all factors occurred for TP concentrations from all three sites combined (Table 4.4). Despite the three-way interaction and singular time interval effect, no significant mean differences between time intervals were observed (Figure 4.5, Appendix Table A.1). Contrasts indicated that TP mean concentrations increased linearly with manure rate (data not shown). The range of TP mean concentrations in runoff from varying manure rates was similar for both incorporation methods. Under mean comparison the greatest differences between TP concentrations occurred between the 5 and 10 g m^{-2} rates of the unincorporated treatments and between the 10 and 20 g m^{-2} rates of the incorporated treatments. TP concentrations for a given target rate tended to be greater for the unincorporated plots relative to the incorporated plots but these differences were significant only at the 10 g m^{-2} rate. This trend at the 10 g m^{-2} rate also occurred for each site when analyzed individually (data not shown).

Sites had subtle differences when analyzed individually. At Beaverlodge, the three-way interaction was not significant but incorporation method by target TP manure rate and by time interval interactions and all singular effects were significant (Table 4.4). As with sites combined, contrasts for Beaverlodge indicated a significant linear TP concentration response to manure rate (data not shown). TP concentrations from the incorporated plots did not exceed 3.3 mg L^{-1} of the manured rates ranging from 0 to 10 g m^{-2}. This was considerably lower than concentrations from comparable treatments of other sites. These differences did not impact the overall trends of the site relative to trends observed for the three sites combined up to a target rate of 10 g m^{-2}.

Lacombe had only a target TP manure rate by incorporation method interaction and a target rate effect but trends also varied little from the combined results (Table 4.4). In addition to the differences observed between the incorporated 10 and 20 g m^{-2} rates, a significant difference between the incorporated 0 and 5 g m^{-2} manure rates occurred (data not shown).

Raymond only had significant target TP manure rate and time interval effects (Table 4.4). The significant linear positive relationship between TP concentration and manure rate occurred for Raymond as did for all sites combined (data not shown). The greatest mean TP concentrations of the three sites occurred at Raymond and are likely attributable to the greater amount of TP actually applied in manure at this site. Mean comparisons identified significant differences between all manure rates (data not shown). Despite the significant time interval effect, no significant differences of means between time intervals occurred. Incorporation as an effect or as part of an interaction was not significant (Table 4.4). However, unincorporated TP mean concentrations were significantly greater than the incorporated means at the 10 g m^{-2} manure rate as noted for all other sites. Because the three-way interaction was not significant, this observation is based on an unprotected F-test.

Incorporation appears to have been most effective in reducing TP concentration in runoff water when 10 g m^{-2} of Manure TP was targeted. This is consistent with regression results of TP fwmc compared to Manure TP for all sites combined (Section 4.3.3.1). Incorporation had the least effect on TP concentrations from the unmanured and lesser manured plots. This may be implying a delayed TP fwmc response to manure rate when manure was incorporated. However, at higher TP application rates (20 g m^{-2}) incorporation did not appear to have a decreasing effect on TP concentrations in runoff.

No differences in TP concentrations across the 30 minutes of simulation runoff were evident at the three sites. Daverede et al. (2003) similarly found unchanging TP concentrations over the duration of their simulations. Alternately, McDowell and Sharpley (2002) found TP concentration decreased over 30 minutes of runoff from unmanured soils attributed to higher initial transport of finer soil particles that would have contained more phosphorus than coarser particles.

4.3.4.2 Particulate Phosphorus Concentrations over Time

Particulate phosphorus concentrations were calculated for the Raymond site only. PP accounted for a very small portion of the TP runoff concentrations measured throughout this study with means ranging from 0.3 to 1.7 mg L^{-1} compared to TP means of 1.3 to 16.1 mg L^{-1}. Two-way target TP manure rate by time interval and by incorporation method interactions and a singular rate effect were the only significant interactions and effects for PP mean concentrations measured at the Raymond site (Table 4.4). Despite the significant target rate by time interval interaction identified by ANOVA, no significant differences between means were observed (data not shown). Contrasts identified a significant linear-positive trend of PP mean concentration with manure rate (data not shown). Mean PP concentrations from unincorporated treatments increased with each increasing manure rate though a significant difference was only detected between the 5 and 10 g m^{-2} rates (data not shown). Mean PP concentrations from incorporated treatments did not differ significantly among manure rates. The incorporated unmanured PP mean concentration was significantly greater than the unincorporated unmanured mean value (data not shown). PP concentrations for the 10 and 20 g m^{-2} rates had the opposite significant differences.

4.3.4.3 Total Dissolved Phosphorus Concentrations over Time

Total dissolved phosphorus concentrations were analyzed for the Raymond site only. Target TP manure rate and time interval effects occurred for Raymond TDP concentrations in runoff but no incorporation effect or interactions were significant (Table 4.4). The positive linear relationship between TDP concentration and target rate was significant according to contrasts (data not shown). Mean comparisons confirmed this relationship, identifying significant TDP concentration increases with increasing target rates (Figure 4.6, Appendix Table A.2). Despite the time effect identified by ANOVA, no significant differences occurred between means of differing time intervals.

Though the three-way interaction was not significant, similar patterns to TP concentrations were observed for TDP concentrations at Raymond. An unprotected F test identified significant differences between incorporation methods at the 10 g m^{-2} rate (data not shown). Also, greatest increases were noted between 5 and 10 g m^{-2} rates for the unincorporated treatment and between 10 and 20 g m^{-2} rates for the incorporated. These results coincide with regression results found between Manure TP and TDP fwmc (Section 4.3.3.3), noting actual Manure TP rates were double the target rates.

4.3.4.4 Dissolved Reactive Phosphorus Concentrations over Time

A significant three-way time interval by incorporation method by target TP manure rate interaction was detected for the runoff DRP concentrations from all three sites combined (Table 4.4). In fact all factors individually and all two-way interactions were also significant. Trends for DRP concentrations were similar to those observed for TP concentrations in runoff. Contrasts identified a significant positive linear trend between DRP mean concentration in runoff and manure rate (data not shown). The range of means for DRP concentrations was similar for both incorporation methods. As with TP, mean comparisons identified a significant increase in DRP concentrations from 5 to 10 g m^{-2} rates for unincorporated treatments while the incorporated treatment increased most dramatically between the 10 and 20 g m^{-2} rates (Figure 4.7, Appendix Table A.3). The unincorporated manured treatments tended to have greater DRP concentrations than the incorporated manured treatments, though only significantly for the 10 g m^{-2} rate. This trend is similar to regression results of DRP fwmc to Manure TP that show unincorporated models increasing sharply at lower Manure TP rates than incorporated models. Very little difference was observed between incorporation methods for the unmanured (0 g m^{-2}) treatments, also consistent with regression results. Despite a significant three-way interaction detected by ANOVA, mean comparisons did not reveal significant differences of the linear relationships across time intervals.

Trends in DRP runoff concentrations at Beaverlodge were closely aligned with those from all three sites combined (Table 4.4). This site was the only one to not have a significant time interval effect. It had considerably lower DRP concentrations than the other sites, for target manure rates up to 10 g m^{-2}, with means ranging from 0.1 to only 3.7 mg L^{-1}. Similar to regressions of Manure TP and DRP fwmc, DRP concentrations from unincorporated treatments were greater than from incorporated treatments and this difference increased with increasing manure rates (data not shown).

For Lacombe, the two-way interactions between all three effects on DRP runoff concentrations were significant, while the three-way interaction and incorporation method as a single factor were not (Table 4.4). DRP concentrations closely followed patterns found for sites combined, with the largest increase of unincorporated plots occurring between 5 and 10 g m^{-2} rates and from 10 to 20 g m^{-2} for incorporated plots (data not shown). Consistent with TP from sites combined, Lacombe unincorporated means of the 10 g m^{-2} rate were significantly greater than incorporated means. For all other target rates, unincorporated means tended to be less than incorporated, though differences were insignificant.

At the Raymond site, all factors either singly, two-way or three-way were significant for DRP concentrations in runoff (Table 4.4). This site yielded the highest DRP concentrations among the three sites, with concentrations ranging from 0.2 to 19.7 mg L^{-1}. A more steady increase in DRP concentrations with manure rate was observed for unincorporated plots (data not shown). Unincorporated treatments were significantly greater than those from the respective incorporated treatments (data not shown). The Raymond incorporated treatments followed a similar pattern to sites combined with the largest DRP increase between 10 and 20 g m^{-2} rates. A significant difference also occurred between the unincorporated 0 and 5 g m^{-2} rates. Unincorporated DRP concentrations were significantly greater from incorporated plots within the 10 and 20 g m^{-2} rates. These differences were observed in the regression analysis for Manure TP and DRP fwmc but were not significant (Section 4.3.3.4).

Though DRP concentrations from this study did not notably change over 30 minutes of runoff, other studies found changes over longer time periods. Laflen and Tabatabai (1984) observed decreases in runoff DRP concentrations over 90 minutes of runoff. The largest decreases over time occurred from the plots with highest initial DRP concentrations, the unincorporated inorganic fertilizer treatments. The incorporated fertilized and unfertilized treatments had more subtle or no decreases over time. Tabbara (2003) observed a similar decreasing trend during a 90-minute runoff event with the highest DRP concentrations from broadcast manure treatments showing the greatest decrease. Wright et al. (2003) also observed decreasing trends over 90 minutes of laboratory and field simulation runoff from a wide range of soil types, some with long-term histories of beef or hog manure applications.

4.3.5 Thirty-minute Loads

4.3.5.1 Total Phosphorus Thirty-minute Loads

Beaverlodge TP loads, regressed against STP, fit best to a nonlinear model for the unincorporated treatment and a linear model for the incorporated treatment (Table 4.2). Similar to TP fwmc, TP load estimates of the S-curved unincorporated model were greater than estimates of the incorporated treatment and the difference increased with increasing STP values. The Manure TP/TP load relationships for both incorporation treatments were linear (Table 4.2). The Manure TP by incorporation treatment effect and singular effects were significantly different with unincorporated TP load estimates greater than estimates of the incorporated model (Table 4.3). Beaverlodge TP loads ranged between 0 and 200 g m^{-2}.

Lacombe TP loads regressed against STP and Manure TP best fit a nonlinear model for the unincorporated treatment a linear model for the incorporated treatment (Table 4.2). Similar to TP fwmcs, the unincorporated S-curve twice intersected the incorporated linear models relating TP load to STP and Manure TP (data not shown). Unincorporated TP loads tended to be lower than incorporated TP loads at STP values less than 200 mg kg^{-1} and Manure TP values less than 6 g m^{-2}. Beyond these values, TP load was more variable for both incorporation treatments and no discernable differences were noted. Lacombe TP loads were similar in magnitude to Beaverlodge.

TP loads from Raymond were best fit to an S-curve model for both incorporation treatments (Table 4.2). The incorporated model had significantly greater TP load estimates at the inflection point (y_i) and curve maximum (a) than the unincorporated model (Table 4.3). These differences were opposite to differences observed for the STP to TP fwmc relationships. When TP load was regressed against Manure TP, linear models best represent the relationships for each incorporation treatment (Table 4.2). No significant interactions or effects between the incorporation treatments occurred (Table 4.3). Raymond TP loads were similar in magnitude to Beaverlodge and Lacombe.

Trends for TP loads were consistent with TP fwmcs in that both tended to increase with increasing STP and Manure TP application rates. However, unincorporated relationships tended to be nonlinear while incorporated relationships tended to be linear. Generally, TP loads were more variable than TP fwmc when regressed against STP and

Manure TP because of the effect of runoff volumes as discussed previously in this chapter. Beaverlodge runoff volumes, and subsequently TP loads, had the largest differences between incorporation treatments. Raymond TP loads showed opposite trends to TP fwmcs of greater loads from incorporated treatments. This difference may be attributed to slightly greater volumes from incorporated than unincorporated treatments.

4.3.5.2 Particulate Phosphorus Thirty-minute Loads

Particulate phosphorus loads were calculated for the Raymond site only. When regressed against STP and Manure TP, PP loads fit best to an S-curve model for the unincorporated treatment (Table 4.2). PP loads did not correlate with STP or Manure TP for the incorporated treatment. These loads ranged between 0 and 10 g m^{-2}, a very small portion of TP loads.

4.3.5.3 Total Dissolved Phosphorus Thirty-minute Loads

Total dissolved phosphorus loads were calculated for the Raymond site only. Relationships between STP and TDP load fit best to an S-curve model for both incorporation methods (Table 4.2). A linear relationship fit best for the Manure TP/TDP load regressions (Table 4.2). No significant differences between S-curve or linear models of the incorporation treatments were found (Table 4.3). Magnitudes of TDP loads were similar to TP loads ranging between 0 and 200 g m^{-2}.

4.3.5.4 Dissolved Reactive Phosphorus Thirty-minute Loads

When regressed against STP and Manure TP, Beaverlodge DRP loads best fit an S-curve model for the unincorporated treatment and a linear model for the incorporated treatment (Table 4.2). Similar to DRP fwmcs, DRP loads were greater from the unincorporated than the incorporated treatment and the difference increased with increasing STP and Manure TP values (Table 4.3). For Beaverlodge, DRP loads ranged between 0 and 60 g m^{-2}, less than half the TP load range. Daverede et al. (2003) also observed an S-curve relationship between Bray P1 soil extraction values (no manure added) and DRP loads with tilled treatments loads notably greater than untilled. Several additional studies found greater DRP loads in runoff from unincorporated manure treatments (Daverede et al. 2004, Eghball and Gilley 1999, Kleinman et al. 2002, Mueller et al. 1984, Tabbara 2003).

Similar to Lacombe DRP fwmcs, the Lacombe unincorporated treatments for STP and Manure TP to DRP load relationships were best represented by S-curve models and the incorporated treatments by linear models (Table 4.2). The unincorporated DRP loads were less than incorporated at STP values below 180 mg kg^{-1} and Manure TP values below 6 g m^{-2}. Above these points, the unincorporated DRP loads were more scattered, ranging to values greater than and less than incorporated DRP loads at similar STP and Manure TP levels. Differences in DRP loads between incorporation methods were not as large for Lacombe as for Beaverlodge. Also, DRP loads were greater for Lacombe, ranging between 0 and 150 g m^{-2}.

At Raymond, the STP/DRP load relationships for both incorporation treatments best fit an S-curve model while a linear model best suited the Manure TP/DRP load relationships (Table 4.2). In both cases, no significant differences occurred between the model coefficients (Table 4.3). If fact, the curves and lines on these figures, representing models from both incorporation treatments, are almost indiscernible from one another (data not shown). For Raymond, DRP loads were similar in magnitude to Lacombe.

As with other studies, loads from this study had trends similar to those observed for concentrations of each phosphorus fraction. However, as with TP loads, DRP loads tended to be more variable due to the influence of runoff rate.

4.3.6 Loads over Time

4.3.6.1 Total Phosphorus Loads over Time

A three-way time interval by incorporation method by target TP manure rate interaction was significant for TP load in runoff when all sites were combined (Table 4.4). Target rate by incorporation and by time interval interactions and singular rate and time effects were also significant. Contrasts identified a significant positive linear relationship between TP load and target rate (data not shown). However, this relationship showed significant nonlinearity when separated by incorporation methods. TP loads were often greater from the unincorporated than the incorporated treatments and were significantly different within the 10 g m^{-2} rate during the latter two time intervals (Figure 4.8, Appendix Table A.4). Similar to TP concentrations in runoff, the largest TP load increase from the unincorporated treatments occurred between the 5 and 10 g m^{-2} rates. Differing from concentrations, unincorporated TP loads experienced little to no change between the 10 and 20 g m^{-2} rates. TP loads from the incorporated treatment increased greatest between 10 and 20 g m^{-2}, also consistent with TP concentrations. Over the 30 minutes of runoff, TP loads consistently increased within each manure rate. Significant increases were observed between the middle two time intervals of the unincorporated 10 and 20 g m^{-2} rates and the incorporated 20 g m^{-2} rate. These increases over time are largely a function of increasing runoff rates as opposed to changing concentrations over time.

When viewed independently, Beaverlodge showed similar, though more dramatic, trends compared to the three sites combined. All two and three-way interactions and singular effects were significant (Table 4.4). According to contrasts, the TP load to target manure rate relationship was significantly linear (data not shown). Since the primary cause of nonlinearity for all three sites involved the 10 and 20 g m^{-2} rates, comparisons to Beaverlodge are not possible due to its lack of a 20 g m^{-2} manure rate. Despite Beaverlodge's lower manure rates and runoff TP concentrations, TP loads from unincorporated treatments were greatest of the three sites, especially as manure rate and time interval increased, with loads as high as 57 g m^{-2}. Though TP load from the incorporated treatments tended to increase with time and manure rate, these differences were not significant (data not shown). Unincorporated TP loads were consistently greater than incorporated loads and were significantly greater for the 2.5, 5 and 10 g m^{-2} rates. A similar trend was observed in the regression analysis results for Manure TP and TP load (Section 4.3.5.1). The effect of manure incorporation on TP loads at Beaverlodge was magnified relative to TP concentrations because of the extreme decrease in runoff volumes as a result of tillage.

Lacombe TP loads in runoff had significant two-way target TP manure rate by incorporation method and by time interval interactions as well as singular rate and time effects but the three-way interaction was not significant (Table 4.4). Despite this difference, trends observed for this site were similar to trend of the three sites combined.

Raymond TP loads had a significant two-way target TP manure rate by time interval and singular target rate and time effects only (Table 4.4). The positive linear relationship between TP load and manure rate was significant, according to contrasts (data not shown). During the initial two time intervals, significant differences between means occurred only between the 10 and 20 g m^{-2} manure rates (data not shown). For the latter two time intervals, significant differences occurred between 0 and 5 g m^{-2} rates and between 10 and 20 g m^{-2} rates. Mean TP loads from both incorporation methods behaved similar to unincorporated loads from Beaverlodge and Lacombe. TP loads increased significantly between the initial and latter two time intervals of the 5, 10 and 20 g m^{-2} manure rates (data not shown).

Trends between Manure TP and TP loads were similar to trends for TP concentrations with the added variability due to runoff rates. Loads tended to increase over the 30 minutes of runoff collected in direct proportion to increased runoff rates.

4.3.6.2 Particulate Phosphorus Loads over Time

Particulate phosphorus loads were calculated for the Raymond site only. As with PP concentrations, PP loads measured at all sites comprised a relatively small portion of TP loads, 0.5 to 1.8 g m^{-2} compared to 0.5 to 42.1 g m^{-2}. A target two-way TP manure rate by incorporation method interaction and a time interval effect were significant for Raymond (Table 4.4). Mean PP loads from the unincorporated treatments increased steadily but were only significant between the unmanured and the 20 g m^{-2} manured treatments (data not shown). Mean PP loads from the unmanured incorporated treatment was greater but not significantly different from the manured incorporated means (data not shown). No mean differences were found between incorporation treatments. PP mean loads were similar within the first 10 minutes and increased steadily till the end of the simulation (data not shown). The mean PP load for the final interval was significantly greater than the loads of the initial 10 minutes (data not shown). As for TP loads, the increasing trend of PP loads over time is a results of increased runoff rates.

4.3.6.3 Total Dissolved Phosphorus Loads over Time

Total dissolved phosphorus loads were calculated for the Raymond site only. Similar to TP loads in runoff, a two-way target TP manure rate by time interval interaction and the associated singular effects occurred for TDP loads in runoff but a three-way interaction was not significant (Table 4.4). A significant positive linear relationship occurred between TDP load and manure rate, according to contrasts (data not shown). TDP trends and magnitudes were very similar to those observed for TP loads at Raymond. No incorporation effects were observed (Table 4.4). Significant TDP load increases were observed during the latter two time intervals from the 0 to 5 and 10 to 20 g m^{-2} rates (Figure 4.9, Appendix Table A.5). During the initial two time intervals, TDP load only increased significantly between the 0 and 20 g m^{-2} target manure rates. As with TP and PP loads, runoff rates largely drove trends for TDP loads in runoff.

