UNIVERSITY OF ALBERTA

EFFECTS OF LIQUID HOG MANURE APPLICATION TO SOILS UNDER SEMI-ARID FORAGE LANDS

BY

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ABSTRACT

Despite expansions in hog production into semi-arid Alberta, limited information exists on the effects of liquid hog manure (LHM) to soils under permanent forages. This research was conducted to evaluate the effects of LHM applied to four sites (two tame pastures, two native rangelands), in two seasons (fall and spring), using two application methods (injection and broadcast), at five target rates of N (10, 20, 40, 80, 160 $kg.ha^{-1}$). Changes in ammonia loss and soil nutrients following application were quantified. Greater LHM rates increased soil-N, but also increased ammonia loss. After one growing season, applied-N from LHM was depleted. Injecting LHM increased soil-N and reduced ammonia loss compared to broadcasting. Tame pasture soils experienced greater initial ammonia losses compared to native range, and showed marked declines in soil-N one year later. This research provides information relevant to producers and regulators to develop improved guidelines for applying LHM in semi-arid Alberta.

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I dedicate this thesis to my sister Heather Lambert, for providing constant support, encouragement, tenacity, perspective, and humor.

"This mind thinks, this body works hard, and most of all this spirit burns. So long as learning and discovery occurs, there can be no such thing as failure, only success."

"So what do you have here, a big elaborate joke that's only funny to two people in the whole universe? –Yes, and we happen to think it's hilarious."

"You had us pegged all along, damn."
-Ian McKaye

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CHAPTER 1

Introduction

1.1. Overview of the Issue

Recent changes in the livestock industry have resulted in increased confinement feeding and larger concentrations of livestock (Jackson et al. 2000; Adeola 1999; Janzen et al. 1999; McKenna and Clark 1970). These changes have been a result of both economic factors and regulations aimed at reducing the pollution effect of livestock operations, especially under the influence of a public's growing concern and awareness for environmental safety (Innes 2000, Jongbloed and Lenis 1998). Currently, little information exists on the effects of liquid hog manure (LHM) application to soils under permanent cover crops such as native rangeland and tame pastures. This includes a lack of information regarding the proper techniques for applying LHM to forage-land soils. Such a lack of information has created reluctance by landowners and managers to apply LHM in these areas. Environmental issues can be a key driver of management decisions, and may be regulated by government legislation in the near future (Neeteson 2000).

The application of LHM to forage lands may be beneficial as it could increase forage production, extend the length of the grazing season, and improve forage quality (Bittman et al. 1999, 1997, Sanderson and Jones 1997). However, excessive amounts of LHM may result in excessive nutrient additions to the soil, odor issues, ground or surface water contamination, and the loss of valuable nutrients. Manure management must be done in a manner that does not contribute to soil or water pollution, and must be compatible with efficient and timely crop production (Evans et al. 1977).

Recently, large-scale hog production facilities have expanded into semi-arid regions of Alberta (CAESA 1991). While such expansion may prevent conflicts over aesthetics and odors, concerns still exist (Jackson et al. 2000; Adeola 1999; Janzen et al. 1999; McKenna and Clark 1970). Traditional sinks for manure have been annually cropped, cultivated lands that allow for annual uptake of added nutrients, removed in harvested grain. As more hog operations move into semi-arid regions a socially and environmentally conscientious method to manage manure, in this case LHM, is necessary. From a cost-efficiency perspective, it is unrealistic to transport manure great distances to where suitable cultivated lands exist (Freeze and Sommerfeldt 1985).

The widely available but less productive rangelands and tame pastures adjacent to the hog production facilities in semi-arid areas could provide an alternative sink for LHM. Such a management method could change LHM from a costly and troublesome liability into a valued asset. Despite this, little information currently exists on the soil nutrient changes under tame pastures and native rangelands that could occur with the potential application of LHM (Gillen 1998; Choudhary et al. 1996).

The research documented in this thesis was conducted to evaluate the effects of LHM applied to soils under tame pasture and native rangeland. Another goal of this research was to provide additional information that could assist producers, managers, and regulators to develop effective guidelines on the proper rate, method, and season of application for LHM in semi-arid Alberta. Such guidelines could demonstrate the compatibility of joint hog and beef production within the province of Alberta, particularly where these activities occur in close proximity to each other. Maximizing profit from livestock operations is rapidly leading large-scale producers to the concept of manure management at minimum cost while remaining below a certain 'nuisance' level (McKenna and Clark 1970).

1.2. Current Information

Although much research had been done on the impacts of fertilization on forage lands (Lowrance et al. 1998; Bittman et al. 1997; Sanderson and Jones 1997; Gangbazo et al. 1995; Schmitt et al. 1994, Westerman et al. 1987; Burns et al. 1987), relatively little has examined the effects of LHM application, particularly to native rangelands in western Canada (Power and Alessi 1971). In Alberta, this lack of information is at least partly due to a strong historical focus for LHM use on cultivated croplands. Thus, manure application guidelines [see the Code of Practice for Responsible Livestock Development and Manure Management (2000)] for the province of Alberta are developed with a strong emphasis on crops that may change annually with crop rotation. In addition, because the system is based upon cultivated cropping systems, it largely addresses recommendations for the agronomic regions of the province.

The most widely recognized benefit of fertilizing and/or manuring on pasture and rangeland is the potential to increase forage production (Johnston et al. 1967; Smoliak 1965), in part by increasing the water use efficiency of existing plants (Black and Wight 1979). Black and Wight (1979) and Kilcher et al. (1965) found that nitrogen rather than phosphorus was the limiting factor for forage production, likely due to P being stranded at the surface, whereas N will more readily move into the soil The major benefit of applying LHM to forage crops is nutrient recovery through increased plant production and forage quality (Gangbazo et al. 1999).

Johnston et al. (1968) found native range to be less affected by nutrient additions relative to tame (seeded) forages. This may be due to the large belowground root mass in native rangeland communities that act as a nutrient-deficient sink capable of absorbing large amounts of N and P to form thereby promoting root growth (Black and Wight 1979). Power (1972) found that within the Mixedgrass Prairie ecoregion, up to 200 and 300 $kg.ha^{-1}$ of N was immobilized belowground in the first and second years, respectively, with subsequent additions needed to eventually increase plant growth. Smith et al. (1968) found that although fertilization of fescue grassland was advantageous, the process was not economically feasible given the cost of fertilizer and its application. Such studies collectively suggest that nutrient additions to rangelands (or rangeland soils) may be beneficial, provided the nutrient source is readily available and economical (such as manure would be).