4.3.6.4 Dissolved Reactive Phosphorus Loads over Time

A significant three-way interaction occurred for DRP loads with all three sites combined (Table 4.4). Two-way interactions involving target TP manure rate by time interval and by incorporation method and singular effects of target rate and time interval were significant (Table 4.4). Contrasts indicated a positive linear relationship between DRP runoff load and manure rate with a tendency toward a non-linear relationship in the later two time intervals (data not shown). Trends for DRP load were similar to TP and TDP loads though magnitudes were less (Figure 4.10, Appendix Table A.6). For unincorporated treatments, significant DRP load increases with manure rate existed in the later two time intervals with the greatest increases occurring from 0 to 2.5 kg ha^{-1} and 5 to 10 g m^{-2} manure rates. DRP loads for incorporated treatments had only a significant increase from 10 to 20 g m^{-2} manure rates that occurred during all but the first time interval. DRP loads from unincorporated treatments were consistently greater than incorporated treatments for the 2.5, 5 and 10 g m^{-2} rates but the opposite trend occurred for the unmanured 20 g m^{-2} rate treatment. The only significant differenced between incorporation methods occurred during the 10 to 20 minute interval at 10 and 20 g m^{-2} rates and during the 20 to 30 minute interval at 2.5 and 10 g m^{-2} rates.

All two-way and three-way interactions and singular effects were significant for Beaverlodge DRP loads (Table 4.4). As for sites combined, Beaverlodge DRP load had a significant linear relationship to target manure rate with nonlinear tendencies during the latter two time intervals (data not shown). Unincorporated DRP loads were significantly greater than incorporated for all manured plots (data not shown). No significant differences occurred between incorporation methods of the unmanured (0 g m^{-2}) plots. DRP loads from unincorporated plots tended to increase significantly between each manure rate from 0 to 10 g m^{-2}. Loads from these plots also increased with time intervals though significant differences were only detected between the middle two intervals at 2.5, 5 and 10 g m^{-2} rates and between the latter two intervals at the 10 g m^{-2} rate (data not shown). DRP loads from incorporated plots tended to increase with target rate and with time, though nonsignificantly (data not shown).

DRP loads from Lacombe closely followed the trends of all sites combined (Table 4.4). Lacombe DRP loads tended to be slightly greater than for all sites combined, ranging from 0.7 to 44.8 g m^{-2}.

Significant two-way time interval by target TP manure rate and by incorporation method interactions and singular time and target rate effects occurred for Raymond DRP loads (Table 4.4). Contrasts indicated a linear DRP load to target rate relationship with no evidence of nonlinearity (data not shown). No significant differences occurred between incorporation methods (data not shown). These observations are consistent with results from regression analysis comparing DRP loads to Manure TP (Section 4.3.5.4). DRP loads consistently increased with target rate and time interval (data not shown). Loads were significantly different between the 0 and 20 g m^{-2} rates during the 5 to 10 minute time interval and from the 0 to 5 and 10 to 20 g m^{-2} rates from the latter two intervals. The differences in DRP load over time increased with target manure rate.

As for all other phosphorus fractions, DRP loads closely followed trends for DRP concentrations with variation due to runoff rate. Increasing DRP loads over time is a trend consistent with other phosphorus load fractions and a direct result of increasing runoff rates.

4.4 Conclusion

Results of this experiment indicate that phosphorus in runoff:

- Was greater from manured soils than unmanured soils.
- Increased with increasing rates of manure application showing evidence of nonlinearity.
- Tended to be less from soils with incorporated than surface applied manure, most notably at the greater manure rates.
- Did not significantly change over 30 minutes of runoff collected.
- Correlated better to total phosphorus than to water extractable phosphorus manure application rates.

Other noteworthy observation included:

- Similar concentrations of phosphorus in soil with surface applied and incorporated manure, indicated little to no burial of manure below the 2.5 cm sampling depth with double disk incorporation.
- Large portions of total phosphorus occurred as dissolved reactive phosphorus, at two of the three sites, indicating a lesser degree of soil erosion than reported by some similar studies.
- Similar phosphorus load and concentration responses occurred with imposed treatments, although loads were more variable and increased with time as influenced by runoff volumes.

4.5 References

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Table 4.1. Mean soil-test phosphorus (STP), manure total phosphorus (TP) and manure water extractable phosphorus (WEP) values of the three rain simulation sites

Site	Incorporation Method[z]	Target Total Phosphorus Manure Rate	n	Post-treatment STP[y]	Manure TP Rate	Manure WEP Rate
		($g\ m^{-2}$)		----- ($mg\ kg^{-1}$)	------------------ ($mg\ m^{-2}$) [x,w]	-------------
Beaverlodge	UI	0	3	45 b	na	na
		2.5	2	85 a	2586	393
		5	3	96 a	5276	765
		10	3	108 a	10019	1547
	I	0	4	48 b	na	na
		2.5	3	60 a	2971	472
		5	3	83 a	4991	1014
		10	4	113 a	11057	1815
Lacombe	UI	0	4	127 j	na	na
		5	3	169 j	4494	923
		10	3	220 i j	10142	1832
		20	4	341 h i	16757	4732
	I	0	4	107 j	na	na
		5	3	144 j	3667	920
		10	4	165 j	10038	1955
		20	3	395 h	18794	6773
Raymond	UI	0	3	43 r	na	na
		5	3	175 r	13339	2945
		10	2	649 p q r	21017	5555
		20	2	1794 p	34183	7756
	I	0	2	53 r	na	na
		5	2	134 r	9694	3049
		10	3	493 q r	18990	4782
		20	2	1176 p q	37440	6613

z. Unincorporated (UI) and incorporated (I) treatments

y. Mean values for each site followed by the same letter are not significantly different at $P < 0.05$. Significant differences between means were only tested within each site.

x. $100\ mg\ m^{-2} = 1\ kg\ ha^{-1}$

w. not applicable (na)

Table 4.2. Summary of regression results for phosphorus fractions in runoff compared to phosphorus in soil and manure

Site/Runoff Variables[z]	Soil/Manure Variables[y,x,w]											
	Unincorporated Treatment						Incorporated Treatment					
	STP		Manure TP		Manure WEP		STP		Manure TP		Manure WEP	
	(r^2)											
Beaverlodge												
TP fwmc	0.60	Linear	0.73	S-curve	0	nc	0.49	Linear	0.42	Linear	0.09	Linear
DRP fwmc	0.64	S-curve	0.81	S-curve	0.77	S-curve	0.62	Linear	0.19	Linear	0	nc
TP load	0.66	S-curve	0.57	Linear	0.76	S-curve	0.28	Linear	0.78	Linear	0.44	Linear
DRP load	0.57	S-curve	0.83	S-curve	0.70	S-curve	0.82	Linear	0.57	Linear	0	nc
Lacombe								S-curve				
TP fwmc	0.90	S-curve	0.91	S-curve	0.77	S-curve	0.88	S-curve	0.68	Linear	0.70	S-curve
DRP fwmc	0.91	S-curve	0.92	S-curve	0.78	S-curve	0.92	S-curve	0.63	Linear	0.81	S-curve
TP load	0.65	S-curve	0.62	S-curve	0.44	S-curve	0.77	Linear	0.66	Linear	0.63	Linear
DRP load	0.63	S-curve	0.62	S-curve	0.45	S-curve	0.67	Linear	0.71	Linear	0.50	Linear
Raymond												
TP fwmc	0.97	S-curve	0.94	S-curve	0.23	Linear	0.96	S-curve	0.90	S-curve	0	nc
TDP fwmc	0.96	S-curve	0.94	S-curve	0.27	Linear	0.67	Linear	0.90	S-curve	0	nc
DRP fwmc	0.97	S-curve	0.96	S-curve	0.12	Linear	0.93	Linear	0.93	S-curve	0	nc
PP fwmc	0.68	S-curve	0	nc	0	nc	0.08	Linear	0	nc	0	nc
TP load	0.83	S-curve	0.91	Linear	0.66	S-curve	0.89	S-curve	0.55	Linear	0.04	Linear
TDP load	0.80	S-curve	0.90	Linear	0.65	S-curve	0.89	S-curve	0.55	Linear	0.03	Linear
DRP load	0.80	S-curve	0.62	Linear	0	nc	0.82	S-curve	0.71	Linear	0	nc
PP load	0.57	S-curve	0.67	S-curve	0	nc	0	nc	0	nc	0.54	Linear

z. Total phosphorus (TP), total dissolved phosphorus (TDP), dissolved reactive phosphorus (DRP) and particulate phosphorus (PP) flow-weighted mean concentrations (fwmc) and loads

y. Soil-test phosphorus (STP), manure total phosphorus (TP) and manure water extractable phosphorus (WEP)

x. r^2 values are listed of the model (linear or nonlinear) that provided the greatest correlation for a given incorporation treatment. Negative r^2 estimates reflected very low r^2 estimates and were set to zero.

w. No correlation (nc)

Table 4.3. Summary of regression results between incorporation treatments of soil and manure variables and runoff variables

Site	Soil/Manure Variables[z]	Runoff Variables[y,x,w]							
		TP	TDP	DRP	PP	TP	TDP	DRP	PP
		fwmc (mg L^{-1})				Load (mg/m^2)			
Beaverlodge	STP	linear[v]	---	S-curve/lin	---	S-curve/lin	---	S-curve/lin	---
	Manure TP	S-curve/lin	---	S-curve/lin	---	linear[v]	---	S-curve/lin	---
Lacombe	STP	S-curve[u]	---	S-curve[s]	---	S-curve/lin	---	S-curve/lin	---
	Manure TP	S-curve/lin	---	S-curve/lin	---	S-curve/lin	---	S-curve/lin	---
Raymond	STP	S-curve[t]	S-curve/lin	S-curve[t]	S-curve/lin	S-curve[t]	S-curve[s]	S-curve[s]	S-curve/lin
	Manure TP	S-curve[s]	S-curve[s]	S-curve[s]	linear[s]	linear[s]	linear[s]	linear[s]	S-curve/lin

z. Soil-test phosphorus (STP), manure total phosphorus (TP)

y. Total phosphorus (TP), total dissolved phosphorus (TDP), dissolved reactive phosphorus (DRP) and particulate phosphorus (PP) flow-weighted mean concentrations (fwmc) and loads

x. Where two models are listed (S-curve/lin), the model for the unincorporated treatment is listed first and the incorporated treatment second. Where only one model is listed, this applies to both unincorporated and incorporated treatments.

w. linear (lin), not analyzed (---)

v. Incorporation x soil/manure P interaction and singular effects are significant

u. Significant difference between incorporated and unincorporated x_0 (x-values at inflection point)

t. Significant differences between incorporated and unincorporated a (maximum y value) and y_i (y-value at inflection point)

s. No significant differences between incorporated and unincorporated regression coefficients

Table 4.4. Repeated measures analysis of variance results for total phosphorus (TP), total dissolved phosphorus (TDP), dissolved reactive phosphorus (DRP) and particulate phosphorus (PP) concentrations and loads

Site	Effect/Interaction[z]	TP	TDP	DRP	PP	TP	TDP	DRP	PP
		---- Concentration (mg L^{-1}) [y] ----				---------- Load (mg m^{-2}) [y] ----------			
All Sites	Time Interval (T)	*	---	*	---	**	---	**	---
	Target Manure Rate (R)	***	---	**	---	**	---	**	---
	T x R	ns	---	*	---	***	---	***	---
	Incorporation (In)	*	---	**	---	ns	---	ns	---
	T x In	ns	---	**	---	ns	---	ns	---
	R x In	**	---	**	---	*	---	*	---
	T x In x R	*	---	**	---	**	---	**	---
Beaverlodge	T	**	---	ns	---	***	---	***	---
	R	**	---	***	---	***	---	***	---
	T x R	ns	---	**	---	***	---	***	---
	In	***	---	***	---	***	---	***	---
	T x In	**	---	ns	---	***	---	***	---
	R x In	***	---	***	---	***	---	***	---
	T x In x R	ns	---	**	---	**	---	***	---
Lacombe	T	ns	---	**	---	***	---	***	---
	R	***	---	***	---	***	---	***	---
	T x R	ns	---	**	---	**	---	***	---
	In	ns	---	ns	---	ns	---	ns	---
	T x In	ns	---	**	---	ns	---	ns	---
	R x In	**	---	**	---	*	---	**	---
	T x In x R	ns	---	ns	---	ns	---	**	---
Raymond	T	*	**	***	ns	***	***	***	***
	R	***	***	***	**	***	***	***	ns
	T x R	ns	ns	**	**	***	***	***	ns
	In	ns	ns	**	ns	ns	ns	ns	ns
	T x In	ns	ns	*	ns	ns	ns	**	ns
	R x In	ns	ns	**	*	ns	ns	ns	**
	T x In x R	ns	ns	**	ns	ns	ns	ns	ns

z. The Symbol "x" indicates an interaction between terms.
y. Significance is indicated as follows:

***	P < 0.001
**	P < 0.05
*	P < 0.1
ns	not significant
---	not analyzed

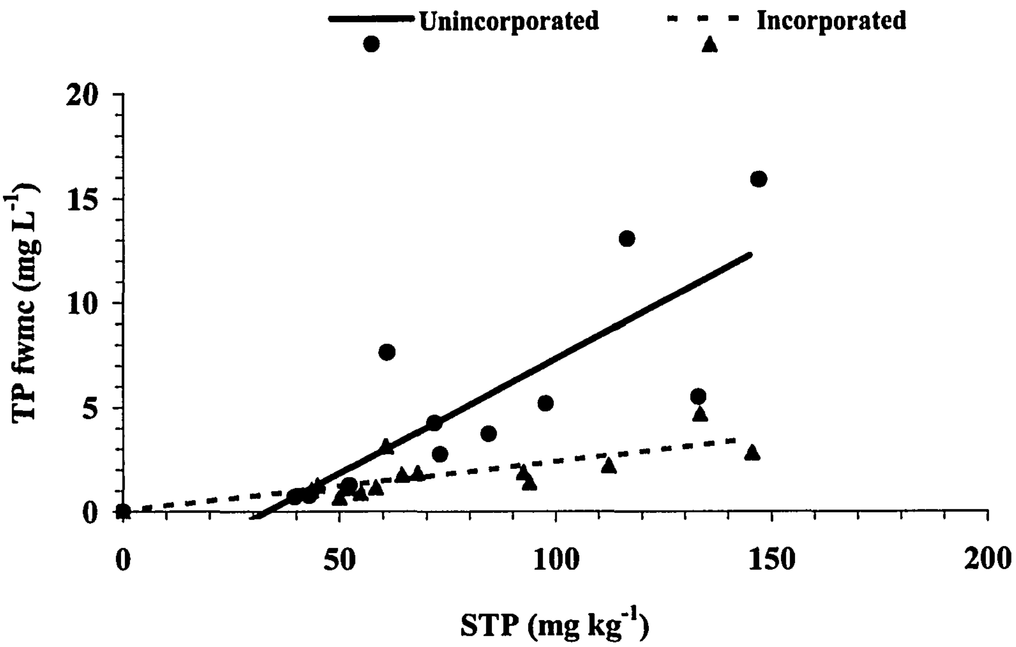

Figure 4.1. Regressions for Beaverlodge soil-test phosphorus (STP) and total phosphorus (TP) flow-weighted mean concentrations (fwmc)

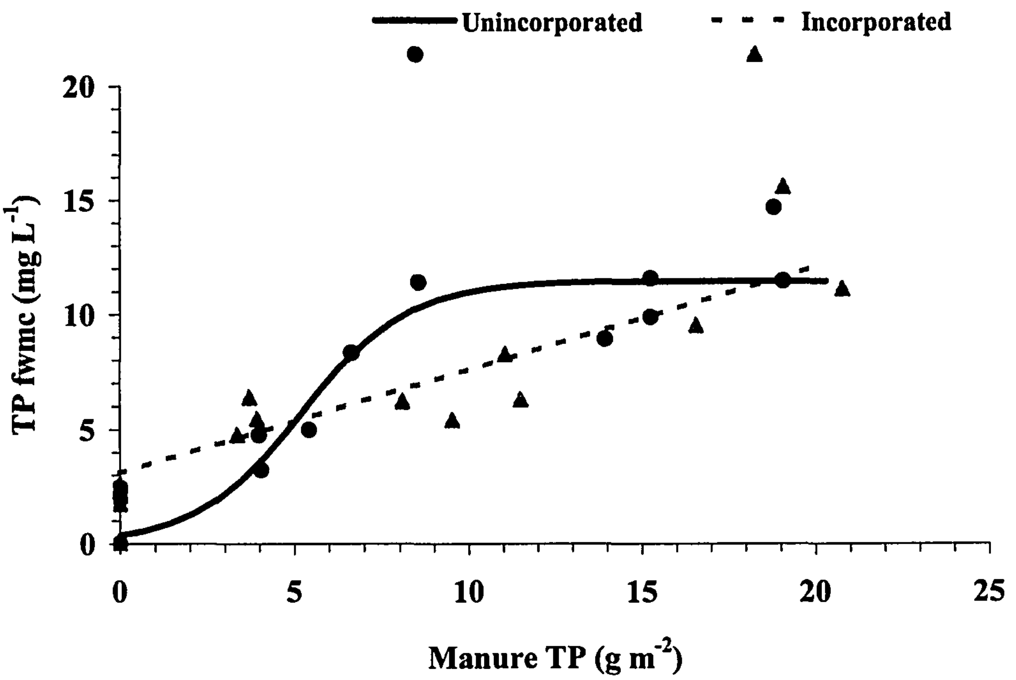

Figure 4.2. Regressions for Lacombe manure total phosphorus (TP) and TP flow-weighted mean concentrations (fwmc)

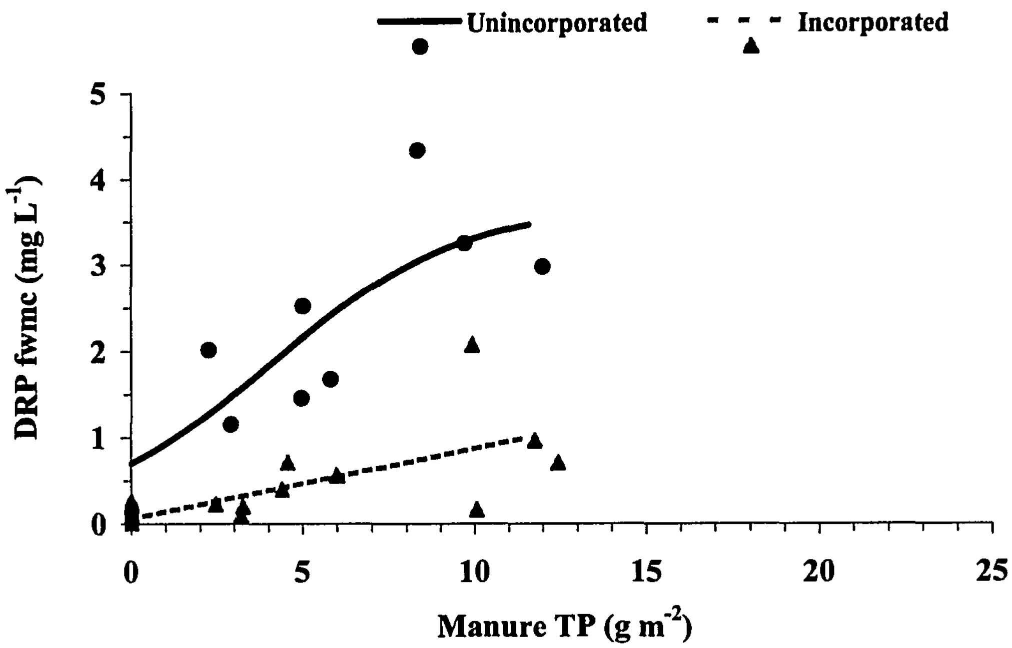

Figure 4.3. Regressions for Beaverlodge manure total phosphorus (TP) and dissolved reactive phosphorus (DRP) flow-weighted mean concentrations (fwmc)