A limitation with respect to nutrient addition research on forage land is the lack of information on long-term effects following a single, particularly large nutrient addition (Johnston et al. 1967), as is typical of manure from hog production. Read (1969) found the greatest response to fertilization on Saskatchewan native range occurred on combined N and P treatments several years after treatment. Smoliak (1965) showed that Mixedgrass Prairie vegetation in southern Alberta displayed increases in yield for 8 years following a single manure and fertilization treatment. Black and Wight (1979) documented persistent changes in forage quality following fertilization treatments, likely due to the mobilization of nutrients from the increased root mass below fertilized areas.

Where manure is applied to permanent forage lands, application options are more restricted than on croplands, as application is limited to either surface broadcast or low disturbance injection. Comparative information on the effects of different manure application methods (e.g. injected *vs.* surface broadcast) on tame pastures is again limited (Bittman et al. 1999), with no studies evaluating the potential benefits of using injection at varying rates of LHM application on native rangelands.

Different application methods may also be important in reducing adverse socio-environmental impacts associated with the emission of various manure odorants, and developing effective management policies for handling LHM (Al-Kanani et al. 1992). One of the main odorous compounds from LHM is ammonia (NH_3). A reduction in NH_3-N loss can be achieved if manure is injected into the soil and/or amended chemically (Al-Kanani et al. 1992). The magnitude of this benefit on permanent forage lands is unknown, however.

1.3. Goals and Objectives of the Research Project

This research project was conducted to assess the application of LHM to soils under perennial crops (e.g. native range and tame pasture) in semi-arid Alberta. The first goal of this project was to assess and quantify changes in soil nutrient composition following application of LHM onto semiarid forage lands of central Alberta. The second goal of the project was to measure ammonia losses (volatilization) following LHM application. The following objectives of the study were used to ascertain effects of LHM application to permanent cover crops related to ammonia volatilization and changes in soil nutrients:

1. Identify the proper application rates to minimize or prevent adverse soil effects.
2. Evaluate the importance of application methods (dribble broadcast *vs.* injection).

3. Determine optimal application timing (fall *vs*. spring).
4. Develop more extensive and site-suitable LHM application guidelines for producers and managers.

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CHAPTER 2

Literature Review

2.1. Hog Production Trends in Alberta

Between 1976 and 2000, hog production in Alberta has undergone a notable increase of 49% (AAFRD 2002). Economies of scale, limited arable land areas, and advances in animal production have contributed to transforming farrowing and finishing of swine from small, on-farm operations to large-scale, intensive livestock operations (ILOs) (Sanderson and Jones 1997). Accompanying these changes has been an expansion in the area of the province in which these operations are situated, including into the semi-arid and arid regions of the prairies (Larson 1991, *in Choudhary et al. 1996*). The use of swine manure can be an agronomically and economically viable management practice for sustainable crop production in regions such as the Canadian prairies (Choudhary et al. 1996). However, as hog operations generate large amounts of animal waste, manure storage and utilization have become important management considerations (Sutton et al. 1984), resulting in new opportunities in waste management (Coffey 1999).

In 1961, 34% of the total farm area in the Prairie Provinces, Manitoba, Saskatchewan, and Alberta, a total of 17.5 million hectares, was classified as unimproved. This land is marginal or sub-marginal for grain production, and thus, supports mostly perennial vegetation used for pasture and hay production. Although seeding is not necessarily the best method for improvement, range fertilization for increased forage production may be (Willms and Jefferson 1993; Read 1969).

To date, most of the [swine] manure research has been conducted on annual crops (Long et al. 1975). In contrast, the effectiveness of LHM has not been comprehensively studied on temperate pastures. Furthermore, forage grasses and legumes in this region are perennials with extensive root systems, are winter hardy, and commence growth very early in the spring, and are therefore capable of making optimum use of available plant nutrients (Choudhary et al. 1996).

2.2. Manure Management and Beneficial Effects

The world swine population produces about 1.7 billion tonnes of liquid manure annually. At an application rate of 20 tonnes per hectare, this could fertilize about 85 million hectares of land annually. In the past, manure disposal was an economic liability because disposal costs often exceeded the value of the nutrients in the manure (McKenna and Clark 1970). Freeze and Sommerfeldt (1985) reported that manure might be cost effective for crop production if the distance of transport is less than 18 km. The value of manure also increases as energy costs increase. It is therefore imperative that precautions are taken to ensure nutrients within manure are conserved as much as possible (Beauchamp et al. 1982).

Inorganic fertilizer application to arid and semiarid rangelands is beneficial but often not practical because of high costs and lack of carry-over effects (Jurado and Wester 2001), especially in semi-arid regions where low precipitation is a limiting factor to plant growth (Black and Wight 1979). At the interface of cultivated agriculture and swine production, Honeyman (1996) indicated problematic issues can occur at any of four levels, including the farm, rural community, society or consuming public, and the ecosystem or environment. It may be postulated that in the future, hog production will have to increasingly deal with constraints imposed by social concerns related to animal health and welfare, animal product quality based on the production system, nutrient utilization, and the environment. Management or production practices such as the application of nutrients via manure and/or chemical fertilizers to fields should be in close balance with crop uptake, with minimal losses via leaching or volatilization. Nutrient emissions from agriculture to the environment are a growing concern and should be minimized (Neeteson 2000). Society demands not only safe and sufficient high quality food, but also sustainable, environmentally friendly production methods. High input of nutrients through the use of fertilizers, manure and animal feed make it possible to reach high levels of agricultural production. However, high nutrient inputs may also result in large nutrient losses, and thus, adverse effects on the soil, groundwater, surface water, and atmosphere.

Agricultural production is heavily dependent on N fertilizer. Between a quarter and a third of energy used in farming in developed countries is attributable to fertilizer manufacture. Avoidable N loss from agricultural systems represents an expensive waste of resources (Janzen et al. 1999). Although nutrients in manure constitute a liability if managed as a waste for disposal, nutrients are also the source of economic benefit when managed as a key production input. By using sound information, the ecological problems of applying manure can be avoided, the economic value captured, and both ecological and economic goals met (Janzen et al 1999).

Chase et al. (1991) evaluated the effect of various application rates of liquid manure in Iowa, and found greater economic returns from land treated with manure applied at rates comparable to commercial fertilizer. They concluded that with increasing fertilizer costs, the profitability of LHM as a nutrient source would increase. Improved grass production can reduce the amount of imported feed needed, providing additional economic and environmental benefits (Sullivan et al. 2000).

2.3. Manure Composition

The housing system, and method of manure collection, storage, and handling can all affect manure composition (Choudhary et al.1996). Application of swine manure to cropland is one of the most obvious methods of recycling plant nutrients. Plant nutrients are removed from the soil within the harvested product fed to livestock and can be returned to the soil as excreta. The availability of plant nutrients from swine manure depends upon manure composition and other factors such as management practices and soil characteristics (Choudhary et al. 1996). In general, swine manure, when spread contains a greater proportion of N and lower dry matter than liquid beef manure (Evans et al. 1977).

Manure in storage facilities must be sampled to determine nutrient content. A substantial proportion of the phosphorus in hog manure is absorbed on particulates and settles on the bottom of storage facilities, rather than being spread in liquid manure (Jackson et al. 2000). Hog operations employing anaerobic lagoon storage and spray irrigation lost an estimated 80% of total manure N into the atmosphere compared to 34% by ILOs using earthen basins and soil injection of liquid manure (Lorimer 1997). Although manure creates costs in waste disposal systems, it simultaneously generates revenue through nutrient recovery. Paradoxically, processes such as volatilization of

NH_3, which reduce nutrient concentration, are attractive in waste disposal systems because they ultimately reduce disposal costs, but are unattractive in resource recovery systems because they diminish the value of the product (Janzen et al 1999).

2.4. Environmental Concerns

Negative effects of swine production on the environment have already led to new legislation that limits or controls either the use of animal manure, or the expansion or concentration of pig operations in some countries. There is an increasing awareness of the impact that livestock production systems have on the environment, especially in countries or regions with a dense animal population (e.g., Netherlands) (Jongbloed and Lenis 1998).

Environmental concerns can be divided into three categories, including those related to the soil (accumulation of nutrients), water (eutrophication), and air (global warming and odors). The major thrust in the Netherlands has been on finding an acceptable balance between the input and output of N (and other minerals) per hectare of cultivated land (Jongbloed and Lenis 1998). Land spread manure slurries can pollute the environment by various mechanisms. Water pollution can take the form of leached nitrate into groundwater, leached phosphorus in dissolved or particulate form, and can also occur due to surface runoff (overland flow) transporting whole slurry with a high biological oxygen demand (BOD) and contaminating nitrogenous and phosphorus components.

2.4.1. Legislation, Regulation, and Monitoring

Despite the advantages of large-scale animal production, legislation in some countries limits the use of animal manure and/or the density of animals (Jongbloed and Lenis 1998). A survey by Welsh and Hubbell (1999) found that contract producers maintain higher animal units per hectare and spread manure over smaller areas than independent operators. However, contract hog producers tend to adopt pollution control and monitoring techniques more often than their independent counterparts, both because they realize they are pushing the capacity of their farms and their operations are more frequently shaped by public scrutiny. On average, large-scale corporate livestock operations do a better job of managing manure than smaller-scale independent producers (Welsh and Hubbell 1999).

The environmental consequences of livestock production and waste management are an increasing source of concern among the public and regulators/administrators (Innes 2000). The Netherlands was the first country in the world to enact legislation regarding animal manure for alleviating the impact of animal production on the environment. With respect to soil protection, Dutch policy states that in the long-term, no harm to plant growth or health risk for humans and animals is permitted. Furthermore, NH_3 emissions were slated to be reduced by 50 to 70% in the year 2000, relative to levels from 1980, and European Union guidelines indicate groundwater should contain less than 50 mg of $NO_3\text{-}N.L^{-1}$ (Kuipers et al. 1999). The legislation strives to balance the production of nitrogen and phosphorus on an animal basis with the amount of nutrients that can be sustainably applied to cropland. Although initially imposed gradually, the limits became more restrictive after 2000 and will impose fines for exceeding the limits (Adeola 1999). Greater use of manure injection or incorporation immediately after application is enforced to reduce ammonia emission. Where P_2O_5 production per hectare of cropland exceeds the amount allowed, the producer must pay a tax on the surplus, which is then transported to other regions (Jongbloed and Lenis 1998).

In Alberta, the *Code of Practice for Responsible Livestock Development and Manure Management* (2000) states that manure, when applied in appropriate locations at rates that are in balance with crop uptake, poses a minimal risk to the environment. Manure utilization through land application must consider meteorological, topographical, and soil conditions together with the application time and rate to avoid groundwater or surface water contamination. Crop nutrients from all sources must be managed, including commercial fertilizers, food processing and municipal waste products, manure, and residual soil nutrients. The *Code* also states that odor nuisance associated with the land spreading of manure can be minimized through proper timing, siting, method of incorporation, and frequency of application. As well, a nutrient management plan is strongly recommended for all new and expanding ILOs that includes balancing long-term nutrient applications with crop uptake while assessing potential environmental risks (e.g. nutrients entering water sources). It should be noted that the *Code of Practice for Responsible Livestock Development and Manure Management* (2000) varies from the previous *Code of Practice For the Safe and Economic Handling of Animal Manures* (1995), primarily due to the land-limiting constituent (LLC). The LLC is the component or nutrient within the manure that determines the maximum amount that can be applied to land. In the 1995 *Code*, most assumptions and recommendations are based upon nitrogen being the LLC. However, the 2000 *Code* bases its recommendations on phosphorus being the LLC. While phosphorus levels in manure are not as high as nitrogen levels, plant removal of P is not as high. Hence, the potential for P buildup or runoff (especially after repeated applications) and subsequent water contamination, is of greater concern.

2.4.2. Air Quality

2.4.2.1. Ammonia Losses (Volatilization)

Generally 50% of N in hog manure slurry is present in the ammonium N form and the remaining 50% as organic N (Burns et al. 1987; Sutton et al. 1984, 1982, 1978). The emission of ammonia from stored and land-applied manure to the atmosphere can result in a significant loss of nitrogen for crop production. It is necessary to quantify this loss to evaluate manure-handling practices for maintaining the nutritive value of manure. Minimizing ammonia emissions also reduces agriculture's impact on the environment. A high atmospheric concentration of ammonia can result in acidification of land and water surfaces, cause plant damage, and reduce plant biodiversity in natural systems. Ammonia emissions from manure also coincide with odors, which are a nuisance in areas surrounding ILOs. Reducing ammonia emissions by altering manure management will therefore reduce odor problems (McGinn and Janzen 1998).

Beauchamp (1983) determined that during a growing season, approximately 20% of the organic N in cattle manure was mineralized and becomes available, and 25% of ammonia N was volatilized, resulting in a net availability for crop growth of about 50% of the applied N. Vanderholm (1975) indicated NH_3-N losses from manure ranged from 10 to 99% depending on the type of storage and system of treatment. The least loss was from aerated storage lagoons and the highest loss from feedlot surfaces and anaerobic lagoons. In general, P and K losses are minimal (5-15%) except from open-lot or lagoon handling systems where 40-50% of P can be lost to runoff and leaching (Sutton et al. 1984).