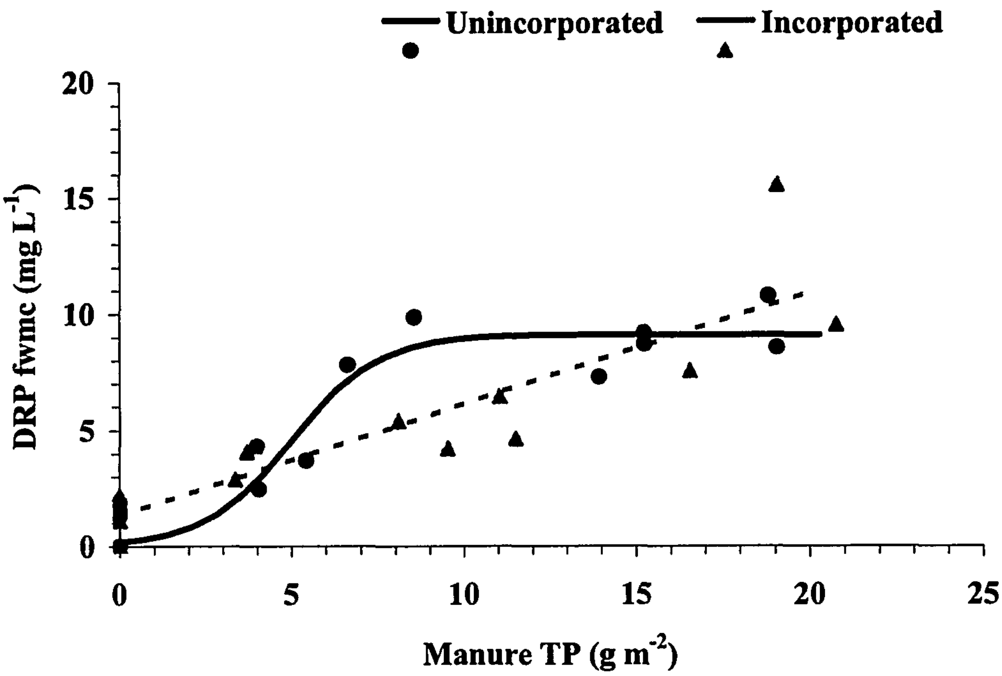

Figure 4.4. Regressions for Lacombe manure total phosphorus (TP) and dissolved reactive phosphorus (DRP) flow-weighted mean concentrations (fwmc)

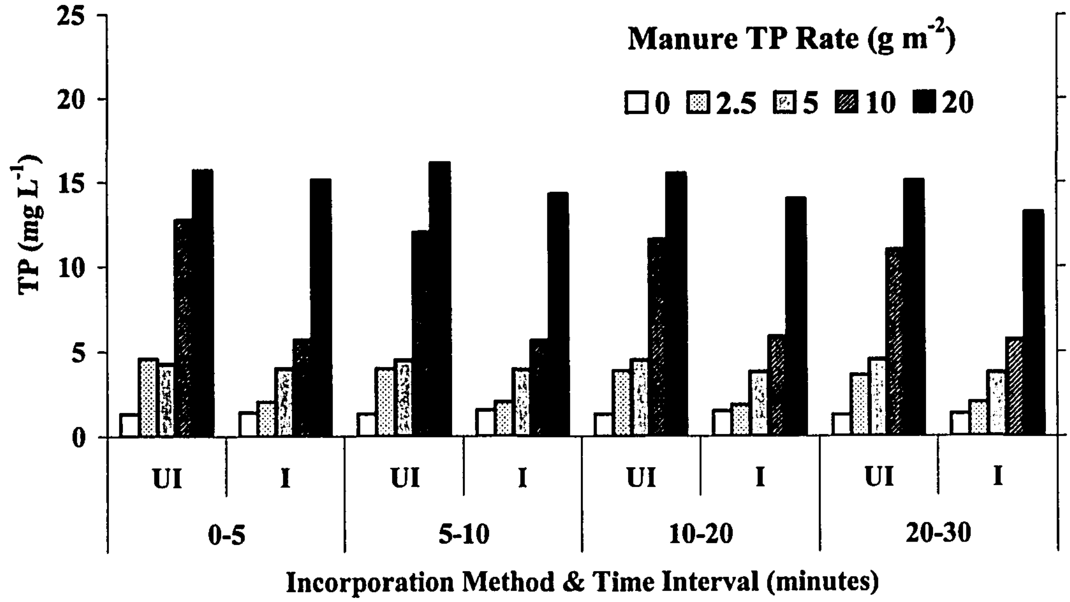

Figure 4.5. Total phosphorus (TP) mean concentrations of unincorporated (UI) and incorporated (I) soils by time interval and manure TP rate from all sites combined

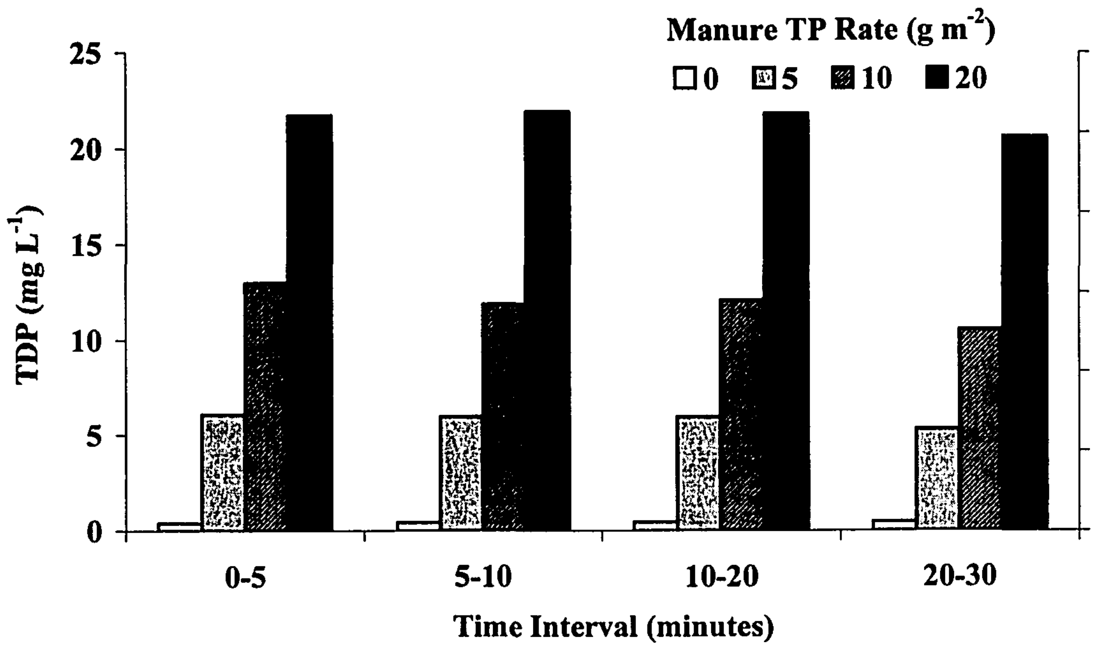

Figure 4.6. Total dissolved phosphorus (TDP) mean concentrations by time interval and manure total phosphorus (TP) rate from Raymond

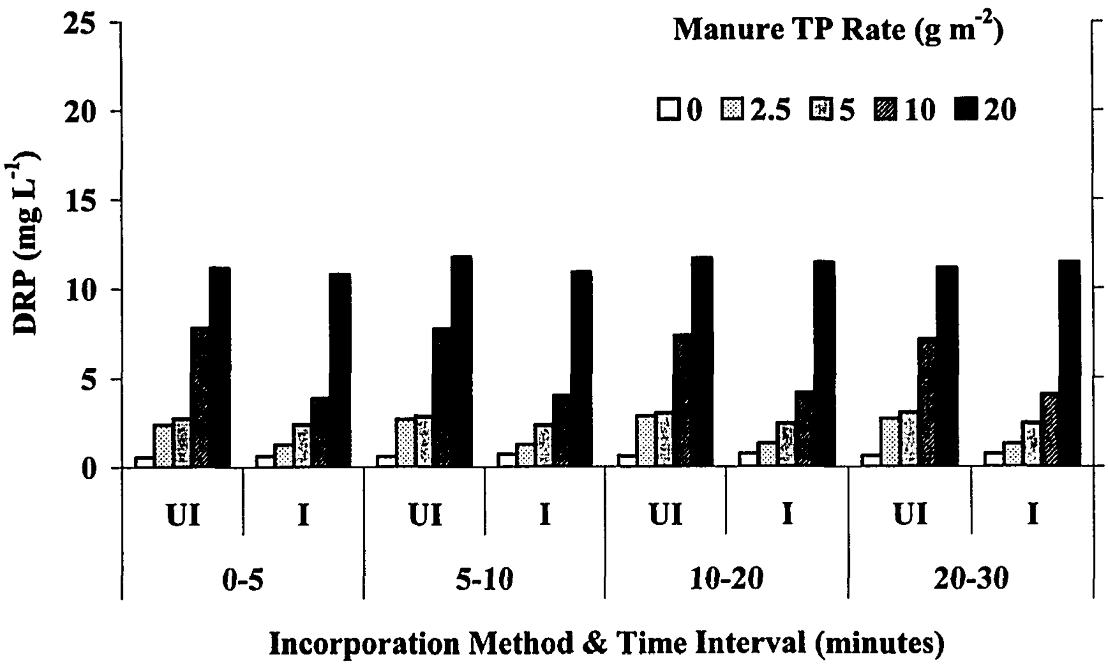

Figure 4.7. Dissolved reactive phosphorus (DRP) mean concentrations of unincorporated (UI) and incorporated (I) soils by time interval and manure total phosphorus (TP) rate from all sites combined

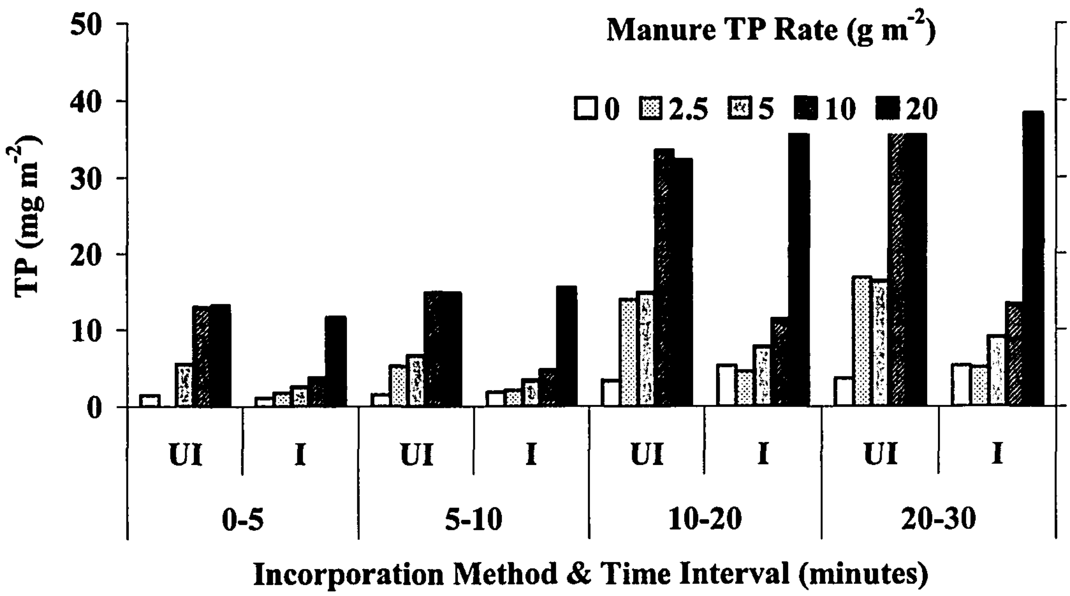

Figure 4.8. Total phosphorus (TP) mean loads of unincorporated (UI) and incorporated (I) soils by time interval and manure TP rate from all sites combined

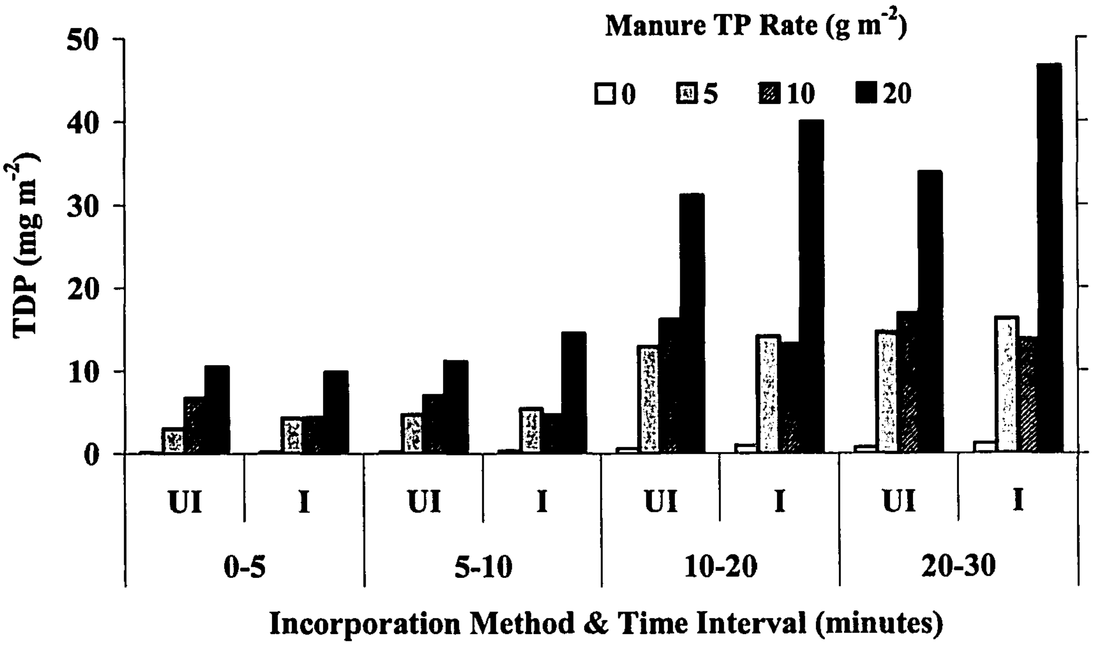

Figure 4.9. Total dissolved phosphorus (TDP) mean loads of unincorporated (UI) and incorporated (I) soils by time interval and manure total phosphorus (TP) rate from Raymond

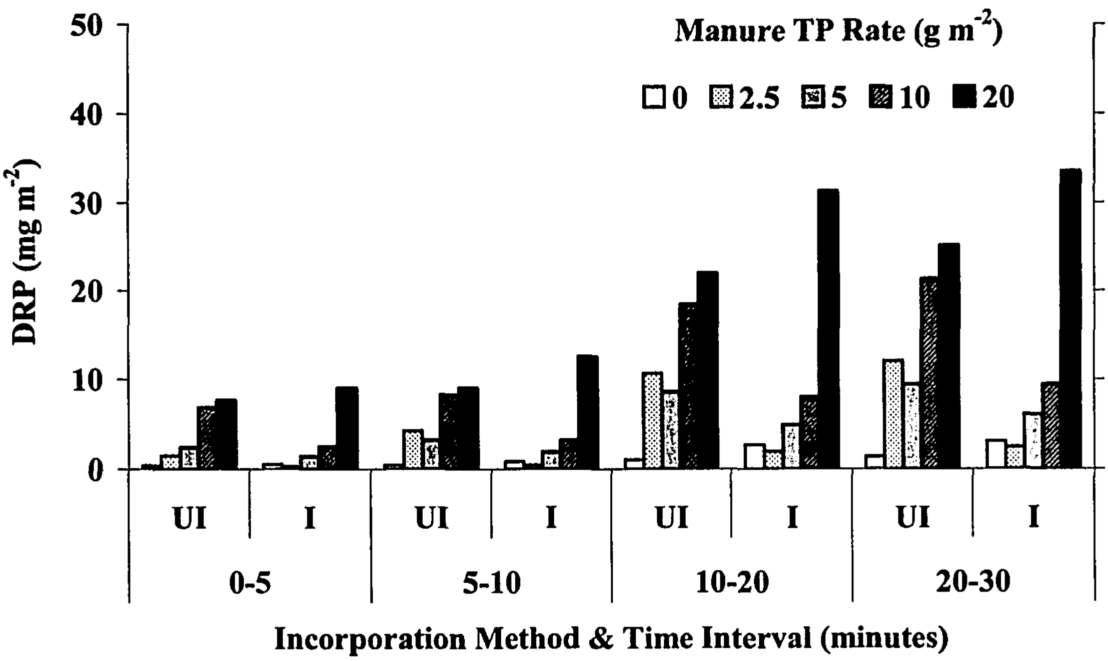

Figure 4.10. Dissolved reactive phosphorus (DRP) mean loads of unincorporated (UI) and incorporated (I) soils by time interval and manure total phosphorus (TP) rate from all sites combined

5. NITROGEN IN SURFACE RUNOFF FROM MANURED AGRICULTURAL LANDS

5.1 Introduction

Nitrogen is an essential nutrient for plant and animal growth and is the primary limiting nutrient in the production of food and fiber (Owens 1994). Thus, nitrogen addition to agricultural land has long been a common practice. However, excessive amounts of nitrogen can be introduced to the environment from anthropogenic sources by surface runoff, leaching and atmospheric deposition. An assessment of nutrients in the Canadian environment concluded that nutrients released to the environment from anthropogenic sources are impairing the health of some ecosystems, contributing to concerns of the Canadian quality of life and, in some cases, are endangering human health (Chambers et al. 2001). A study of water quality in Alberta found nitrogen exceeded water quality guidelines for the protection of aquatic life in streams located in high and moderate intensity agricultural areas (CAESA 1998). This study also found occasional nitrate concentrations in excess of drinking water quality guidelines in shallow groundwater possibly a result of leaching from excessive manure and fertilizer applications to agricultural lands (CAESA 1998).

Nitrogen additions to agricultural lands have led to such environmental concerns as eutrophication and potential depletion of the earth's ozone layer (Ritter and Bergstrom 2001). Eutrophication has previously been discussed in Section 4.1. While phosphorus is the limiting nutrient in eutrophication of freshwater ecosystems, nitrogen plays a predominant role in eutrophication of saltwater ecosystems and can also stimulate the growth of toxic algae (Environment Canada 2001). Nitrogen is also known to contribute to the acidification of lakes and soils (Environment Canada 2001). In excessive amounts, nitrogen can also be toxic to plants, animals, and humans. Nitrates and nitrites cause toxicity by reducing the oxygen carrying capacity of blood (Owens 1994). Nitrates and nitrites are also a potential pollutant of groundwater due to their highly soluble nature.

Governing bodies around the world have taken steps to limit the amount of nitrogen released into the environment from anthropogenic sources to appropriate levels. As an example, the Alberta chronic surface water quality guideline for total nitrogen for the protection of aquatic life is 1.0 ppm (Alberta Environment 1999). Canadian guidelines of nitrate for human and livestock drinking and freshwater and marine aquatic life are 10, 100, 13 and 16 mg L^{-1}, respectively (CCME 1999). The Canadian Ammonia guideline for the protection of fresh water aquatic life ranges from 1.37 to 2.20 mg L^{-1} depending on pH and temperature (CCME 1999).

5.1.1 Nitrogen in Soil

Nitrogen in soil occurs in organic and inorganic forms. Organic forms include proteins, amino acids and amino sugars (Havlin et al. 1999). Inorganic forms include ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), nitrous oxide (N_2O), nitric oxide (NO) and elemental N (N_2) (Havlin et al. 1999). Nitrate is the principal form of nitrogen taken up by plants because of its relative abundance and highly mobile nature (Hausenbuiller 1985).

Nitrogen actively cycles between the earth's soil and atmosphere. Key processes of the nitrogen cycle include nitrogen fixation and mineralization, plant uptake, leaching and runoff, ammonia volatilization and denitrification. The ultimate source of nitrogen used by plants is nitrogen gas (N_2) in the atmosphere (Havlin et al. 1999), which is not directly available to plants (Environment Canada 2001). This N_2 gas is primarily converted to the plant available form of NH_4^+ by nitrogen fixing bacteria such as blue-green algae (cyanobacteria) and bacteria existing symbiotically in the root nodules of legumes (Environment Canada 2001). Also, nitrogen bound in soil organic matter from plant and animal residues is mineralized by microbial activity to form NH_4^+ (Havlin et al 1999). Much of the NH_4^+ fixed and mineralized in soil is converted to NO_3^-, another plant available form of nitrogen, through the process of nitrification (Havlin et al. 1999). Because of the highly soluble nature of NO_3^-, portions are lost to groundwater through leaching and to surface waters through runoff. Some soil nitrogen is also transferred back to the atmosphere by denitrification before it can be used by plants. Denitrification occurs when NO_3^- is converted by microbes into N_2 gas and nitrogen oxides (Havlin et al. 1999). Ammonium is converted to a gas form, ammonia (NH_3), and released to the atmosphere by volatilization (Havlin et al. 1999).

Several factors affect nitrification, the process responsible for transforming the majority of nitrogen used by plants. The primary factor affecting nitrification is the available supply of NH_4^+ which is enhanced by the addition of organic and inorganic fertilizers and by optimal temperature and moisture conditions for mineralization (Havlin et al. 1999). Another factor affecting nitrification is the population size of nitrifying organisms (Havlin et al. 1999). Lesser populations will require more time to mineralize additional ammonium. Also, soil pH can affect nitrification. An optimal pH of 8.5 and the availability of calcium ions will maximize mineralization activities (Havlin et al. 1999). Good soil aeration will also promote nitrogen mineralization in soil. Coarse textures and well developed soil structure will facilitate gas exchange between the soil and atmosphere (Havlin et al. 1999). Closely related to soil aeration is soil moisture content. Soil exceeding field capacity will have reduced mineralization primarily due to reduced amounts of oxygen available (Havlin et al. 1999). Finally, temperature can influence mineralization rates in soil, with microbial activities for mineralization optimized between 25 and 35 °C (Havlin et al. 1999).

5.1.2 Nitrogen Transport

Nitrogen is transported from soil to surface water in particulate and dissolved forms. Ammonium has a low solubility in soil. Being positively charged, it attaches to soil particles through adsorption to the negatively charged soil matrix or by fixing between the layers of 2:1 type clay minerals such as vermiculite (Ritter and Bergstrom 2001). Ammonia as part of the soil's exchange complex is more soluble than ammonia fixed by 2:1 clays. The latter process reduces nitrogen to a form highly unavailable to soil solution and plant uptake. Thus, a large portion of ammonium and some organic forms of nitrogen tend to be transported by runoff in particulate form. Management practices that reduce the soil's susceptibility to erosion, such as adequate residue cover and reduced tillage cropping, can reduce the amount of particulate nitrogen exported from agricultural lands.

Nitrate and nitrite are highly soluble due to their ionic nature and commonly occur in soil solution. These forms of nitrogen are much more susceptible than ammonia to leaching and transport in runoff as dissolved constituents (Ritter and Bergstrom 2001).

Reducing export of dissolved nitrogen in runoff from agricultural lands can be achieved by reducing runoff volumes. Increasing soil infiltration, one of the most effective means of reducing runoff volumes, can be achieved with management practices that encourage soil structure development (incorporation of organic material, reduced tillage) and adequate residue cover to protect the soil surface from sealing.

Several studies have explored the effects of tillage on nitrogen in surface runoff with varying results. Gupta et al. (1997) observed decreases in ammonium and nitrate concentrations after incorporating manure with a disk compared to the surface applied liquid swine manure treatment. Romkens et al. (1973) observed a similar decrease in ammonium and nitrate concentrations and loads with disking compared to a lower impact tillage system. Consistent with these studies, Laflan and Tabatabai (1984) observed ammonium and nitrate concentrations and loads decreasing with tillage where no manure was applied. Eghball and Gilley (1999) also found decreased ammonium concentrations and loads with manure incorporation on no-till managed land but observed increased nitrate concentrations and loads. They believed disking enhanced nitrate loss by disturbing the surface of their high nitrate soils. Seta et al. (1993) also found ammonium and nitrate concentrations decreased with tillage but associated loads increased due to greater runoff volumes from tillage treatments. Alternately, another Alberta based study, Little et al. (*In Press*), found total nitrogen, ammonium and nitrate concentrations and loads increased with tillage.

5.1.3 Nitrogen and Manure

Livestock manure can be an excellent source of nitrogen for crops. Amounts of nitrogen in manure depend upon such factors as the nutrient content of feed, method of manure handling and storage, quantity of added materials such as bedding, and method and timing of application (Havlin et al. 1999). A large portion of nitrogen in manure is organic in nature requiring mineralization for use by plants. The liquid portion of manure, comprised of urea and uric acid, tends to be an unstable form of organic N in manure and is quickly mineralized to ammonium while the solids are mineralized more slowly over the growing season and subsequent years (Havlin et al. 1999).

Several studies have observed increases of various fractions of nitrogen concentrations and loads in runoff with manure application (Edwards and Daniel 1993, Eghball and Gilley 1999, Eghball et al. 2002, Little et al. *In Press*, Pote et al. 2001 and Sharpley 1997). In addition, some of these studies have shown increased nitrogen concentrations and loads in runoff with increasing manure application rates (Eghball et al. 2002) and described the relationship as linear (Edwards and Daniel 1993 and Pote et al. 2001).

5.1.4 Objectives

The objective of this study was to determine the effect of nitrogen in soil, recently applied manure and incorporation of manure on various fractions of nitrogen in runoff from cultivated land. Also examined was the effect of time on nitrogen fractions in runoff over the course of a 30-minute runoff event. Manure nitrate (NO_3-N) and ammonium (NH_4-N) application rates were evaluated relative to runoff NO_3-N and NH_4-nitrogen in regards to their ability to estimate concentrations and loads in runoff.

5.2 Materials and Methods

Materials and methods are described in Section 2.

5.3 Results and Discussion

5.3.1 Soil and Manure Characteristics

Pre-treatment Soil nitrate (NO_3-N) and ammonia (NH_3-N) values from each site were relatively uniform, with no significant differences among target manure rate and incorporation method treatments within each site (data not shown). The Beaverlodge site had mean pre-treatment NO_3-N values ranging from 71 to 133 mg kg^{-1} and NH_3-N values ranging from 5 to 11 mg kg^{-1}. The Lacombe site had mean pre-treatment NO_3-N values ranging from 56 to 71 mg kg^{-1} and NH_3-N values ranging from 16 to 26 mg kg^{-1}. The Raymond site had mean pre-treatment NO_3-N values ranging from 5 to 17 mg kg^{-1} and NH_3-N values ranging from 3 to 7 mg kg^{-1}.

Post-treatment Soil $N0_3$-N and NH_3-N, including incorporated or surface applied manure, for the three sites tended to have a positive relationship with manure rate (Table 5.1). Post-treatment Soil NO_3-N values from the Beaverlodge and Raymond sites increased with the lower three target TP manure rates, though not significantly, while the largest rates for each site had Soil NO_3-N values similar to the zero rate. Post-treatment soil NO_3-N values from the Lacombe site increased consistently, and often significantly, with manure rate. Post-treatment soil NH_3-N increased consistently with manure rate for all three sites but significant differences were only observed at Raymond between the upper two manure rates and between these rates and the unmanured (0 g m^{-2}) treatment. No significant differences were found between the incorporated and unincorporated treatments. This is consistent with soil phosphorus results discussed in Section 4.3.1, further supporting the suggestion that the majority of nutrients applied with manure remained in the upper 2.5 cm of the soil profile after incorporation.

Actual rates of nitrogen applied with manure were calculated from NO_3-N and ammonium (NH_4-N) content of manure samples collected from each plot and the measured weight of manure applied (Table 1). This calculation was explained in Section 2.4. Nitrogen rates varied widely between sites because application was targeted to specific phosphorus rates and because nutrient contents of manure are quite variable in nature. Lacombe had the greatest Manure NO_3-N rates, two orders of magnitude larger than rates from Beaverlodge. Manure samples from the Raymond site had levels of NO_3-N below the laboratory detection limit. Manure NH_4-N rates were similar in magnitude at Beaverlodge and Lacombe and were approximately double at Raymond.

5.3.2 Overview of Relationships to Nitrogen in Runoff

Where not specified in this text, Soil NO_3-N and NH_3-N refer to results analyzed from post-treatment samples including the surface applied or incorporated manure. In most cases, nitrogen loads were similar to flow-weighted mean concentrations (fwmcs) with little influence from runoff rate. Relationships between nitrogen in soil and manure and nitrogen in runoff for both incorporation methods tended to be nonlinear though some linear relationships were identified (Tables 5.2 and 5.3). These relationships were strongest for the Raymond site and poorest for the Beaverlodge site. Nitrogen in manure generally tended to correlate as well as nitrogen in soil to various nitrogen fractions in runoff.

Nitrate concentrations and loads in runoff at all three sites increased with incorporation, most strongly for Lacombe and least for Raymond. Ammonium concentrations and loads in runoff increased with incorporation at Lacombe but decreased at Beaverlodge and Raymond. Tillage may have increased soil water contact within the effective depth of interaction (EDI).

5.3.3 Nitrogen Flow-weighted Mean Concentrations in Runoff

5.3.3.1 Total Nitrogen Flow-weighted Mean Concentrations

Total nitrogen (TN) concentrations were analyzed for samples from the Raymond site only. Because Manure NO_3-N concentrations were below the laboratory detection limit, no comparisons to TN flow-weighted mean concentration (fwmc) were conducted using this regressor. Regressions of Soil NO_3-N and TN fwmc were poorly correlated, thus, further statistical analysis was not conducted (data not shown). Regressions of TN fwmc against Soil NH_3-N and Manure NH_4-N were very well correlated ($r^2 > 0.90$) and these positive relationships best fit to S-curve models (Table 5.2). No significant differences occurred between models of incorporated and unincorporated treatments (Table 5.4, Figure 5.1).

Other studies have also observed increased TN concentrations with manure application relative to unmanured controls (Eghball et al. 2002, Gupta et al. 1997, Little et al. *In Press*, Sharpley 1997) and TN concentration increases with increasing manure application rate (Eghball et al. 2002). Also, similar to this study, Little et al. (*In Press*) observed increased TN concentrations in runoff with manure incorporation using a double disk relative to no-till conditions. However, Gupta et al. (1997) reported opposite findings.

5.3.3.2 Total Dissolved Nitrogen Flow-weighted Mean Concentrations

Total dissolved nitrogen (TDN) concentrations were analyzed for samples from the Raymond site only. Because Manure NO_3-N concentrations were below the laboratory detection limit, no comparisons to TDN fwmc were conducted using this regressor. Total dissolved nitrogen fwmc comparisons to Soil NO_3-N were poorly correlated for the unincorporated treatment and did not correlate at all for the incorporated treatment (Table

5.3). Further statistical analysis of this relationship was not conducted because of the poor correlations. Total dissolved nitrogen fwmcs correlated strongly to Soil NH_3-N and Manure NH_4-N with an S-curve relationship (Table 5.2). No significant differences occurred between incorporation methods (Table 5.4).

Concentrations of TDN and TN in runoff were similar in magnitude at this site indicating relatively small amounts of nitrogen were transported with eroded soil. Flow-weighted mean concentrations of TDN ranged between 0 and 120 mg L^{-1} where as NO_3-N fwmc ranged between 0 and 6 mg L^{-1}. Since nitrite concentrations in these samples were negligible, the largest portion of TDN appears to have been either dissolved NH_3-N or dissolved organic nitrogen, thus explaining why TDN fwmc did not correlate well with NO_3-N concentrations in soil.

5.3.3.3 Particulate Nitrogen Flow-weighted Mean Concentrations

Particulate nitrogen (PN) concentrations were analyzed for samples from the Raymond site only. Comparisons of PN fwmc to Manure NH_4-N and Soil NH_3-N of the unincorporated treatments were better correlated than for the incorporated treatments and were best fit to S-curve models (Table 5.2). The incorporated PN fwmc comparison to Soil NH_3-N was moderately well correlated and best fit a linear model but the comparison to Manure NH_4-N was poorly correlated. Incorporated PN fwmcs had a tendency to be lower than unincorporated PN fwmcs at the greater manure rates (data not shown). This portion of nitrogen in runoff was relatively small compared to the dissolved fraction of total nitrogen, less than 20 mg L^{-1} compared to TP fwmc ranging between 0 and 120 mg L^{-1}.

5.3.3.4 Nitrate Flow-weighted Mean Concentrations

Nitrate fwmcs were regressed against Soil NO_3-N concentrations and Manure NO_3-N application rates. Lacombe had the greatest NO_3-N fwmc and Soil and Manure NO_3-N values of the three sites in the ranges of 0 to 80 mg L^{-1}, 0 to 200 mg kg^{-1} and 0 to 8 g m^{-2}, respectively. Beaverlodge and Raymond NO_3-N fwmcs were lower than those at Lacombe, ranging between 0 and 10 mg L^{-1}. Beaverlodge Soil and Manure NO_3-N values also were lower than those at Lacombe, ranging between 0 and 80 mg kg^{-1} and 0 and 0.2 g m^{-2}, respectively. Raymond Soil and Manure NO_3-N values were the lowest of the three sites. Raymond Soil NO_3-N valued ranged 0 to 30 mg kg^{-1} and Manure NO_3-N values were below the laboratory detection limit.

For Beaverlodge, NO_3-N correlations were extremely weak or non-existent for the unincorporated treatments but were very strong for the incorporated treatments (Table 5.3). Relationships were best represented by S-curve models where positive correlations occurred. No significant differences occurred between the incorporated and unincorporated S-curve models of the Manure NO_3-N regressions (Table 5.4), however, incorporated NO_3-N fwmcs tended to be greater than unincorporated (data not shown).

For Lacombe, all regressions were best fit to an S-curve model (Table 5.3). Correlations were stronger for the Manure NO_3-N regressions than Soil NO_3-N and incorporated correlations were stronger than those for unincorporated treatments. For both regressors, the a (y-value maximum) and y_i (y-value at inflection point) coefficients of the incorporated models were significantly greater than for the unincorporated models (Table 5.4, Figure 5.2). Incorporated NO_3-N fwmcs were notably greater than for unincorporated treatments and the differences increased as soil NO_3-N increased.

For Raymond, comparisons could only be made between Soil NO_3-N and NO_3-N fwmc because NO_3-N concentrations of the manure samples were below the laboratory detection limit. A nonlinear (S-curve) model best represented this relationship for both incorporation treatments though the incorporated relationship correlated much stronger than the unincorporated treatment (Table 5.3). No significant differences occurred between coefficients of these two models (Table 5.4).

Nitrate fwmc showed increasing trends when related to Soil and Manure NO_3-N values from the three sites and all relationships that correlated were best represented by S-curve models. Several other studies have reported increased NO_3-N concentrations in runoff when manure was applied (Edwards and Daniel 1993, Eghball and Gilley 1999, Eghball et al. 2002, Little et al. *In Press*, Sharpley 1997) and increasing NO_3-N concentrations in runoff with increasing manure application rate (Edwards and Daniel 1993, Eghball et al. 2002). However, Edwards and Daniel (1993) described an approximate linear relationship between manure rate and runoff NO_3-N concentrations. In all cases, relationships from incorporated treatments were better correlated than those from unincorporated treatments. Lacombe and Beaverlodge showed trends of increasing NO_3-N concentrations with manure incorporation, while Raymond NO_3-N concentrations in runoff were similar with surface applied and incorporated manure.

5.3.3.5 Ammonia Flow-weighted Mean Concentrations

Ammonia fwmcs of the Beaverlodge and Raymond sites ranged between 0 and 60 mg L^{-1} while Lacombe concentrations were lower, ranging between 0 and 10 mg L^{-1}. Raymond Soil NH_3-N and Manure NH_4-N values were greatest of the three sites ranging between 0 and 600 mg kg^{-1} and 0 and 50 g m^{-2}, respectively while Beaverlodge and Lacombe Soil NO_3-N values ranged 0 to 100 mg kg^{-1} and Manure NH_4-N values ranged 0 to 20 g m^{-2}.

Ammonia fwmcs were regressed against Soil NH_3-N concentrations and Manure NH_4-N application rates. For Beaverlodge, poor and non-existent correlations between both regressors and NH_3-N fwmc occurred for unincorporated and incorporated treatments, respectively (Table 5.2). For the unincorporated treatment, soil NH_3-N correlated slightly better to NH_3-N fwmc than did Manure NH_4-N and both were best represented by S-curve models. Though comparisons could not be made between models of incorporation treatments, unincorporated NH_3-N fwmc tended to be greater than incorporated NH_3-N fwmc, likely a result of relatively impermeable unincorporated soils at this site (data not shown).

Contrary to the Beaverlodge trends, regressions for Lacombe correlated better for the incorporated than the unincorporated treatment and Manure NH_4-N correlated better with NH_3-N fwmc than Soil NH_3-N (Table 5.2). With no correlation occurring between unincorporated Soil NH_3-N and NH_3-N fwmc, comparisons between incorporation treatments for this regressor could not be made. Between the Manure NH_4-N incorporation treatments, the b coefficient (average slope of the curve's rising limb) was significantly less and the x_0 coefficient (x-value at the inflection point) was significantly greater for the incorporated than unincorporated treatment (Table 5.4). In other words, the upward arm of the unincorporated S-curve increased more sharply and within a lower range of Manure NH_4-N values than the incorporated S-curve.

For Raymond, correlations between the soil and manure regressors and NH_3-N fwmc were the strongest of the three sites (Table 5.2). Manure NH_4-N correlated slightly better to NH_3-N fwmc than did Soil NH_3-N. Relationships of the unincorporated treatment with both Soil NH_3-N and Manure NH_4-N were moderately better correlated to NH_3-N fwmc than the incorporated treatment. Soil NH_3-N regressions for unincorporated and incorporated treatments fit best to linear and S-curve models, respectively. Though models differed, NH_3-N fwmcs did not notably differ. Manure NH_4-N regressions for each incorporation method fit best to an S-curve model (Table 5.2). The a and y_i coefficients of the unincorporated model were significantly greater than of the incorporated model (Table 5.4, Figure 5.3). In other words, while NH_3-N fwmcs at lower manure rates were similar between incorporation methods, incorporated concentrations were less than unincorporated concentrations at larger manure rates.

Ammonia fwmc from the three sites generally tended to increase in a curvilinear manner relative to Soil NH_3-N and Manure NH_4-N. Many other studies have also found NH_3-N runoff concentrations increased with manure application (Edwards and Daniel 1993, Eghball and Gilley 1999, Eghball et al. 2002, Little et al. *In Press*, Pote et al. 2001, Sharpley 1997) and also increased with increasing manure rates (Eghball et al. 2002) in a linear fashion (Edwards and Daniel 1993 and Pote et al. 2001). No consistent trends across sites were observed regarding stronger correlations between soil and manure regressor or incorporation treatments. The decreasing NH_3-N fwmcs with incorporation at Beaverlodge were consistent with results from several studies (Gupta et al. 1997, Laflan and Tabatabai 1984, Romkens et al. 1973, Seta et al. 1993). However, the opposite effect observed at Lacombe is supported in results recorded by Eghball and Gilley (1999) and Little et al. (*In Press*). Eghball and Gilley (1999) suggested disking exposed the surface soils of their study, high in NO_3-N, to surface runoff more so than no tillage.

5.3.4 Nitrogen Concentrations over Time

5.3.4.1 Total Nitrogen Concentrations over Time

Total nitrogen concentrations collected from four time intervals were determined for runoff samples collected from the Raymond site only. A significant three-way interaction and singular effects of time, manure rate and incorporation method were observed for TN mean concentrations in runoff from this site (Table 5.5). Contrasts indicated a linear relationship between manure rate and TN concentrations (data not shown). As with the 30-minute TN fwmcs, interval concentration tended to increase with manure rate and differences between means were observed between the 5, 10 and 20 g m^{-2} rates for the unincorporated treatments; between the 0 to 5 and 10 to 20 g m^{-2} rates for the incorporated treatments of the initial two time intervals; and between the 10 and 20 g m^{-2} rates from the incorporated treatments of the later two time intervals. Concentrations tended to increase consistently, though not significantly, with incorporation for the lower two manure rates and decrease with incorporation for the higher two manure rates. Total N concentrations tended to decrease with time across all manure rates and incorporation methods, though significant differences between means only occurred at the highest manure rate (Figure 5.4, Appendix Table B.1). This trend is consistent with non-significant observations with the regression analysis for TN. Eghball et al. (2002) also found TN concentrations decreased significantly over 45 minutes of simulated runoff describing the relationship as linear.

5.3.4.2 Total Dissolved Nitrogen Concentrations over Time

Total dissolved nitrogen concentrations from the four time intervals were determined for runoff samples collected from the Raymond site only. A significant three-way interaction between time, manure rate and incorporation method occurred for TDN mean concentrations in runoff at this site, as well as a two-way interaction and singular effects for manure rate and time (Table 5.5). Contrasts indicated a linear relationship between manure rate and TDN concentrations (data not shown). Mean concentrations increased consistently with manure rate and the majority of differences between means were significant (data not shown). However, conclusions derived from these statistics require a note of caution due to the scattered nature of the data as discussed with regression analysis in Section 5.3.3.2. As with TN mean concentrations, TDN concentrations tended to decrease with time and significant differences occurred intermittently at the greater two manure rates in the latter two time intervals.