Livestock concentration can lead to greater manure management challenges in optimizing the nutrient value of manure while minimizing the risk of environmental problems such as nonpoint source-pollution. Although problems associated with swine operations may occur regardless of size, concentrating animals raises special problems, particularly with the quantity of manure and ammonia production. Transportation costs increase with distance, and where livestock are concentrated, there is a strong incentive to spread manure close to its source (Jackson et al. 2000, Adeola 1999; Gangbazo et al. 1999; Jongbloed and Lenis 1998).

Nitrogen volatilization (almost exclusively as ammonia) occurs during manure storage and field application. Lorimor et al. (1997) estimated that for anaerobic lagoons, about 80% of the total manure N is volatilized into the atmosphere. They also found that concrete lagoons lost 30% less N than earthen basins. The difference between the two storage methods is due to a greater surface area relative to the depth in earthen lagoons. Similarly, sprinkler irrigation of swine manure results in the loss of an estimated 40% of its N content, while injecting slurry into the soil results in only a 5% loss (Lorimor et al. 1997). All of these projections are average values that will vary widely depending on factors such as weather and the content of animal rations. Jackson et al. (2000) estimated that 70% of the total hog manure N was volatilized when ILOs use anaerobic storage combined with spray irrigation, thus contributing heavily to nonpoint source pollution.

Ammonia is the primary neutralizing agent for atmospheric acids and is a common component of aerosols. Atmospheric NH_3 is produced from decomposing feces and hydrolysis of urea in urine to ammonium during the production and application of fertilizers, as well as combustion processes. There is a growing realization of the importance of NH_3 emissions and their role in acidification and eutrophication of terrestrial ecosystems. Natural ecosystems are thought to be net sinks for NH_3 (Neeteson 2000; Sharpe and Harper 1997), and surface application of liquid manure to cropland is a major source of atmospheric ammonia (Braschkat et al. 1997). Environmentally, increasing concentrations of NH_3 in the atmosphere cause aerosol formation of complex sulfates of NH_3 that are components of smog and acid rain (Harper et al. 1983). Measurements of daily ammonia loss on free-draining silt loam soils with perennial ryegrass and white clover pastures in New Zealand indicated that in most cases, over 80% of the total loss occurred within 4 days of grazing or urea application. Loss of N by denitrification was low (7-14 kg N ha^{-1}) and largely confined to the winter period (Ledgard et al. 1996).

Factors that influence NH_3 volatilization include soil pH, exchangeable cations, texture, temperature, soil water content, and the species of ammonium salt (Fenn and Kissel 1973). The rate of loss also depends on the concentration of ammonia gas at the slurry surface (Sommer et al. 1991). Beauchamp et al. (1978) found that NH_3 volatilization losses decreased as soil clay content increased, but losses increased as greater quantities of sewage sludge were applied. The percentage of NH_3 lost from surface applied manure may be linked to greater initial soil moisture (Brunke et al. 1988). Randall et al. (2000) noted that N loss was slightly higher in coarse textured soils compared with fine textured soils, likely due to larger pore size in coarse soils, except when the fine textured soils retained higher levels of moisture thereby reducing aeration and likely increasing denitrification, when they incurred greater losses.

There are several management implications from volatile losses of NH_3 from manure. When manure is spread on land, surface manure N is subject to movement in surface runoff and leaching water. Where the land area is limited relative to livestock numbers, NH_3 volatilization, though undesirable, may decrease the potential for subsequent nitrate leaching into ground water. In regions where the ratio of cropped land to livestock is greater, manure can be used effectively in soil fertility programs. Proper uses of manure can partially or wholly substitute for commercial fertilizer while minimizing the fraction of manure N contributing to water quality degradation. In order to ensure optimum utilization of nutrients, management techniques have to be developed to minimize NH_3 volatilization in both agricultural field and animal production facilities (Lauer et al. 1976).

2.4.2.2. Odor Management

The successful use of hog manure in agricultural systems can be limited because of the emissions of malodorous compounds. Odor from animal manure has become an important issue in areas with intensive livestock production. Methods to attenuate odors from LHM are needed to reduce adverse social impacts associated with the emission of various odorants, and to develop effective management policies for handling LHM (Al-Kanai et al. 1992a). Reduced production of malodorous gases (e.g.: NH_3) from LHM would be advantageous to the agriculture industry. Reduction in NH_3 can be obtained if

LHM is injected into the soil or chemically amended (Safley et al. 1983; Hoff et al. 1981). However, because injection of LHM is not always practical, such as in permanent pastures, producers often prefer to surface apply LHM (Al-Kanani et al. 1992b).

2.4.3. Land-Based Environmental Issues

Manure contains diverse constituents including essential plant nutrients such as N, P, K and S; micronutrients; and salts, which may cause salinity or sodicity problems in soils if not managed properly. The area required for safe assimilation can be calculated for each manure constituent as the quotient of average production rate ($Mg.y^{-1}$), multiplied by the number of commercial operations in a region, divided by the assimilatory capacity ($Mg.ha^{-1}y^{-1}$) of the available land. The constituent (i.e., soil factor) that requires the largest land area for safe disposal, and hence, limits the maximum application rate, is the Land Limiting Constituent (LLC) (Janzen et al 1999, Gangbazo et al. 1995b). Leaching of nitrate from intensively managed grasslands can be a major contributor to the pollution of ground- and surface waters. Although grass swards are efficient at taking up N, the risks of leaching increase as inputs exceed the sward's capacity to utilize N (Cuttle et al. 2001).

Increases in hog production and the distribution of these operations has the potential to aggravate problems of odor and nutrient management. Large-scale facilities concentrate animal production in a small area. Nutrients brought in via animal rations (e.g.: grains and supplements) must be returned to the land as manure, but often there is insufficient cropland within suitable hauling distances to apply manure at high rates similar to agronomic practices. Addition of salts or additives to swine feed can change swine manure composition and accumulate in the soil. Increasing levels of dietary salt (NaCl) and/or other mineral additives (Cu, As, and other minerals) in swine rations also directly affects the concentration of these elements in manure (Sutton et al. 1984 and 1976; Brumm and Sutton 1979). Thus, heavy manure application from such sources may be toxic to plants and may affect soil productivity. Sutton et al. (1984) reported that manure from pigs fed 0.5% salt averaged more than twice the Na content as that from pigs fed 0.2% salt. However, a single application of the manure did not lead to soil contamination or phytotoxicity. Dietary copper at levels of 125 ppm to 250 ppm is generally added as a growth stimulant in swine rations (Wallace et al. 1960). A one-time application of manure from pigs fed high dietary Cu increased soil Cu, Zn, P, Ca and Mg levels slightly compared to a control (Kornegay et al. 1976). Similarly, increasing dietary salt levels increased Na levels in manure and Na loading of the soil (Sutton et al 1984). Bernal and Kirchmann (1992) reported that the addition of swine manure in arid and semi-arid areas could cause salinization. Dubetz et al. (1975) found that soil Ca and Mg were not affected by additions of combinations of barnyard manure, sugar beet tops, and corn residues.

Excessive manure application may result in accumulation of heavy metals near the soil surface, with consequences for plant growth and potential risks for human and animal health (e.g., copper toxicity to sheep) and soil life (Chaney 1994; Heckman et al. 1987; Kornegay et al. 1976). For example, sewage sludge may be utilized on agricultural land as a source of nutrients for crop production and as an organic amendment for the improvement of soil physical properties. While sludge is generally recognized as a nutrient resource, the potential for excessive uptake of heavy metals continues to be a concern. Sewage sludges are extremely variable in composition and may contain high levels of Zn, Cd, Cu, Ni, and Pb. The contamination of soil with these elements can result in phytotoxicity and increased movement of metals into the food chain (Heckman et al. 1987).

Heavy application of manure may result in leaching of NO_3-N, P, and K (King et al. 1990). The leaching of NO_3-N depends on factors such as the rate of manure application, soil type, type and duration of crops grown, and rate and amount of precipitation. In temperate regions, the soil solution NO_3-N concentrations are generally highest in May and decline during the growing season due to crop N uptake and leaching.

Evans et al. (1977) observed higher NO_3-N leaching from cattle manure than LHM. Increasing the application rate of manure increases NO_3-N in the soil profile up to 122 cm depth (Sutton et al. 1984). However, earlier studies did not find any effect of swine manure application rate on NO_3-N leaching (Sutton et al. 1982). They concluded that leaching of soluble nutrients, especially NO_3-N, to lower portions of the soil profile (62-122 cm depth) may be of greater concern when manure is applied by injection rather than broadcast on the soil surface because there is less chance for slurry to evaporate or runoff.

There are also environmental risks of eutrophication through nitrate and phosphorus runoff (Gangbazo et al. 1995a; Westerman et al. 1987; King et al 1985). Several researchers have tried to find a better way to minimize non-point pollution from animal manure applications. For example, there is a direct relationship between animal waste application rates and nutrient concentrations in runoff and leachate water (Pote et al. 2001; Edwards and Daniel 1993a, 1993b, 1994; Westerman et al. 1987). Furthermore, excessive manure or fertilizer application with high precipitation may cause leaching of nitrate to exceed tolerable values in fresh water (e.g.: in the Netherlands 50 mg nitrate/L) (Jongbloed and Lenis 1998). Although up to 75% of hog manure N is in the NH_4-N form, the risk of using it as fertilizer has been mainly associated with NO_3-N environmental problems, especially in groundwater (Gangbazo et al. 1995a). Gangbazo et al. (1999) found that any soil P effects were related to depth. It is well known that P generally accumulates in the upper soil layer (Gangbazo et al. 1999). Mobility of fertilizer and manure-derived forms of P is an important environmental consideration for deep sandy soils given the potential for subsurface transport through larger pores between sand particles (Harris et al. 1994). Because the Canadian Prairie is characterized by frequent moisture deficits, it is usually assumed that NO_3 leaching is unlikely to occur (Campbell et al. 1994).

Maximizing fertilizer N recovery by crops improves production efficiency, increases economic returns to the crop producer, and reduces the potential for NO_3 leaching or other adverse environmental impacts. Nitrogen management practices that change the distribution of fertilizer-derived nitrogen in different portions of the soil-plant system may affect not only fertilizer N use efficiency by plants in the year of application, but also the potential for residual uptake, environmental pollution, or N loss in succeeding years (Jokela and Randall 1997).

2.5. Land Application

2.5.1. Application Methods

Ammonia volatilization from manure is a major mechanism for N loss in soil-plant-animal systems. Several studies report from 5 to 99% losses of ammonia N from manure following land application, especially if some method of incorporation is not utilized (Moal et al. 1995; O'Halloran 1993; Beauchamp et al. 1982). Other studies report similar N losses following surface applications of fertilizer, particularly urea (Fan and MacKenzie 1993; Harper et al 1983).

The rate, time, and method of application depend on numerous factors including climatic conditions, soil properties, type of crop, and rate of nutrient mineralization. Maximum nutrient benefit from hog manure is obtained when it is incorporated immediately after land application to minimize nutrient loss (Sutton et al. 1984; AAFRD 1984; Hoff et al.1981). Manure must also be applied uniformly to minimize localized salt concentration, especially Na, which can reduce germination and crop yields. Knifing manure into soil is recommended when there is a particularly high concern for odor, but this procedure also reduces the rate of manure that can be applied. Vanderholm (1975) reported 5, 15, and 30-90% losses of NH_3-N from manure applied with plowing down, disking, and surface applied techniques, respectively. Hoff et al. (1981) reported 0-2.5% NH_3-N losses with LHM injection compared with 10-16% from surface broadcast. Similar findings were reported using swine (Sutton et al 1982; Safley et al. 1983) and cattle (Beauchamp 1983; Beauchamp et al. 1982; Klausner and Guest 1981; Lauer et al. 1976) manure.

Solid animal manures and slurries contain a greater percentage of the original dry matter-N than effluent or LHM, and a lower proportion of NH_3 than liquid hog manure. With overhead sprinkler irrigation or surface broadcast application, much of the effluent is intercepted by the crop canopy and reduces effluent entry into the soil (Sharpe and Harper 1997). Schmitt et al. (1995) found broadcast applications of manure to corn resulted in the lowest soil inorganic N concentrations among all manure application methods. Given that incorporation did not occur for at least 1 week and mineralization was probably minimal because the manure's organic N was on the soil surface, volatilization of ammonium was the likely N loss pathway. Schmitt et al. (1992) found a positive linear trend in increasing soil NH_4-N concentrations as manure application rates increased, even though volatilization increased similarly. Additionally, despite an initial increase from multiple manure additions, soil pH eventually declined. The decrease in soil pH was most likely due to nitrification, while the initial increase was partially due to the transformation of organic and urea-N to ammonium, as well as the reduction process occurring at the manure-soil interface (Schmitt et al. 1992).