5.3.4.3 Particulate Nitrogen Concentrations over Time

Particulate nitrogen concentrations from the four time intervals were determined for runoff samples collected from the Raymond site only. Significant two-way interactions between time and manure rate and between manure rate and incorporation method, as well as singular effects of manure rate and incorporation, occurred for PN mean concentrations in runoff from this site (Table 5.5). Contrasts indicated a linear relationship between manure rate and TDN concentrations (data not shown). Concentrations tended to increase with manure rate and significant differences occurred intermittently between the greater three manure rates (data not shown). No significant differences between means were detected between the 0 and 5 g m^{-2} manure rates. Similar to non-significant observation of TN fwmcs over 30 minutes, mean PN concentrations of the greater two manure rates decreased significantly with manure incorporation (data not shown). Particulate nitrogen concentrations tended to increase significantly over time at the 10 g m^{-2} manure rate but similar patterns were not observed for other manure rates (data not shown).

5.3.4.4 Nitrate Concentrations over Time

No significant interactions or singular effects of time interval, manure rate or incorporation method occurred for NO_3-N mean concentrations in runoff when data from all three sites were combined (Table 5.5). However, some significant effects and interactions were observed within each site.

A significant interaction and singular effects of time interval and incorporation method were observed for NO_3-N mean concentration in runoff at Beaverlodge (Table 5.5). Though not supported by mean comparisons (data not shown), NO_3-N concentrations tended to be greater for the unincorporated than incorporated treatments and tended to decrease with time for both incorporation methods (data not shown). Other studies have also observed decreases in NO_3-N concentrations from simulated rainfall experiments with runoff measured for 30 minutes (Little et al. *In Press*), 45 minutes (Eghball et al. 2002) and 120 minutes (Laflan and Tabatabai 1984).

All significant two and three-way interactions and singular effects for time interval, manure rate and incorporation method were observed for NO_3-N mean concentrations in runoff at Lacombe (Table 5.5). Contrasts indicated that NO_3-N concentrations increased linearly with manure rate (data not shown). When means were compared, NO_3-N concentrations were significantly greater for the incorporated than unincorporated treatments for all manure rates excluding the 5 g m^{-2} rate (Figure 5.5, Appendix Table B.2). Unincorporated NO_3-N concentrations of the larger two manure rates were significantly greater than concentrations of the smaller two manure rates. Incorporated NO_3-N concentrations were significantly greater between the largest manure rate and the smaller three manure rates. NO_3-N concentrations also showed a consistently decreasing trend over time, though not significant.

Similar to Beaverlodge, Raymond had a significant time interval and incorporation method interaction and significant singular effects on NO_3-N mean concentrations (Table 5.5). Though significant differences between means were rare, NO_3-N concentrations consistently decreased with time and were greater for incorporated than unincorporated treatments (data not shown). One exception to these trends, the incorporated NO_3-N concentration of the initial time interval was notably lower than all other concentrations.

5.3.4.5 Ammonia Concentrations over Time

For all sites combined, time interval and manure rate had significant effects on NH_3-N mean concentrations in runoff (Table 5.5). Contrasts indicated that NO_3-N concentrations increased linearly with manure rate (data not shown). Though not supported by mean comparisons, NH_3-N concentrations consistently increased with manure rate and decreased with time (data not shown). Other studies have also observed decreases in NH_3-N concentrations over time from simulated rainfall experiments with runoff measured for 30 minutes (Little et al. *In Press*), 45 minutes (Eghball et al. 2002) and 120 minutes (Laflan and Tabatabai 1984).

Individually, Beaverlodge NH_3-N concentrations in runoff showed significant two-way time by incorporation and manure rate by incorporation interactions and singular time, manure rate and incorporation effects (Table 5.5). Contrasts indicate that NO_3-N concentrations increased linearly with manure rate (data not shown). Concentrations also decreased significantly with incorporation (data not shown). Concentrations tended to decrease with time and increase with manure rate, though significant only for the unincorporated treatments (data not shown).

All two-way interactions and singular effects of time, manure rate and incorporation method for NH_3-N were significant at Lacombe (Table 5.5). Contrasts indicate that NO_3-N concentrations increased linearly with manure rate (data not shown). Similar to Beaverlodge, Raymond NH_3-N concentrations tended to decrease with time, though only significantly at the largest manure rate, and increase significantly with manure rate and incorporation (data not shown).

At Raymond, NH_3-N mean concentrations in runoff had significant two-way time and incorporation method by manure rate interaction and singular time, incorporation method and manure rate effects (Table 5.5). Contrasts indicate that NO_3-N concentrations increased linearly with manure rate (data not shown). Similar to Lacombe, Raymond NH_3-N concentrations tended to decrease with time across all manure rates but only significantly at the largest manure rate (data not shown). Concentrations increased significantly with manure rate except between the 0 and 5 g m^{-2} rates (data not shown). Incorporation had the opposite effect on NH_3-N concentrations at Raymond, compared to Similar to Beaverlodge, Raymond NH_3-N concentrations were significantly lower for the incorporated than unincorporated treatments of the 10 and 20 g m^{-2} manure rates (data not shown).

5.3.5 Thirty-minute Loads

5.3.5.1 Total Nitrogen Thirty-minutes Loads

Total nitrogen loads were analyzed from samples of the Raymond site only. Comparisons of TN loads to Soil NH_3-N and Manure NH_4-N had some of the strongest correlations of all the nitrogen regression analysis (Table 5.2). Total nitrogen increased with these two regressors and relationships with the two regressors for both incorporation methods fit best to S-curve models. Eghball et al. (2002) also observed TN concentrations in runoff increased from unmanured to manured treatments and increased with increasing manure rates. As with TN fwmcs, TN loads did not differ significantly between model coefficients of incorporation treatments with either Soil NH_3-N or Manure NH_4-N (Table 5.4). Conflicting evidence had been recorded in the literature with

Little et al. (*In Press*) observing TN load increases with tillage and Gupta et al. (1997) observing the opposite trend.

5.3.5.2 Total Dissolved Nitrogen Thirty-minute Loads

Total dissolved nitrogen loads were analyzed for samples from the Raymond site only. Regressions of TDN loads against Soil NH_3-N and Manure NH_4-N were strong for the unincorporated treatments and poor for the incorporated treatments (Table 5.2). All four comparisons best fit S-curve models with no significant differences between incorporation methods (Table 5.4). When compared to Soil NO_3-N, these loads correlated stronger to the incorporated than unincorporated treatments and both relationships fit best to S-curve models (Table 5.3). Though, as with TDN fwmc, correlations were poor. Model coefficients were not significantly different between incorporation treatments (Table 5.4) and no notable differences were observed between mean TDN loads of the different incorporation treatments. Total dissolved nitrogen loads ranged between 0 and 800 mg m^{-2}, a similar magnitude to TN loads, indicating the majority of nitrogen in runoff was dissolved.

5.3.5.3 Particulate Nitrogen Thirty-minute Loads

Particulate nitrogen loads were analyzed for samples from the Raymond site only. Correlations were strong between PN load comparisons to Soil NH_3-N and Manure NH_4-N for both incorporation methods and these four relationships fit best to S-curve models (Table 5.2). Model coefficients did not significantly differ between incorporation treatments for PN load comparisons to either Soil NH_3-N or Manure NH_4-N (Table 5.4). Particulate nitrogen loads were between 0 and 70 mg m^{-2}, a relatively small portion of TN in runoff.

5.3.5.4 Nitrate Thirty-minute Loads

Nitrate loads were regressed against Soil NO_3-N concentrations and Manure NO_3-N application rates. As with concentrations, NO_3-N loads from Lacombe were greatest of the three sites, ranging between 0 and 800 mg m^{-2}. Beaverlodge and Raymond loads were lower, ranging between 0 and 100 mg m^{-2} and between 0 and 25 mg m^{-2}, respectively.

For Beaverlodge, unincorporated NO_3-N loads did not correlate with Soil NO_3-N and only weakly with Manure NO_3-N (Table 5.3). However, strong correlations occurred for the incorporated treatments using both regressors. All comparisons that correlated were best represented by S-curve models. No significant differences occurred between the incorporated and unincorporated models of the Manure NO_3-N to NO_3-N load comparisons (Table 5.4). For NO_3-N loads, greater runoff rates from the unincorporated treatments masked the effect of differences in runoff concentrations by incorporation method.

Similar to Beaverlodge, Lacombe incorporated NO_3-N loads correlated better with Soil and Manure NO_3-N than unincorporated loads which correlated poorly (Table 5.3). Correlation strengths of NO_3-N loads to soil and manure regressors did not notably differ. The Manure NO_3-N to NO_3-N load comparison best fit to an S-curve model while the remaining three comparisons best fit linear models. No significant differences between unincorporated and incorporated linear models with the Soil NO_3-N regressor occurred (Table 5.4). Though, similar to NO_3-N fwmcs, unincorporated NO_3-N loads were observed greater than unincorporated (Figure 5.6).

For Raymond, comparisons were only made between Soil NO_3-N and NO_3-N load because NO_3-N concentrations the manure were below the laboratory detection limit. The incorporated comparison had a stronger correlation and was best fit to an S-curve model while the unincorporated comparison had a weaker correlation and was best fit to a linear model (Table 5.3). Despite differing models, no notable differences were observed between NO_3-N loads of the incorporation methods. This observation is similar to results for NO_3-N fwmcs.

Despite some poor correlations between loads and the soil and manure regressors, general increasing trends, both linear and nonlinear, were observed. Similar studies have also observed greater NO_3-N loads for manured compared to unmanured soil (Edwards and Daniel 1993, Eghball and Gilley 1999, Eghball et al. 2002, Little et al. *In Press*) and increasing NO_3-N loads with increasing manure rates (Edwards and Daniel 1993, Eghball et al. 2002). Edwards and Daniel (1993) described the relationship between manure rate and NO_3-N concentration in runoff as linear. Of the three sites, only Lacombe had notable differences between incorporation treatments, showing NO_3-N load increases with incorporation.

5.3.5.5 Ammonia Thirty-minute Loads

Ammonia loads were regressed against Soil NH_3-N concentrations and Manure NH_4-N application rates. Beaverlodge had the greatest NH_3-N loads, ranging between 0 and 700 mg m^{-2}, despite having the lowest range of Soil NH_3-N and Manure NH_4-N values. Raymond loads were half that of Beaverlodge, ranging 0 to 300 mg m^{-2}. Lacombe loads were half that of Raymond, ranging 0 to 120 mg m^{-2}.

For Beaverlodge, correlations were generally poor (Table 5.2). Similar to NH_3-N fwmcs, unincorporated NH_3-N loads tended to be greater than incorporated loads (data not shown). This was likely a reflection of the highly impermeable nature of the unincorporated soils at this site.

For Lacombe, correlations were greater for incorporated than unincorporated treatments (Table 5.2). Ammonia loads regressed against Soil NH_3-N did not correlate for the unincorporated treatment. The same comparison for incorporated treatments best fit a linear model while the loads regressed against Manure NH_4-N best fit S-curve models. Differences between these S-curve models by incorporation method were not significant (Table 5.4). However, incorporated NH_3-N loads tended to be greater than unincorporated loads at greater manure rates.

For Raymond, correlations with Manure NH_4-N as the regressor were greater than correlations with Soil NH_3-N, though the latter correlations were better than most similar correlations of the other two sites (Table 5.2). Comparisons between soil and load NH_3-N values of the unincorporated treatment best fit a linear model while the equivalent comparison of the incorporated treatment best fit an S-curve model. The incorporated and unincorporated comparisons with Manure NH_4-N as a regressor also best fit S-curve-models. The a, x_0 and y_i coefficients of the incorporated model were significantly less than the corresponding coefficients of the unincorporated model (Table 5.4, Figure 5.7). As with NH_3-N fwmcs, NH_3-N loads were similar between incorporation treatments at low manure rates but unincorporated loads were increasingly greater with added Manure NH_4-N.

Though some relationships were poorly correlated, general increasing trends were observed between soil and manure regressors and NH_3-N loads. Several other studies have also found greater NH_3-N loads with manure application (Edwards and Daniel 1993, Eghball and Gilley 1999, Eghball et al. 2002, Little et al. *In Press*, Pote et al. 2001) and increasing loads with increasing manure rate (Edward and Daniel 1993, Eghball et al. 2002, Pote et al. 2001).

5.3.6 Loads over Time

5.3.6.1 Total Nitrogen Loads over Time

Total nitrogen loads were determined for runoff samples collected from the Raymond site only. A significant time by manure rate interaction and singular effects of time and manure rate occurred for TN mean loads in runoff from this site (Table 5.5). Contrasts indicated a significant linear trend between manure rate and TN load (data not shown). TN loads consistently increased with manure rate and mean differences were almost always significant (Figure 5.8, Appendix Table B.3). Contrary to TN mean concentrations, loads consistently increased over time with the most notable significant difference occurring between the initial and latter two time intervals. In this case, increasing loads over time more strongly reflect increasing runoff rates than decreasing concentrations.

5.3.6.2 Total Dissolved Nitrogen Loads over Time

Total dissolved nitrogen loads were determined for runoff samples collected from the Raymond site only. Similar significant interactions and singular effects occurred for TDN and TN mean loads at this site (Table 5.5). Contrasts also indicated a significant linear trend between manure rate and TDN load (data not shown). Mean loads consistently increased with manure rate and significant differences occurred between the 0 and 20 g m^{-2} manure rates of the initial two time intervals and between the 20 g m^{-2} and the other three manure rates of the final two time intervals (data not shown). Loads tended to increase over time with the most notable differences occurring between the middle two time intervals, significant for the 20 g m^{-2} manure rate.

5.3.6.3 Particulate Nitrogen Loads over Time

Particulate nitrogen loads were determined for runoff samples collected from the Raymond site only. Significant effects of time and manure rate occurred for PN mean loads in runoff from this site (Table 5.5). Contrasts indicated a linear relationship between manure rate and PN load (data not shown). Loads increased consistently with manure rate and with time but differences were not significant (data not shown).

5.3.6.4 Nitrate Loads over Time

Similar to NO_3-N concentrations, no significant interactions or singular effects of time interval, manure rate or incorporation method occurred for NO_3-N mean loads in runoff when data from all three sites were combined (Table 5.5). However, some significant effects and interactions were observed within each site.

For Beaverlodge, significant two-way interactions between time interval, manure rate and incorporation method were observed for NO_3-N mean loads in runoff (Table 5.5). Contrasts indicated a nonlinear relationship between manure rate and NO_3-N loads (data not shown). Of the incorporated treatments, the mean load at the zero manure rate was significantly greater than the three manured treatments and the 20 g m^{-2} manure rate was significantly greater than the lesser two manured treatments (Figure 5.9, Appendix Table B.4).

Loads from the unincorporated treatments had no significant trends relative to manure rate. Because of these differences, trends between incorporation methods were inconsistent across manure rate and time. The incorporated mean of the zero manure rate was significantly greater than the unincorporated mean. The opposite effect was observed at the 5 g m^{-2} manure rate. A significantly greater incorporated than unincorporated mean load was observed during the final time interval only (data not shown). Mean loads from the incorporated treatments increased consistently with time and were significantly greater during the latter two time intervals. Loads from the unincorporated treatments had no significant trends with time.

Significant two and three-way interactions and singular effects of time interval, manure rate and incorporation method were observed for NO_3-N mean loads in runoff at the Lacombe site (Table 5.5). Contrasts indicated a linear relationship between manure rate and NO_3-N loads (data not shown). Mean loads generally increased with manure rate though significant differences did not consistently occur (Figure 5.10, Appendix Table B.5). Loads tended to increase with incorporation and significant differences were observed for the final two time intervals of the unmanured treatments and all time intervals of the 20 g m^{-2} manure rate. The opposite trend occurred at the 10 g m^{-2} manure rate but differences were not significant. These differences may indicate that the unincorporated loads had nonlinear (a complete S-curve) relationship with manure rate while the incorporated loads had a nonlinear relationship with manure rate that more closely resembled an exponential curve or the initial upward swing of an S-curve relationship (Figure 5.10). Loads tended to increase with time but mean differences were only observed in some instances.

At Raymond, a significant two-way interaction between time and incorporation method and singular effects of time, manure rate and incorporation method were observed for NO_3-N loads in runoff (Table 5.5). No observable trends of mean differences occurred between manure rate and NO_3-N loads (data not shown). Loads consistently increased with incorporation but were only significant during the 10 to 20 minute time interval (Figure 5.11, Appendix Table B.6). Loads also tended to increase with time but few significant differences between means existed.

5.3.6.5 Ammonia Loads over Time

With data from all sites combined, a significant time by manure rate interaction and time interval effect were observed for NH_3-N mean loads in runoff (Table 5.5). Contrasts indicated a significant linear relationship between manure rate and NH_3-N load (data not shown). Loads tended to increase with manure rate across all time intervals, though significant differences were only observed between the unmanured and the greatest manure rate in the final two time intervals (Figure 5.12, Appendix Table B.7). Loads also tended to increase with time. Though no significant mean differences occurred across time, the most notable increase occurred between the middle two time intervals.

Significant two and three-way interaction and singular effects of time, manure rate and incorporation method occurred for NH_3-N loads in runoff from the Beaverlodge site (Table 5.5). Contrasts indicated a significant linear relationship between manure rate and NH_3-N load (data not show). Mean loads tended to increase with manure rate but significant differences only occurred between the lesser two manure rates and between the greater two manure rates of the unincorporated treatments (data not shown). Loads consistently decreased with incorporation and significant differences occurred within the manured treatments (data not shown). Loads tended to increase with time but few significant differences occurred (data not shown).

Similar to Beaverlodge, significant two and three-way interaction and singular effects of time, manure rate and incorporation method occurred for NH_3-N loads in runoff from the Lacombe site (Table 5.5). Contrasts indicated a significant linear relationship between manure rate and NH_3-N load (data not show). Loads tended to increase with manure rate with significant differences between the lesser and greater two manure rates of unincorporated treatments for the latter two time intervals and between the 20 g m^{-2} and the three lower manure rates of the incorporated treatments for all time intervals (data not shown). Contrary to Beaverlodge, loads also tended to increase with incorporation but significant mean differences only occurred within the 20 g m^{-2} manure rate (data not shown). As well, loads increased over time with significant mean differences occurring within the greater two manure rates (data not shown).

A significant three-way interaction for time, manure rate and incorporation method, as well as, a two-way interaction for time by rate and time by incorporation and singular effects of time and rate, occurred for NH_3-N mean loads in runoff from the Raymond site (Table 5.5). Contrasts indicated a significant linear relationship between manure rate and NH_3-N loads (data not shown). Loads consistently increased with manure rate though not all mean comparisons were significantly different (data not shown). No significant differences or notable trends were observed between incorporation methods (data not shown). Loads consistently increased over time but significant differences were only observed between the initial and latter two time intervals of the 20 g m^{-2} manure rate (data not shown).

5.4 Conclusions

Results of this experiment indicate that:

- Nitrogen in runoff was greater from manured soils than unmanured soils.
- Nitrogen in runoff increased with increasing rates of manure application, showing evidence of nonlinearity.
- Nitrogen in manure tended to correlate as well as nitrogen in soil to various nitrogen fractions in runoff.
- Ammonia-nitrogen in runoff decreased with incorporation at two of the three study sites while nitrate-nitrogen tended to increase or remained unchanged with incorporation.
- Nitrogen concentrations in runoff decreased over 30 minutes of runoff collected.

Other noteworthy observation included:

- Nitrogen concentrations were similar in soil with surface applied and incorporated manure, indicating little to no burial of manure below the 2.5 cm sampling depth with double disk incorporation.
- Nitrogen load and concentration responses were similar with imposed treatments, although loads increased with time as influenced by runoff rates, despite decreasing concentrations with time.