Sweep or horizontal injection provides a practical alternative to knife injection of liquid manure on cultivated cropland, but not permanent forage lands. Complete coverage of the sweep-injection zone by soil is important to prevent volatile N loss, and may be just as important as the direct incorporation of broadcast manure. With sweep injection, manure is spread in a thin horizontal band under the soil surface and should provide better manure distribution than knife injection, and thus, may improve the uniformity of N uptake and yield (Sawyer et al 1991). On a silty loam soil, injected LHM increased corn grain yield compared with the broadcast method at similar rates

(Sutton et al. 1982). The authors attributed the lower yield to NH_3-N volatilization from the broadcast manure. Chase et al. (1991) reported similar findings. On the other hand, Xie and MacKenzie (1986) found no significant difference in corn yields on a sandy loam soil between surface spreading and incorporated manure.

Sweep injection is generally not feasible for manure application on lands with permanent vegetation, although this type of equipment could be used for a form of reduced-agitation surface dribble broadcast. Bittman et al. (1999) compared slurry manure applied with splash plate (broadcast) and drag-shoe (surface banded sweeps) applicators, to broadcast mineral fertilizer, in spring, summer, and autumn. Yield response to manure banded with the drag-shoe applicator was similar to fertilizer applied at equivalent rates of mineral N. Apparent recovery of mineral N from manure was 20 to 30% greater with drag-shoe than splash plate application in summer, and 18% greater when application took place in early spring (Bittman et al. 1997). Shallow slurry injection has been effective in reducing NH_3 emissions by 50-99% compared to conventional surface application (Weslien et al 1998), and this method may be recommended as a practical method for reducing emissions (Chadwick et al. 2001, de Klein et al. 1996). Injection of manure slurries has become obligatory in the European Union, and is only allowed during the growing season (Kuipers et al. 1999).

2.5.2. Timing of Application

From an agronomic perspective, spring and fall dairy manure applications can improve the yield of the first (spring) harvest. Early and late season applications also increase flexibility in manure handling, providing a longer season of application (Sullivan et al. 2000). Applying hog manure in the fall results in greater N loss and water contamination due to both winter and spring runoff (Gangbazo et al. 1995a, 1995b). Therefore, hog manure should be applied earlier in the growing season at rates that accommodate crop requirements. In order to reduce nitrate leaching, manure application is less desirable during the autumn and winter in the absence of crop growth, and when soils are frozen (Choudhary et al. 1996).

Timing of manure application is a critical part of dairy farm plans because it affects water quality, crop production, and manure handling costs. In moist areas of the Pacific Northwest in U.S. and Canada, farm planners usually discourage manure applications from October through February because of concerns about leaching and runoff (Sullivan et al. 2001). Since cool season forages have a long growing season in the Pacific Northwest, a longer season of manure application may be possible when producing grass forage. A longer season of application can benefit dairy farmers by reducing manure storage requirements and increasing the flexibility of application. Because the first harvest of grass is often the largest, early season application of manure could also provide a benefit at a high production time of year. Spring rather than fall applications are recommended in areas with higher potential for runoff, because the former result in less nutrient loss, especially as NH_4^+-N. Splitting large applications may also be advantageous to reduce nutrient losses (Gangbazo et al. 1999).

2.5.3. Application Rates

Kowalenko and Bittman (2000) found the effect of N application rate was greater on average, than the timing of N availability during the growing season. Although there were only small, whole-season yield increases associated with distributing N applications uniformly throughout the season, the temporal distribution of herbage was changed considerably. Soil data showed relatively little leaching of N during the growing season under contrasting weather conditions throughout the three growing seasons. Retention of N within the soil root zone contributed to residual effects on plant nutrient uptake and yield, and these effects frequently lasted to the end of the growing season. Soil extractable ammonium concentration was increased by high rates of N application, but the effect was small and largely limited to sampling after the first harvest. The soil always contained 10-15 mg kg^{-1} extractable ammonium in the surface 30 cm, with a tendency for greater concentrations in early spring.

Excessive rates of manure may result in accumulation of some nutrients and salts to levels that adversely affect crop growth. Problems reported with knife injection have occurred on fields having adequate soil test values for pH, soluble salts, and for nutrients such as P, K, and Zn (Sawyer et al. 1991). Manure management plans require the selection or calculation of manure application rates appropriate for the nutrient needs of the crop to be grown. One important factor is the availability of nutrients from manure, especially N. Method of application has a large influence on N availability due to placement within the soil profile, and can be managed for individual fields and conditions (Schmitt et al. 1995).

Land application of liquid animal manures offers the potential for recycling large volumes of slurries by using the nutrients available for plant growth in place of conventional inorganic fertilizers. Loading rates that do not exceed the assimilative capacity of the site are a function of the nutrient uptake rates of the plants and microorganisms, the physical and chemical adsorption properties of the soils, climate, and the management regime. Rates that exceed a site's assimilative capacity can adversely impact the environment by providing significant nutrient loadings to treated soils and associated water resources (Vellidis et al. 1996).

Increasing the rate of LHM application generally increases crop yields (Chase et al. 1991; Xie and MacKenzie 1984; Sutton et al. 1978), although the magnitude of these increases depend on actual application rates, soil type, concentration of nutrients in manure, and growing conditions. For example, Chase et al. (1991) obtained increased corn yields with surface applied LHM at 7570 to 45 420 L.ha^{-1} (2000 to 12 000 US gallons. ha^{-1}) on a fine loamy soil. Burns et al. (1990) also reported increased forage yield with increasing manure application. Sutton et al. (1978) reported increases in corn yield with increasing rates of surface applied LHM varying from 0 to 134 tonnes.ha^{-1} on a silt loam soil. In contrast, no response of corn yield was obtained when manure rates were increased further from 135 tonnes.ha^{-1} to 180 tonnes.ha^{-1} (Sutton et al. 1982), or from 180 to 270 tonnes.ha^{-1} (Sutton et al. 1984). Power (1972) described the N-cycle of native grasslands and postulated that "nitrogen may be eliminated as a growth-limiting factor within a soil-plant system by providing sufficient inorganic N to completely saturate the capacity of the system to immobilize N, thereby setting up a new equilibrium condition whereby annual immobilization and irreversible losses are balanced by mineralization plus inorganic N additions".

2.5.4. Site Specific Application Criteria

2.5.4.1. Soil Characteristics

Numerous studies have been conducted on the effect of cattle and poultry manure application to cropland (Powers et al. 1975). However, limited research has been done on crop responses, or on changes in soil chemical composition and groundwater quality resulting from application of LHM (Sutton et al. 1978). The application frequency depends on both the type of soil (related to texture and permeability) and crop (uptake and use). Additionally, methods of application should be compatible with the soil and crop type receiving manure. Crop requirements should be respected in order to reduce nutrient loss and prevent excessive nutrient buildup. The sensitivity of soil inorganic N levels to fertilizer application is primarily through soil texture, with earlier and greater accumulation in coarse than in fine-textured soil (Kowalenko and Bittman 2000).