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Table 5.1. Mean nitrate (NO_3-N) and ammonia (NH_3-N) values in soil and manure

Site	Incorporation Method[z]	Total Phosphorus Target Manure Rate ($g\ m^{-2}$)	n	Post-treatment Soil NO_3-N[y] ----- ($mg\ kg^{-1}$) -----	Post-treatment Soil NH_3-N[y] ----- ($mg\ kg^{-1}$) -----	Manure Rate NO_3-N	Manure Rate NH_4-N
						------------- ($mg\ m^{-2}$)[x]	-------------
Beaverlodge	UI	0	3	47 a	9 a	0	0
		2.5	2	54 a	20 a	24	1601
		5	3	61 a	29 a	31	3959
		10	3	44 a	51 a	63	5307
	I	0	4	57 a	8 a	0	0
		2.5	3	59 a	19 a	14	1341
		5	3	67 a	36 a	17	2238
		10	4	54 a	43 a	53	6429
Lacombe	UI	0	4	54 k	18 h	0	0
		5	3	83 k	39 h	725	753
		10	3	112 i j	44 h	3370	1564
		20	4	158 h	67 h	2496	7467
	I	0	4	46 k	16 h	0	0
		5	3	66 k	14 h	552	1353
		10	4	76 j k	22 h	1085	6291
		20	3	145 h i	71 h	3586	2958
Raymond	UI	0	3	6 p	15 r	0	0
		5	3	17 p	75 r	0	2224
		10	2	17 p	203 q r	0	4466
		20	2	14 p	494 p	0	25998
	I	0	2	5 p	7 r	0	0
		5	2	15 p	51 r	0	2833
		10	3	16 p	188 q r	0	7570
		20	2	7 p	367 p q	0	12162

z. *Unincorporated (UI) and incorporated (I) treatments*

y. Mean values for each site followed by the same letter within each site are not significantly different at $P < 0.05$

x. 100 mg/m^2 = 1 kg/ha

Table 5.2. Summary of ammonia (NH_3-N) and particulate nitrogen (PN) regression results

Site/ Runoff Variables[z]	Soil/Manure Variables							
	Unincorporated Treatment				Incorporated Treatment			
	Soil NH_3-N		Manure NH_3-N		Soil NH_3-N		Manure NH_3-N	
	$(r^2)^y$							
Beaverlodge								
NH_3-N fwmc	0.43	S-curve	0.32	S-curve	nc		nc	
NH_3-N load	0.45	S-curve	0.33	S-curve	0.21	Linear	0.27	Linear
Lacombe								
NH_3-N fwmc	nc		0.24	S-curve	0.54	S-curve	0.65	S-curve
NH_3-N load	nc		0.23	S-curve	0.66	Linear	0.59	S-curve
Raymond								
TN fwmc	0.94	S-curve	0.96	S-curve	0.91	S-curve	0.94	S-curve
TDN fwmc	0.96	S-curve	0.96	S-curve	0.65	S-curve	0.63	S-curve
PN fwmc	0.77	S-curve	0.76	S-curve	0.54	Linear	0.13	Linear
NH_3-N fwmc	0.92	Linear	0.94	S-curve	0.91	S-curve	0.83	S-curve
TN load	0.93	S-curve	0.99	S-curve	0.97	S-curve	0.99	S-curve
TDN load	0.94	S-curve	0.99	S-curve	0.30	S-curve	0.33	S-curve
PN load	0.82	S-curve	0.79	S-curve	0.83	S-curve	0.79	S-curve
NH_3-N load	0.88	Linear	0.99	S-curve	0.54	S-curve	0.98	S-curve

z. flow-weighted mean concentration (fwmc)

y. Values of r^2 presented are the greater of linear and nonlinear models for a given incorporation

nc = no correlation, r^2 <0.1

nr = no regressor available, NO_3-N concentrations in manure were below laboratory detection limit

Table 5.3. Summary of nitrate (NO_3-N) and total dissolved nitrogen (TDN) regression results

Site/ Runoff Variables[z]	Soil/Manure Variables							
	Unincorporated Treatment				Incorporated Treatment			
	Soil NO_3-N		Manure NO_3-N		Soil NO_3-N		Manure NO_3-N	
	$(r^2)^y$							
Beaverlodge								
NO_3-N fwmc	nc		0.14	S-curve	0.94	S-curve	0.95	S-curve
NO_3-N load	nc		0.17	S-curve	0.88	S-curve	0.90	S-curve
Lacombe								
NO_3-N fwmc	0.35	S-curve	0.55	S-curve	0.69	S-curve	0.79	S-curve
Raymond								
TDN fwmc	0.33	S-curve	nr		0		nr	
NO_3-N fwmc	0.28	S-curve	nr		0.78	S-curve	nr	
TDN load	0.28	S-curve	nr		0.64	S-curve	nr	
NO_3-N load	0.27	Linear	nr		0.63	S-curve	nr	

z. flow-weighted mean concentration (fwmc)

y. Values of r^2 presented are the greater of linear and nonlinear models for a given incorporation treatment.

nc = no correlation, r2 <0.1

nr = no regressor available, NO3-N concentrations in manure were below laboratory detection limit

Table 5.4. Summary of regression results for nitrate (NO_3-N), ammonia (NH_3-N), total nitrogen (TN), total dissolved nitrogen (TDN) and particulate nitrogen (PN) between incorporation treatments

Site	Soil/Manure Variables	Runoff Variables[z,y]									
		NO_3-N	NH_3-N	TN	TDN	PN	NO_3-N	NH_3-N	TN	TDN	PN
		---- Flow-weighted Mean Concentration (mg L^{-1}) ----					---- 30-minute Load (mg m^{-2}) ----				
Beaverlodge	Soil NO_3-N	nc/S-curve	---	---	---	---	nc/S-curve	---	---	---	---
	Soil NH_3-N	---	S-curve/nc	---	---	---	---	S-curve/lin	---	---	---
	Manure NO_3-N	S-curve[x]	---	---	---	---	S-curve[x]	---	---	---	---
	Manure NH_3-N	---	S-curve/nc	---	---	---	---	S-curve/lin	---	---	---
Lacombe	Soil NO_3-N	S-curve[u]	---	---	---	---	Linear[x]	---	---	---	---
	Soil NH_3-N	---	nc/S-curve	---	---	---	---	nc/lin	---	---	---
	Manure NO_3-N	S-curve[u]	---	---	---	---	S-curve/lin	---	---	---	---
	Manure NH_3-N	---	S-curve[x,w]	---	---	---	---	S-curve[x]	---	---	---
Raymond	Soil NO_3-N	S-curve[x]	---	---	S-curve/nc	---	lin/S-curve	---	---	S-curve[x]	---
	Soil NH_3-N	---	lin/S-curve	S-curve[x]	S-curve[x]	S-curve/lin	---	lin/S-curve	S-curve[x]	S-curve[x]	S-curve[x]
	Manure NO_3-N	nr	---	---	nr	---	nr	---	---	nr	---
	Manure NH_4-N	---	S-curve[u]	S-curve[x]	S-curve[x]	S-curve/lin	---	S-curve[x,u]	S-curve[x]	S-curve[x]	S-curve[x]

z. Where two models are listed (S-curve/lin), the unincorporated treatment is listed first and the incorporated treatment is second. Where only one model is listed, this applies to both unincorporated and incorporated treatments.

y. lin = linear relationship
curve = S-curve relationship
--- = not analyzed
nc = no correlation, r2 <0.1
nr = no regressor available, NO3-N concentrations in manure were below laboratory detection limit

x. No significant differences between incorporated and unincorporated regression coefficients

w. Significant difference between incorporated and unincorporated x_0 coefficient (x-values at inflection point)

v. Significant difference between incorporated and unincorporated b coefficient (average slope of the curves rising limb)

u. Significant differences between incorporated and unincorporated a (maximum y value) and y_i (y-value at inflection point)

Table 5.5. Repeated measures analysis of variance results for total nitrogen (TN), total dissolved nitrogen (TDN), particulate nitrogen (PN), nitrate (NO_3-N) and ammonia (NH_3-N) concentrations and loads

Site	Effect/Interaction[z]	Runoff Variables[y]									
		TN	TDN	PN	NO_3-N	NH_3-N	TN	TDN	PN	NO_3-N	NH_3-N
		Concentration (mg L^{-1})					Load (mg m^{-2})				
All Sites	Time Interval (T)	---	---	---	ns	**	---	---	---	ns	**
	Target Manure Rate (R)	---	---	---	ns	*	---	---	---	ns	ns
	T x R	---	---	---	ns	ns	---	---	---	ns	**
	Incorporation (In)	---	---	---	ns	ns	---	---	---	ns	ns
	T x In	---	---	---	ns	ns	---	---	---	ns	ns
	R x In	---	---	---	ns	ns	---	---	---	ns	ns
	T x In x R	---	---	---	ns	ns	---	---	---	ns	ns
Beaverlodge	T	---	---	---	*	**	---	---	---	***	***
	R	---	---	---	ns	***	---	---	---	ns	***
	T x R	---	---	---	ns	ns	---	---	---	*	***
	In	---	---	---	**	***	---	---	---	ns	***
	T x In	---	---	---	**	**	---	---	---	**	***
	R x In	---	---	---	ns	***	---	---	---	**	**
	T x In x R	---	---	---	ns	ns	---	---	---	ns	***
Lacombe	T	---	---	---	***	***	---	---	---	***	***
	R	---	---	---	***	***	---	---	---	***	***
	T x R	---	---	---	***	***	---	---	---	***	***
	In	---	---	---	***	**	---	---	---	***	**
	T x In	---	---	---	***	**	---	---	---	***	**
	R x In	---	---	---	***	**	---	---	---	***	**
	T x In x R	---	---	---	*	ns	---	---	---	***	***
Raymond	T	***	***	ns	**	***	***	***	***	***	***
	R	***	***	***	ns	***	**	**	**	*	**
	T x R	***	**	**	ns	**	***	***	ns	ns	***
	In	ns	ns	**	*	**	ns	ns	ns	*	ns
	T x In	ns	ns	ns	**	ns	ns	ns	ns	*	*
	R x In	ns	ns	**	ns	*	ns	ns	ns	ns	ns
	T x In x R	*	**	ns	ns	ns	ns	ns	ns	ns	**

z. The symbol "x" indicates an interaction between terms.

y. Significance is indicated as *** for P < 0.001, ** for P < 0.05, * for P < 0.1, ns for not significant and --- for not analyzed

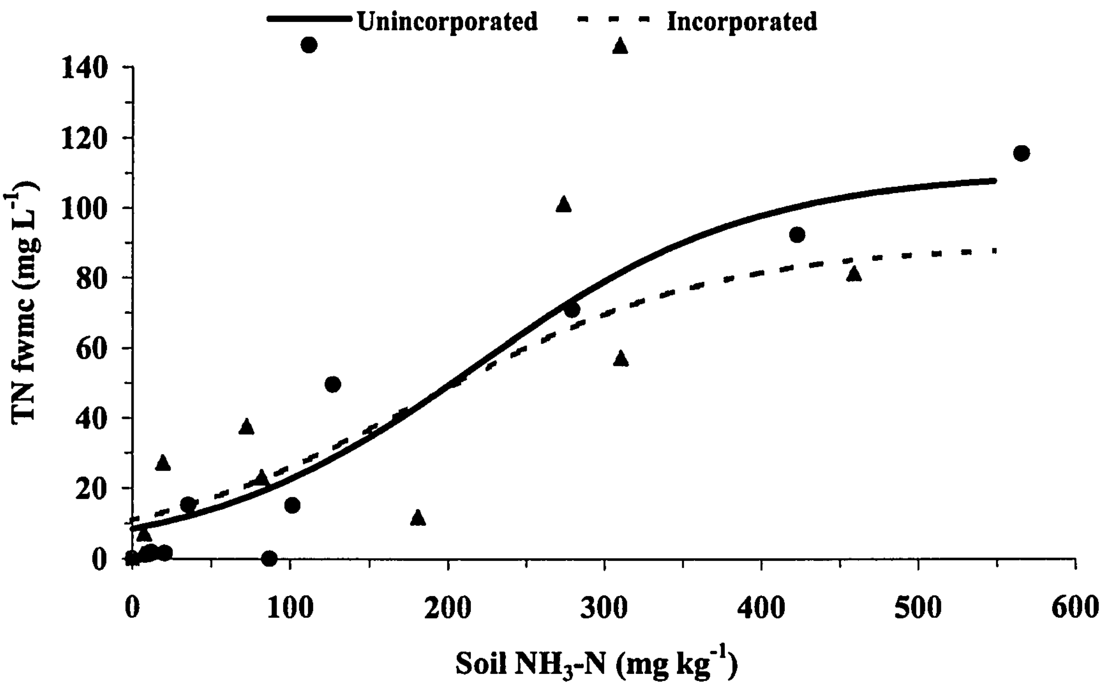

Figure 5.1. Regressions for total nitrogen (TN) flow-weighted mean concentration (fwmc) and soil ammonia (NH_3-N) from Raymond

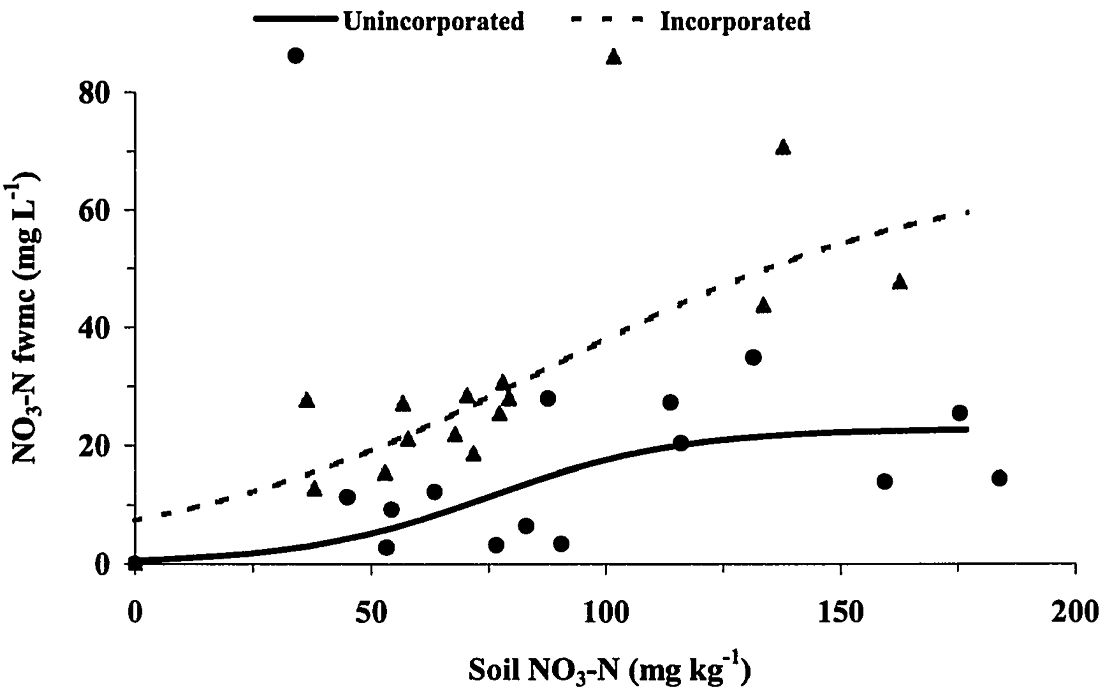

Figure 5.2. Regressions for nitrate (NO_3-N) flow-weighted mean concentration (fwmc) and soil nitrate (NO_3-N) from Lacombe

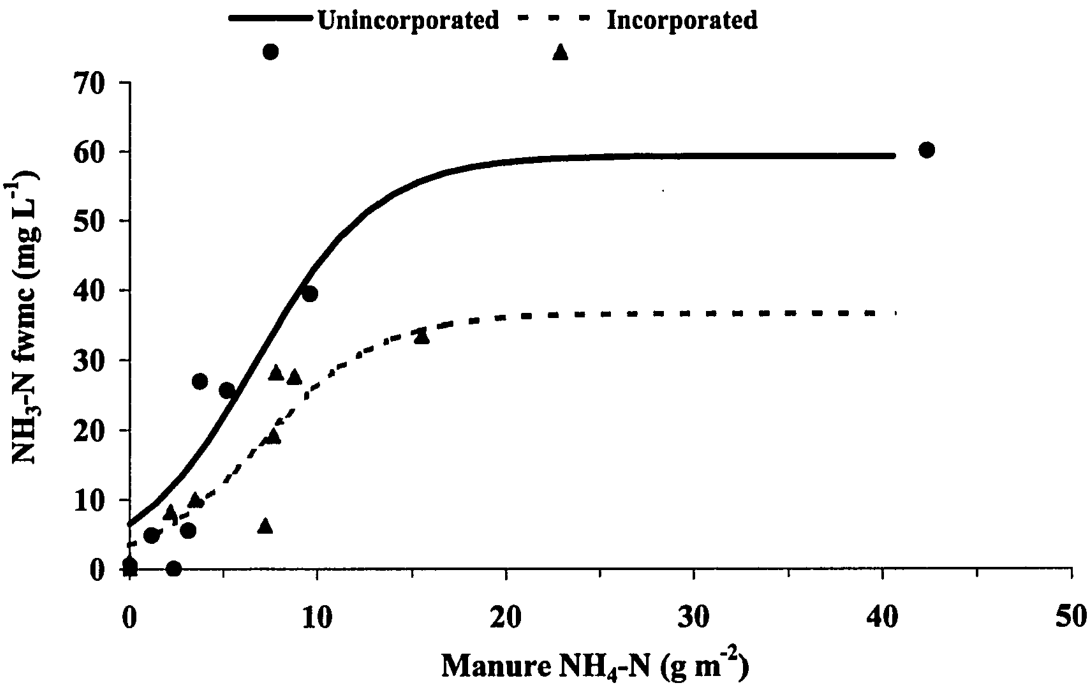

Figure 5.3. Regressions for ammonia (NH_3-N) flow-weighted mean concentration (fwmc) and manure ammonium (NH_4-N) from Raymond

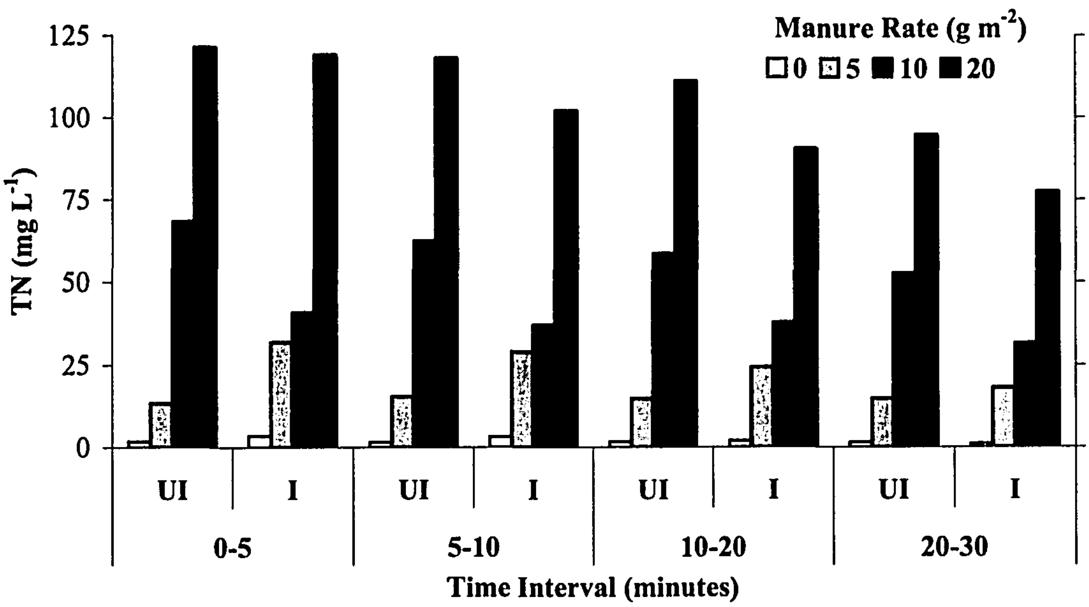

Figure 5.4. Total Nitrogen (TN) mean concentrations of unincorporated (UI) and incorporated (I) soils from Raymond

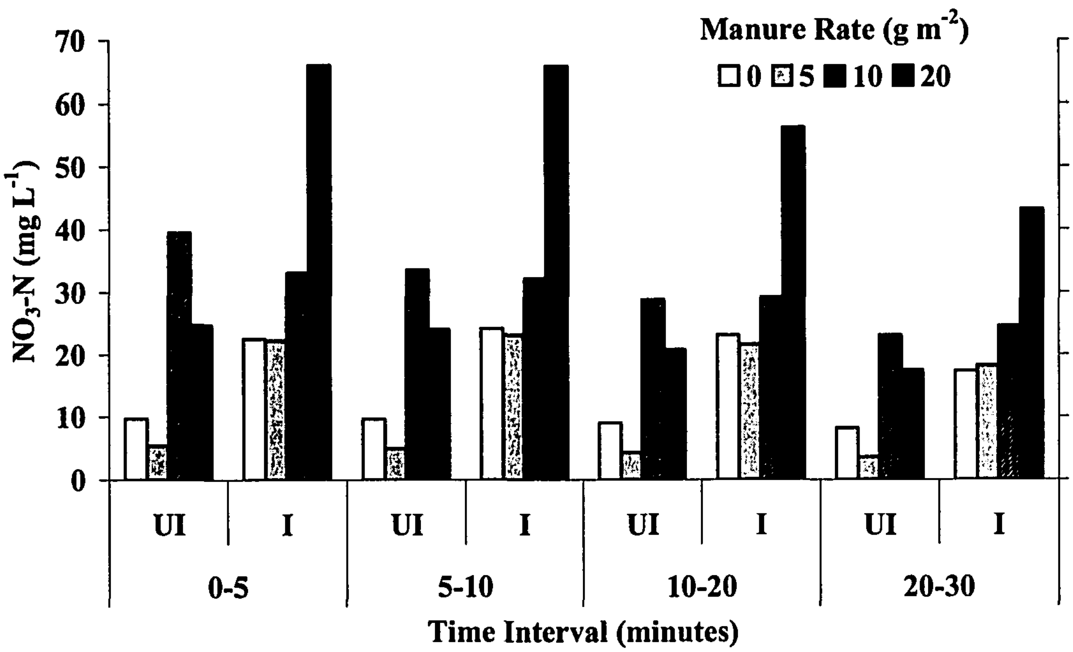

Figure 5.5. Nitrate (NO_3-N) mean concentrations of unincorporated (UI) and incorporated (I) soils from Lacombe

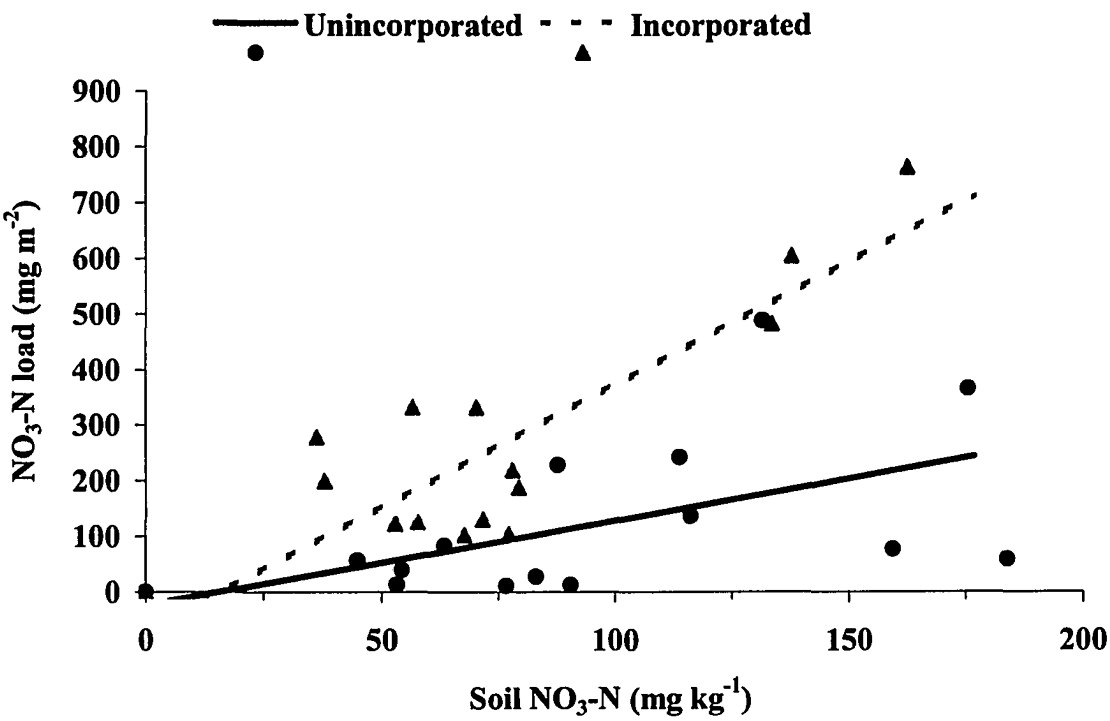

Figure 5.6. Regressions for nitrate (NO_3-N) load and soil nitrate from Lacombe

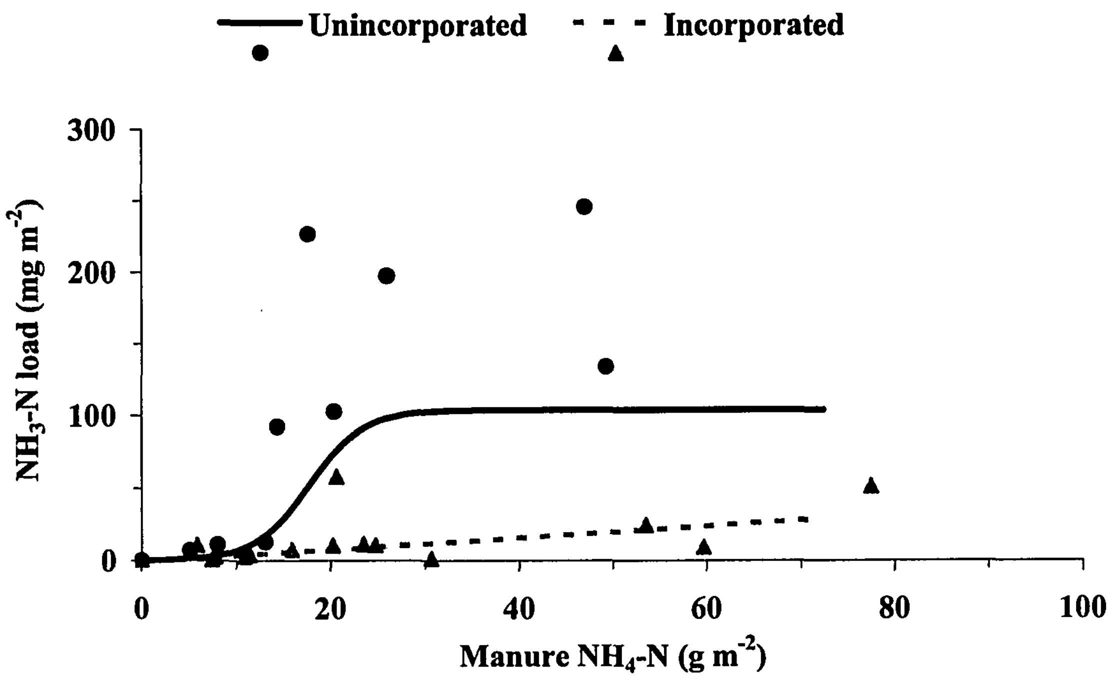

Figure 5.7. Regressions for ammonia (NH_3-N) load and manure ammonium (NH_4-N) from Raymond

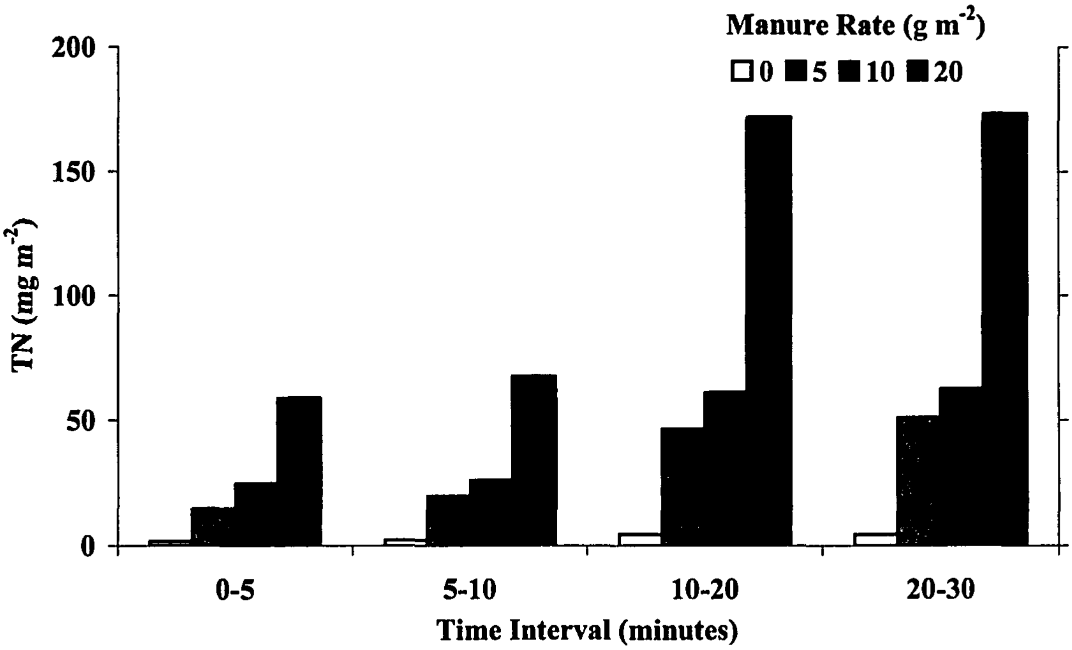

Figure 5.8. Total nitrogen (TN) mean loads from Raymond

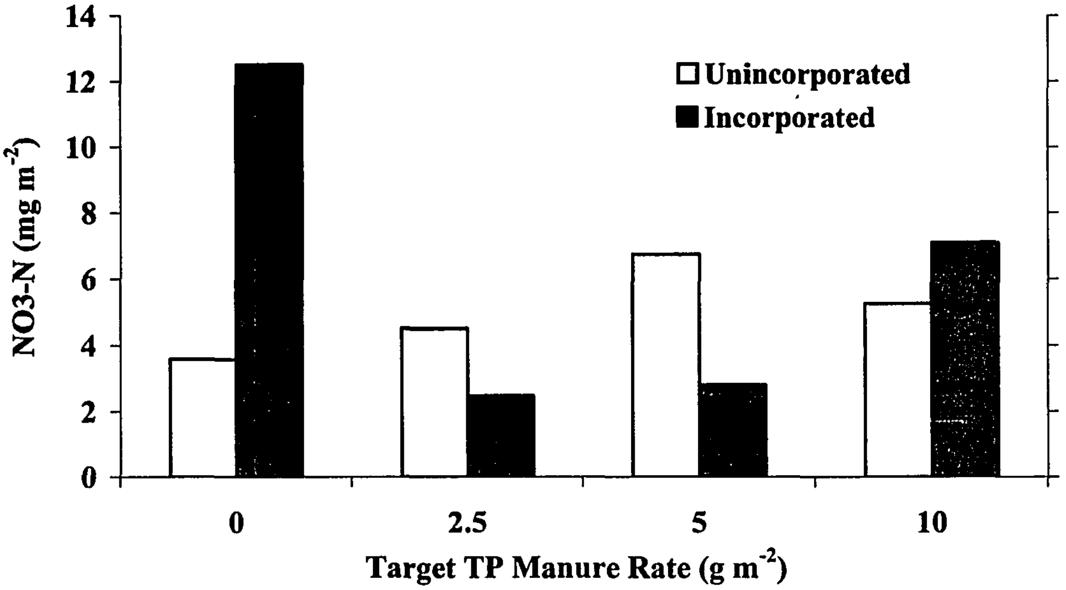

Figure 5.9. Nitrate (NO_3-N) mean loads from Beaverlodge

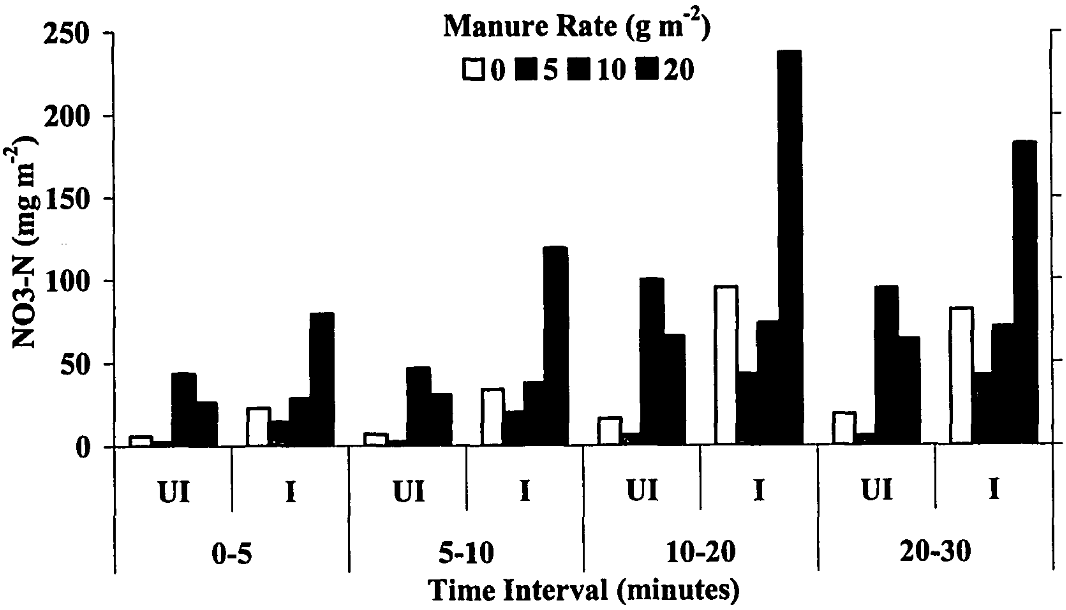

Figure 5.10. Nitrate (NO_3-N) mean loads from Lacombe

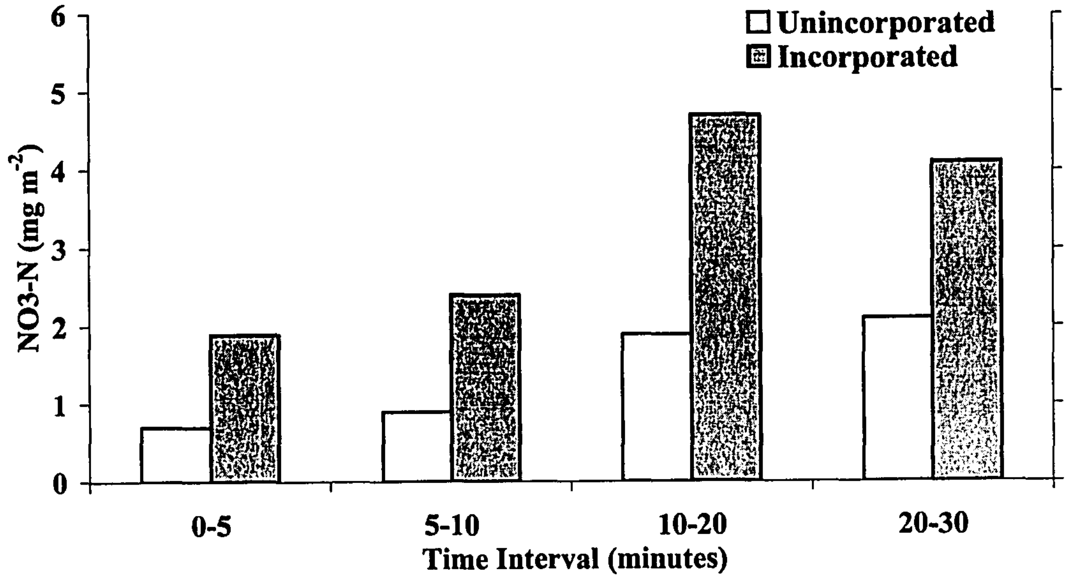

Figure 5.11. Nitrate (NO_3-N) mean loads from Raymond

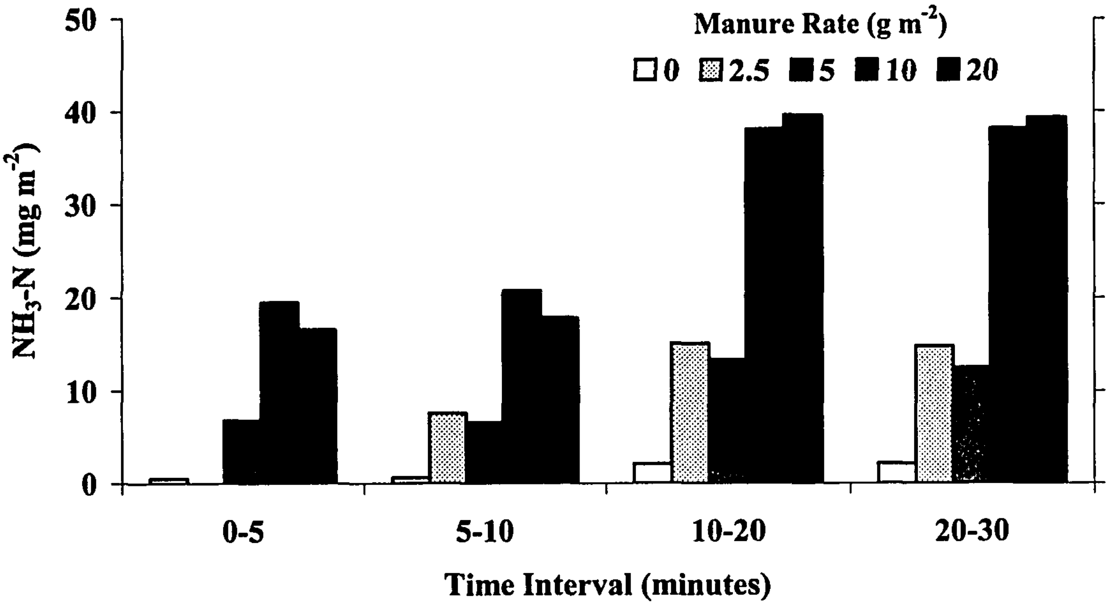

Figure 5.12. Ammonia (NH_3-N) mean loads from all sites combined

6. SYNTHESIS

As the earth's human population grows in numbers and increases its technology, costs to the earth's environmental health are increased. In particular, the quantity and quality of water resources have become global concerns. Nutrients such as phosphorus and nitrogen are necessary components of plant and animal life, however, excessive amounts of either or both can alter the balance of aquatic ecosystems, detrimentally affecting the environment as well as human quality of life.

Agriculture has been identified in many countries around the world as a source of nonpoint pollution to the environment. With augmented applications of fertilizers to cropland for increased yields and an increasing concentration of agricultural activities within economically beneficial areas, risks to the surrounding environment have increased. Studies in Canada have concluded that excessive nutrients from agricultural, municipal and industrial activities have impacted the quality of surface waters in the country. In Alberta, studies have linked increasing concentrations of nutrients in surface waters with areas of greater agricultural intensity.

The increased concentration of livestock production in select areas of many countries has lead to legislation regarding manure handling and disposal. Often, large livestock operations produce more manure than is needed to meet the growth requirements of crops within the operation's land base. The result is a buildup of nutrients in the surface soils due to manure applications. These excess nutrients can be leached to shallow groundwater and/or transported via runoff to nearby surface water bodies.

6.1 Rain Simulations and Scaling Issues

Rainfall simulation studies have been used extensively in research to explore the hydrologic aspects of surface runoff. In recent years, rainfall simulations have been applied to water quality studies as well. Rainfall simulations can be an efficient and inexpensive alternative to measuring runoff generated by natural rainfall. The ability to collect larger amounts of data in a short time under controlled conditions, without having to wait for natural precipitation, is an appealing advantage to many researchers. Factors under the researcher's control include the frequency, intensity, spatial and temporal consistency and kinetic energy of the rainfall. Greater control of such factors facilitates comparisons of differing soil conditions and management practices, and enhances the confidence in the conclusions drawn from such research. However, specific magnitudes of such factors as runoff volumes and nutrient concentrations cannot be easily estimated for watersheds from small-plot studies. While the basic processes occurring at the small-plot scale may remain intact at the watershed scale, interactions between these processes increase in complexity with an increasing spatial scale.

6.2 Use of Nutrient Concentrations and Loads

Loads are an important measure of the total mass of nutrients being added to surface waters over a given time. This measure of nutrients can be important for assessing relative amounts of nutrients added to surface water systems from various sources. Water quality objectives based on maximum nutrient loads require measurements of concentration and flow volume. However, nutrient concentrations are a simpler measure for surface water quality objectives, requiring only one measured parameter.

6.3 Research Rational

Currently in Alberta, manure applications to agricultural land are regulated according to nitrate-nitrogen and electrical conductivity limits in soil and to set-back zones from common water bodies. While limiting applications of manure based on nitrogen limits is beneficial, the amount of phosphorus applied with manure at acceptable nitrogen rates are often in excess of crop phosphorus needs. Therefore, research has been undertaken in Alberta, as in other places, to further our understanding of the relationship between phosphorus in soils and manure and phosphorus in runoff. With this information, regulatory bodies can create scientifically sound phosphorus-based limits for manure application to protect water quality.