Applying manure close to the planting date will promote more efficient nutrient use by crops with fewer losses, especially in areas of high rainfall and permeable soils (Sutton et al. 1984; AAFRD 1984). Fine textured soils have low permeability and promote low rates of decomposition, hence, the rate of manure application should be lower compared with coarse textured soils that are highly permeable and promote rapid decomposition of manure (Xie and MacKenzie 1986). On the other hand, high application rates of manure to coarse textured soil may contaminate groundwater due to nutrient leaching, while high application rates of manure on heavy textured soil may be beneficial because of the high nutrient loading capacity of these soils. Manure should not be applied to snow or frozen ground, particularly when the land is subject to rapid spring runoff (Larson et al. 1991). Furthermore, heavily manured fields should not be summer fallowed to avoid N leaching and the possibility of groundwater contamination. Soil types and nutrient concentrations of land application sites must also be determined. In general, the frequency, volume, and timing of manure application on cropland must coincide with nutrient utilization and harvesting to achieve effective nutrient removal and prevent losses (Adeola 1999).

Ernst and Massey (1960) found that increases in soil pH increased the volatilization of ammonia formed from urea and offered two explanations for this relationship. One is that a greater degree of Ca^{2+} saturation of the soil exchange complex occurs with increasing pH, leading to less adsorption of NH_4^+ formed by urea hydrolysis. Another explanation is that there is increased OH^- activity in soil solution, thereby favoring the volatilization of ammonia.

There is little to no information available on the effect of LHM on soil physical properties. However the effects of LHM may be similar to those reported for various cattle manures, which has been reported to improve soil aggregation, lower bulk density, and improve soil structure and water holding capacity due to increased organic matter (Choudhary et al. 1996).

Changes in soil chemical composition due to LHM application are variable and highly influenced by factors such as soil texture, rate, time, and method of manure application, LHM composition, amount of precipitation, crops grown, and time of sampling. Heavy application of manure increased NO_3-N, available P, exchangeable K and Na, more than did inorganic fertilizer (Evans et al. 1977). King et al. (1985) reported an accumulation of NO_3-N, Mehlich I extractable P, and exchangeable Na in subsoil following manure effluent application; the level of accumulation increased with increasing manure rates. Manures have lower N/P ratios than crop plants. As a result, when N is supplied through manure, more P is applied than is required by plants and may result in downward movement of P, or possible losses of P-enriched soils when eroded. At high rates of manure application, Ca and Mg may be displaced from exchange sites by competing ions present in the manure, such as Na^+, K^+, and NH_4^+, and may be leached from the topsoil with some accumulation in deeper layers.

2.5.4.2. Vegetation Type and Management

Manure is most often used for annual crop production because it can be applied before planting or after harvest. The types of crops fertilized with LHM vary from one region to another, and include rice, wheat, corn, mustard, legumes, oilseeds, and forages. Grasses and cereal grains, because of their extensive root systems and relatively high N requirements, derive more benefit from manure than legumes (Choudhary et al. 1996). However, cereal crops are typically grown on an annual basis, whereas application of LHM is less common on permanent cover crops. Swine manure application can result in similar or higher crop and pasture yields than inorganic fertilizers (Chase et al. 1991; Burns et al. 1987; Xie and MacKenzie 1986; Sutton et al. 1984, 1982, 1978; Evans et al. 1977).

In forages, the magnitude and length of the residual yield effect is influenced by the amount of applied nutrients removed from the stand at each successive harvest (Kowalenko and Bittman 2000). Higher soil nitrate concentrations occur in grazed swards than those used for feed conservation due to recycling of N through the manure of grazing livestock. However, soil tests, particularly for nitrogen, may not be effective in giving an adequate indication of nutrient status within perennial pasture and haylands. A large quantity of the nutrients are stored in roots, soil microbial biomass and humus, information that is not indicated in standard soil tests (McCartney et al. 1998; Black and Wight 1979).

The quality of soil organic matter is sensitive not only to differences in parent material and plant cover, but also vegetation management. Once native prairie has been disturbed, in spite of replacement with introduced grass species, soil biological activity decreases in the first 2 or 3 years (Dormaar and Willms 2000). An assessment of vegetation recovery and concomitant soil characteristics on abandoned farmland under semiarid climatic conditions indicated that, under moderate grazing by livestock, more than 55 years were required for soil to return to the condition of native range (Dormaar and Willms 1990).

Altering the plant community from native Mixed Prairie to either a sequence of cropping followed by an introduced grass monoculture, or directly to an introduced grass monoculture, resulted in decreased root mass and organic matter, and monosaccharide content of dry aggregates (Dormaar et al. 1995). Seeded grasses could neither return nor maintain the chemical quality of soils similar to that of native rangeland (Dormaar et al 1995). Native rangeland contained about 2 to 3 times more root mass than seeded species in the 0- to 7.5-cm depth and about equivalent mass from the 7.5- to 40-cm depth (Dormaar et al. 1995). Soils under native rangeland had greater organic matter and lower NO_3-N, urease activity, and available P in the upper 7.5 cm of soil. Altering the plant community from Mixed Prairie to cropland and then to crested wheatgrass or Russian wild rye, significantly reduced the chemical quality of soils by reducing root mass and organic matter (Dormaar et al 1995).

Fertilizer N applied in excess of the immobilizing capacity of the soil-grass ecosystem appears to remain in the soil until utilized by vegetation, unless it is leached. Consequently, it appears that fertilizer N applied to semiarid grasslands can be effectively stored in the soil until required. By applying sufficient N to saturate the N-immobilizing capacity of the soil-plant system, N deficiencies can be eliminated as growth-limiting factors, even in semiarid grasslands, resulting in maximum production from the available water supply (Power and Alessi 1971).

These findings suggest that considerable fertilizer N may be immobilized by other components of the soil-plant system in addition to the top growth. Once sufficient fertilizer N is applied to saturate mineral-N immobilization, the system operates at a new and higher equilibrium level. Any fertilizer N applied in excess to this requirement remains in the soil in mineral form. Consequently, it appears feasible, and possibly desirable, to apply fertilizer N to semiarid grassland soils to obtain maximum production from whatever water is available. One component of the soil-plant system that is probably of major importance in immobilizing fertilizer N is grass roots. This large mass of low-N material would certainly immobilize considerable fertilizer N (Black and Wight 1979). Approximately 85% of the roots are in the upper 30 cm of soil (Power and Alessi 1971; Coupland and Johnson 1965). Grassland plants can also act as a physical barrier that impedes liquid manure infiltration into the soil. One mechanism for perennial crops is that soil is kept dry in the rooting zone and can therefore accept rain/LHM without the water going below the rooting zone. Hence, compared to cultivated land, higher losses of ammonia can be expected following surface manure application to grasslands (Braschkat et al. 1997).