Until recently, many nutrient/runoff studies used manure application rates based on nitrogen requirements of crops. This study has based manure applications targeted to specific total phosphorus amounts, facilitating comparisons of phosphorus behavior in runoff among sites. While phosphorus is the key nutrient of interest in much of the runoff water quality research currently being conducted, continuing to include nitrogen in these studies is important to accommodate linkages between previous nitrogen-focused research studies and current phosphorus studies.

Many similar studies conducted in the United States have reported relatively large amounts of eroded sediment and particulate phosphorus in runoff from manured soil. Their findings indicate that, while manure incorporation reduces the dissolved fraction of phosphorus in runoff, the act of tillage increases erosion activity and particulate phosphorus. Thus, many recommendations for reducing phosphorus export from agricultural lands have focused on erosion-reducing management practices. Previous studies conducted in Alberta have observed notably less particulate phosphorus in runoff even with manure incorporation by tillage. With a large portion of the total phosphorus (TP) in the dissolved state, erosion-controlling practices would be ineffective for reducing phosphorus export. Thus, one of the objectives of this study was to further the understanding of phosphorus fractions in runoff from manured agricultural soils in Alberta.

6.4 Effects of Manure Application

In this study, concentrations and loads of phosphorus and nitrogen fractions in runoff consistently increased with manure application compared to unmanured soils and also tended to increase with increasing manure rates. These relationships of nutrient concentrations and loads to manure rate were often nonlinear (S-curve shaped), especially evident where greater manure rates occurred. For phosphorus, well correlated relationships tended to be nonlinear, whereas a linear relationship was more commonly detected where more scatter existed in the data. This highlights the importance of reducing experimental error as much as practically possible in order to identify important trends that may exist. More scattered data tended to occur at the greater than the lesser manure rates, most likely a reflection of the variable nature of nutrients in manure.

Nonlinear relationships detected in the data provide important information regarding the behavior of nutrients in soil and runoff. The initial, slowly rising portion of the S-curves indicated that lesser amounts of manure applied to land tended to produce relatively small increases of nutrients in surface runoff. This may have been caused by the clumped nature of manure, resulting in its uneven distribution across the soil surface.

Consequently, portions of surface runoff may have had little or no contact with the manure. However, a change point occurred where increasing manure additions were related to a greater rate of increasing nutrients in runoff. Many studies have explored this apparent change point where the soil's ability to sorb nutrients is reduced, leaving excessive amount of nutrients highly susceptible to transport by surface runoff. This change point can be viewed as the point at which potential risk for nutrient loss is markedly increased. In the case of freshly applied manure, it is possible that greater surface coverage by manure may have increased the amount of manure/water contact that occurred. The slower rate of increase observed at the upper portion of the curve is most likely a reflection of the maximum amount of nutrients that could diffuse into runoff under the given conditions.

6.5 Manure Total Phosphorus as an Estimate of Post-application Soil-test Phosphorus

Generally, associated nutrients in runoff correlated with total phosphorus, nitrate and ammonium application rates of manure as well as or almost as well as nutrient concentrations in soil after manure application. However, dissolved phosphorus in runoff correlated poorly with water extractable phosphorus manure rates. While stronger relationships between fractions of dissolved phosphorus in runoff and water extractable concentrations of phosphorus in manure were expected, as have been recorded in other studies, correlations with water extractable phosphorus manure rates within this study and other studies were poor. In order for phosphorus-based soil limits to be used for restricting manure applications to agricultural lands, producers will require the ability to estimate appropriate application rates to ensure post-application soil concentrations remain below the set allowable limits. Results of this study indicate that total phosphorus in manure could be a useful measure to achieve this goal.

6.6 Total Phosphorus as an Environmental Measure

Much research has been conducted on total phosphorus and the more immediately biologically available forms of phosphorus in surface water. While the more available forms of phosphorus are the most crucial to aquatic environments in the short term, the entire amount of phosphorus added to these systems can become available over a longer period of time. Proper conservation measures can allow a water body to recover from past enrichments of highly available phosphorus in a relatively short time. However, the more stable forms of phosphorus remain in lake and river sediment, slowly releasing to water, decades after nutrient additions have been restricted. For this reason, further research should focus on TP concentrations in runoff. In addition, TP in runoff is a consistent measure of phosphorus across watersheds. Phosphorus may exchange between dissolved and particulate forms as affected by runoff, in-stream and lake processes, where as TP measures the net effect of these processes with respect to phosphorus additions and exports from aquatic systems. Much research is available regarding the effects of TP concentrations in water on aquatic organisms. Alberta Environment reflects this research with the current use of TP concentration limits in surface water determined for the protection of aquatic life.

Particulate and dissolved fractions of phosphorus also remain critical components in nutrient/runoff studies for understanding phosphorus behavior among soil, manure and water. Observing the effects of various management practices on these two phosphorus fractions will assist in the evaluation of best management practices for preserving water quality.

6.7 Effects of Manure Incorporation

While some results of the study were consistent across the three study sites, others varied among sites. These variabilities can be primarily attributed to pre-existing soil and landscape conditions which were not controlled for the purposes of this experiment. The Beaverlodge site had a Luvisolic soil compared to the Chernozemic soils at the Lacombe and Raymond sites. Surface soils of the Beaverlodge site had clay and clay loam textures, were underlain by heavy clay textured soils and had a history of conventional tillage. As a result of these factors, infiltration rate and initial abstraction of the untilled Beaverlodge soils were lowest of the three sites. When manure was incorporated into the soil, the act of tillage dramatically increased these two hydrologic parameters, resulting in the greatest changes observed among the three sites. Manure incorporation at Beaverlodge also resulted in the most significant decreases of TP, dissolved reactive phosphorus (DRP) and ammonia-nitrogen (NH_3-N) concentrations in runoff of the three sites. These decreases may have been caused by burial of manure below the depth of soil in contact with surface runoff, often referred to as the effective depth of interaction. However, the occurrence of similar phosphorus and nitrogen concentrations between unincorporated and incorporated soils indicates that the majority of the manure remained in the upper 2.5 cm of the soil profile. Field observations at all three sites confirm this finding and other studies have stated similar findings. Alternately, these nutrient decreases in runoff might also be associated with the greater initial abstraction values observed after incorporation. With larger volumes of water required to infiltrate the incorporated soils before runoff could be produced, a notable amount of nutrients could have been leached below the effective depth of interaction before runoff occurred. Another possibility is that the acidic nature of the Beaverlodge topsoil may also have encourage greater phosphorus sorption after incorporation. Though, the manure was only in contact with the soil for approximately 24 hours before simulating rain. Only an insignificant amount of phosphorus would have likely sorbed to the soil in such a short period of time. Suspended sediment concentrations at Beaverlodge elevated above the other two sites confirm that this site generated greater erosion activity. However, these suspended sediment concentrations did not change with manure incorporation, indicating relatively little change in erosional activity.

The Chernozemic soil at the Raymond site had a surface soil texture similar to that of the Beaverlodge soil but was underlain with a coarse-textured subsoil which may have encouraged greater water infiltration. This site also has a history of no-till management, known to increase infiltration by enhancing macropore development. Additionally, the Raymond simulations were conducted in the spring, an entire year after the site's most recent soil disturbance activity, seeding, the previous spring. Alternately, the other two sites were simulated in the autumn with only the span of a growing season since seeding was conducted. This difference may have further encouraged increased macropore development, and thus, infiltration capacity of the soil at Raymond before tillage. At this site, incorporating the manure reduced initial abstraction values but did not affect runoff and infiltration rates. Raymond concentrations and loads of TP, total dissolved phosphorus (TDP), DRP, total nitrogen (TN), total dissolved nitrogen (TDN) and NH_3-N in runoff from incorporated soils tended to remain the most similar to those from unincorporated soils of all three sites. However, particulate phosphorus (PP) and particulate nitrogen (PN) concentrations and loads, though variable in nature, decreased with incorporation, indicating that erosion of soil or manure from the surface may have been slightly reduced with incorporation.

The Lacombe Chernozemic soil was coarser in texture than the Beaverlodge and Raymond soils. The Lacombe site also had a greater hill slope and a history of conventional tillage practices. Manure incorporation did not result in any observable differences in initial abstraction, runoff or infiltration rates at this site. Interestingly, the initial abstractions from unincorporated and incorporated soils of this site were similar to initial abstractions after manure incorporation at the other two sites. Regardless of the initial soil conditions, manure incorporation appears to have resulted in similar post-tillage hydrologic characteristics across the three sites. Lacombe tended to have slight decreases in phosphorus concentrations and loads for the middle manure application rates, not occurring with unmanured or highly manured soils. This indicates that incorporation may be an effective management strategy for reducing nutrients in runoff from some soils at moderate manure application rates but that the positive effects may not exist at higher rates. However, further investigation of this concept would be required for scientifically sound conclusions.

Unlike other nutrient fractions in runoff from these three sites, nitrates in runoff increased notably with manure incorporation at all sites. With several months since the soil had last been disturbed, nitrates may have stratified with greater concentrations residing at lower depths due to leaching during rainfall and snowmelt events. Manure incorporation by tillage may have increased the area of contact between soil and water within the effective depth of interaction causing greater transfer of the highly soluble nitrates in soil to runoff.

While ammonia tended to decrease with incorporation at Beaverlodge and Raymond, an opposite effect was observed at Lacombe. However, ammonia concentrations in runoff at Lacombe were relatively small compared to the other two sites and the difference with and without incorporation was rather unnoteworthy.

The Agricultural Operation Practices Act (AOPA) of Alberta suggests an advantage to incorporating manure within 48 hours of application by requiring this practice for all manure applications excluding application to forages or direct seeded crops and frozen or snow-covered land. Best management practices recommended for decreasing nutrient loss to surface waters suggest not applying manure if significant rainfall is expected. Results of this study confirm that an advantage of incorporating manure may exist under some soil and landscape conditions. In fact, other studies suggest that more thorough incorporation with additional passes or different tillage implements may have an even greater impact of phosphorus reduction with manure incorporation. This effect is likely a result of nutrients in manure being buried below the effective depth of interaction between soil and surface runoff.

6.8 Effects over Time

The various fractions of nitrogen concentrations tended to decrease over 30 minutes of runoff produced by the rain simulations while phosphorus fractions remained relatively constant over this runoff period. However, other studies have shown phosphorus concentration decreases over runoff periods of up to two hours. Responses of this study are characteristic of the two nutrients as portions of nitrogen are highly soluble and could conceivably be flushed in large concentrations during the initial minutes of runoff. Alternately, phosphorus is a less soluble nutrient, expected to provide a slow, steady supply to runoff, with any decreases occurring over a longer period of time. Subsequent studies exploring phosphorus changes over time should involve longer periods of runoff collection to adequately capture occurring trends.

At all three sites, runoff rates and coefficients increased over the 30 minutes of runoff as infiltration rates decreased. In response to these increasing runoff rates, nutrient loads also tended to increase with time. While this is expected in light of unchanging phosphorus concentrations, increasing nitrogen loads over time with opposing decreases in concentration indicate that the effects of runoff rate overpowered the effects of concentration on nitrogen loads.

6.9 Economic Implications of Phosphorus-based Guidelines for Soil

Typical nitrogen fertilizer recommendations for dryland crops in the prairie provinces can be approximately five times the phosphorus recommendations. Using commonly published values of approximate nitrogen and phosphorus concentrations in manure, application rates to meet crop phosphorus requirements have been estimated as half the rates needed to meet crop nitrogen requirements. With this estimation in mind, there would be economic consequences of moving from nitrogen to phosphorus-based limits for Alberta soils. A given amount of manure would require roughly twice the land base for application and supplemental commercial nitrogen fertilizer would be required, applied in an additional application or banded with seed.

6.10 Further Research

While much research has focused on nutrients in runoff from agricultural land in recent years, further understanding is required to make scientifically sound changes to current legislation and agricultural practices. Further study should include investigation of:

- The effects of manure application rate and incorporation over a series of time increments after application.
- The effects of these variables with different soil types and conditions as well as differing landscapes and management practices.
- The effects of various in-stream processes that alter nutrient concentrations from the field's edge.
- Total, dissolved and particulate fractions of nutrients in runoff from agricultural land and how the fractions change once runoff reaches streams and lakes.
- Practical ways to reduce nutrient content of manure or encourage nutrient binding to soil.
- The effects of soil properties such as texture and organic content on the soil phosphorus sorption capacity.
- Soil phosphorus sorption capacity and its effects on the soil:runoff phosphorus relationship

APPENDIX A. PHOSPHORUS MEAN TABLES

Table A.1. Total phosphorus (TP) mean concentrations (mg L^{-1}) of unincorporated (UI) and incorporated (I) soils from all sites combined

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})				
		0	2.5	5	10	20
0-5	UI	1.3	4.6	4.3	12.8	15.7
	I	1.4	2.1	4.0	5.7	15.1
5-10	UI	1.3	4.0	4.5	12.0	16.1
	I	1.6	2.0	4.0	5.7	14.3
10-20	UI	1.3	3.9	4.5	11.6	15.5
	I	1.5	1.9	3.8	5.9	14.0
20-30	UI	1.3	3.6	4.5	11.0	15.0
	I	1.3	2.0	3.8	5.7	13.2
	$LSD_{0.05}$	*4.7*				

Table A.2. Total dissolved phosphorus (TDP) mean concentrations (mg L^{-1}) from Raymond by target total phosphorus (TP) manure rate

Time Interval (minutes)	Target TP Manure Rate (g m^{-2})			
	0	5	10	20
0-5	0.4	6.1	13.0	21.7
5-10	0.4	6.0	11.9	21.9
10-20	0.4	5.9	12.1	21.8
20-30	0.5	5.3	10.6	20.6
$LSD_{0.05}$	*3.2*			

Table A.3. Dissolved reactive phosphorus (DRP) mean concentrations (mg L^{-1}) of unincorporated (UI) and incorporated (I) soils from all sites combined by target total phosphorus (TP) manure rate

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})				
		0	2.5	5	10	20
0-5	UI	0.6	2.4	2.7	7.8	11.2
	I	0.6	1.3	2.4	3.9	10.8
5-10	UI	0.6	2.7	2.9	7.8	11.8
	I	0.7	1.3	2.4	4.0	10.9
10-20	UI	0.6	2.9	3.0	7.4	11.7
	I	0.7	1.3	2.4	4.1	11.4
20-30	UI	0.6	2.7	3.1	7.2	11.1
	I	0.7	1.3	2.4	4.1	11.5
	$LSD_{0.05}$	*4.7*				

Table A.4. Total phosphorus (TP) mean loads (mg m^{-2}) of unincorporated (UI) and incorporated (I) soils from all sites combined

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})				
		0	2.5	5	10	20
0-5	UI	1.5	0	5.5	12.9	13.2
	I	1.1	1.8	2.6	3.7	11.6
5-10	UI	1.5	5.2	6.6	14.9	14.8
	I	1.9	2.1	3.4	4.7	15.5
10-20	UI	3.3	13.9	14.9	33.5	32.3
	I	5.2	4.5	7.7	11.3	37.2
20-30	UI	3.6	16.8	16.4	36.7	37.6
	I	5.2	5.1	9.1	13.3	38.3
	$LSD_{0.05}$	*12.5*				

Table A.5. Total dissolved phosphorus (TDP) mean loads (mg m^{-2}) of unincorporated (UI) and incorporated (I) soils from Raymond by target total phosphorus (TP) manure rate

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})			
		0	5	10	20
0-5	UI	0.2	3.1	6.7	10.5
	I	0.2	4.3	4.4	9.9
5-10	UI	0.2	4.7	7.0	11.2
	I	0.4	5.4	4.6	14.5
10-20	UI	0.6	12.9	16.1	31.1
	I	1.0	14.2	13.2	40.0
20-30	UI	0.8	14.6	16.8	33.8
	I	1.2	16.2	13.7	46.6
	$LSD_{0.05}$	*13.0*			

Table A.6. Dissolved reactive phosphorus (DRP) mean loads (mg L^{-1}) of unincorporated (UI) and incorporated (I) soils from all sites combined by target total phosphorus (TP) manure rate

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})				
		0	2.5	5	10	20
0-5	UI	0.4	1.5	2.4	6.9	7.7
	I	0.5	0.3	1.5	2.5	9.0
5-10	UI	0.5	4.3	3.3	8.3	9.1
	I	0.9	0.5	1.9	3.2	12.5
10-20	UI	1.0	10.7	8.6	18.4	22.0
	I	2.7	2.0	5.0	8.0	31.3
20-30	UI	1.3	12.1	9.5	21.3	25.1
	I	3.1	2.5	6.1	9.5	33.6
	$LSD_{0.05}$	*9.2*				

APPENDIX B. NITROGEN MEAN TABLES

Table B.1. Total nitrogen (TN) mean concentrations (mg L^{-1}) of unincorporated (UI) and incorporated (I) soils from Raymond by target total phosphorus (TP) manure rate

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})			
		0	5	10	20
0-5	UI	1.7	13.5	68.4	121.4
	I	3.5	32.0	40.8	119.1
5-10	UI	1.6	15.5	62.4	118.0
	I	3.3	29.1	37.2	102.0
10-20	UI	1.6	14.9	58.6	111.0
	I	1.9	24.5	37.9	90.3
20-30	UI	1.5	14.9	52.5	94.6
	I	1.0	18.1	31.5	77.3
	$LSD_{0.05}$	24.6			

Table B.2. NO_3-N mean concentrations (mg L^{-1}) of unincorporated (UI) and incorporated (I) soils from Lacombe by target total phosphorus (TP) manure rate

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})			
		0	2.5	5	10
0-5	UI	9.7	5.5	39.5	24.7
	I	22.5	22.3	33.1	66.0
5-10	UI	9.6	5.0	33.5	24.0
	I	24.2	23.2	32.2	65.8
10-20	UI	9.0	4.4	28.8	20.7
	I	23.1	21.6	29.2	56.1
20-30	UI	8.2	3.6	23.1	17.4
	I	17.3	18.2	24.5	43.1
	$LSD_{0.05}$	10.8			

Table B.3. Total nitrogen (TN) mean loads (mg m^{-2}) from Raymond by target total phosphorus (TP) manure rate

Time Interval (minutes)	Target TP Manure Rate (g m^{-2})			
	0	5	10	20
0-5	1.7	14.6	24.7	58.7
5-10	2.2	19.6	25.9	67.5
10-20	4.5	46.4	61.0	171.7
20-30	4.5	51.0	62.6	173.2
$LSD_{0.05}$	6.4			

Table B.4. Nitrate (NO_3-N) mean loads (mg m^{-2}) from Beaverlodge by target total phosphorus (TP) manure rate

Target TP Manure Rate (g m^{-2})	Incorporation Method	
	Unincorporated	Incorporated
0	3.6	12.5
2.5	4.5	2.5
5	6.8	2.8
10	5.3	7.1
LSD 0.05	3.6	

Table B.5. Nitrate (NO_3-N) mean loads (mg m^{-2}) of unincorporated (UI) and incorporated (I) soils from Lacombe by target total phosphorus (TP) manure rate

Time Interval (minutes)	Incorporation Method	Target TP Manure Rate (g m^{-2})			
		0	5	10	20
0-5	UI	5.7	2.3	43.5	25.9
	I	22.7	14.4	28.6	79.0
5-10	UI	6.9	2.6	46.6	30.2
	I	33.7	19.8	37.4	118.6
10-20	UI	16.1	6.1	99.3	65.6
	I	94.7	42.6	73.5	237.1
20-30	UI	18.8	5.7	94.2	63.5
	I	81.4	41.9	70.8	182.1
	LSD 0.05	45.7			

Table B.6. Nitrate (NO_3-N) mean loads (mg m^{-2}) from Raymond

Time Interval (minutes)	Incorporation Method	
	Unincorporated	Incorporated
0-5	0.7	1.9
5-10	0.9	2.4
10-20	1.9	4.7
20-30	2.1	4.1
LSD 0.05	2.0	

Table B.7. Ammonia (NH_3-N) mean loads (mg m^{-2}) from all sites combined by target total phosphorus (TP) manure rate

Time Interval (minutes)	Target TP Manure Rate (g m^{-2})				
	0	2.5	5	10	20
0-5	0.5	0.0	6.7	19.5	16.6
5-10	0.6	7.6	6.5	20.7	17.8
10-20	2.1	15.1	13.3	38.0	39.6
20-30	2.2	14.8	12.5	38.1	39.3
LSD 0.05	37.0				