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CHAPTER 3

Ammonia Volatilization Trends Following Liquid Hog Manure Application to Forage Land

3.1. Introduction

Recent changes in the livestock industry have resulted in increased confinement feeding and larger concentrations of livestock (McKenna and Clark 1970). These changes have arisen from both economic factors and regulations aimed at reducing pollution from livestock operations. Manure management must be done in a manner that does not contribute to soil, water, or air pollution, and must be compatible with efficient and timely crop production (Evans et al. 1977).

Although the trend toward increased confinement feeding has spawned worldwide research into developing proper guidelines for manure management, the majority of studies have investigated the application of manure to cultivated land. For example, considerable research has quantified the effects of varying rates of manure addition on intensively farmed soil properties and crop yields (Schmidt et al 2001, 2000; Randall et al. 2000; Gupta et al 1997; Lory et al. 1995; Trehan and Wild 1993; Sawyer et al. 1990).

In Alberta, large-scale hog production facilities have recently expanded into less densely populated semi-arid regions (CAESA 1991). While such expansion may prevent conflict over aesthetics and odor, there are other emerging concerns. Annual croplands, the traditional sinks for liquid hog manure (LHM), are often unavailable in these areas. Given that it is unrealistic to transport manure to distant cultivated regions from a cost-perspective, alternative lands must be considered for LHM application. As hog operations continue to establish in these regions, socially and environmentally acceptable methods of LHM management will be required.

The widely available, but historically less productive, native rangelands and tame pastures adjacent to these operations could provide an alternative sink for LHM, thereby converting manure into a valued asset. The major benefits of applying LHM to forage crops are increased plant production and improved forage quality (Bittman et al. 1999, 1997; Sanderson and Jones 1997).

Most previous research evaluating the impacts of nutrient application on foragelands have addressed rates of commercial fertilizer application, and usually in relatively mesic environments (e.g., Kowalenko and Bittman 2000; Vetsch et al. 1999; Bittman et al. 1997; Ledgard et al. 1996; Rehm et al. 1995; Campbell et al. 1994). Furthermore, most research investigating manure application has been restricted to examining tame pastures (Schmitt et al. 1999; Lowrance et al. 1998; Bittman et al. 1997; Kaffka and Kanneganti 1996; Sanderson and Jones 1997; Gangbazo et al. 1995; Schmitt et al. 1994; Westerman et al. 1987; Burns et al. 1987). The limited information on the effects of nutrient addition to native rangelands generally involves either fertilization (e.g., Black and Wight 1979; Power and Alessi 1971; Johnston et al 1967; Kilcher et al. 1965) or the application of biosolids (Harmel et al. 1997). The known exception is an investigation by Smoliak (1965) examining solid beef manure additions to native plant communities in southern Alberta. In general, specific information on the effects of manure application to native rangelands is lacking (Gillen and Berg 1998). Given the diverse variation in vegetation and climate found in southern Alberta, there is a need to assess the consistency of responses among different forage lands subject to manure application.

Where manure is applied to permanent forage lands, application options are more restricted than on croplands, as application is limited to either surface broadcast or low disturbance injection. Comparative information on the effects of different manure application methods (e.g. injected *vs*. surface broadcast) on tame pastures is again limited (Bittman et al. 1999), with no studies evaluating the potential benefits of using injection at varying rates of LHM application on native rangelands.

The concept of profit maximization from livestock operations is rapidly leading large-scale producers to the concept of manure management at minimum cost while remaining below a certain ‘nuisance’ level (McKenna and Clark 1970). Although investigations into the agronomic benefits of manure application are relatively common, little research has examined the ammonia losses associated with LHM application on agricultural lands, particularly tame pastures and native rangeland. Nitrogen volatilization (almost exclusively as ammonia) occurs during manure storage and field application. Lorimor et al. (1997) estimated that 80% of the total manure N in anaerobic lagoons is volatilized. Jackson et al. (2000) estimated that 70% of the total hog manure N was volatilized following field application, thereby contributing to non-point source air pollution. The issue of nitrogen retention has particular relevance on permanent forage lands where manure incorporation is limited to low-disturbance injection. On these areas, injection may reduce ammonia volatilization.

Different application methods may also be important in reducing adverse socio-environmental impacts associated with the emission of various manure odors, and for developing effective management policies for handling LHM (Al-Kanani et al. 1992). One of the main odorous compounds from LHM is ammonia (NH_3). A reduction in NH_3-N loss can be achieved if manure is injected into the soil and/or amended chemically (Al-Kanani et al. 1992). The magnitude of this benefit on permanent forage lands is unknown, however.

The purpose of this chapter is to report on original research evaluating comparative ammonia losses associated with LHM application to semi-arid forage lands in southeast Alberta. Specific objectives included the evaluation of ammonia losses from: (1) varying LHM application rates, (2) different application methods including surface applied and coulter injection, as well as (3) different types of forage land including native rangeland and tame pasture. This information will contribute to our understanding of the potential importance of utilizing injection technology for the safe and sustainable disposal of manure in this region.

3.2. Materials and Methods

3.2.1. Study Area and Design

Manure application treatments were conducted on tame pasture and native rangeland in south-central Alberta, near Little Fish Lake, 40 kilometers east of Drumheller, Alberta (51°22' N, 112°13' W). Study sites are located near the transition from the Mixed Grass Prairie to the southern Aspen Parkland (Strong and Leggat 1992). Sites were selected to represent a wide range of common soil and growing conditions in Alberta from Dark Brown to Black soils (*Canadian System of Soil Classification* 1987). The region has a continental climate, with warm summers and cool winters, and a semi-arid mean annual precipitation of 394 mm. This figure is the long-term (30 year) average compiled from the nearest weather station at Craigmyle, Alberta, 30 kilometers north of the study area. The study area is also representative of the area wherein hog production is known to be particularly high (CAESA 1991).

Native rangeland in the region is representative of a diverse mix of plant communities from xeric Mixedgrass Prairie to mesic Fescue Grasslands. The two native study sites include: (1) an upland bench (Mixedgrass Prairie) consisting of a *Stipa-Agropyron* range type on a loam textured Orthic Dark Brown Chernozem soil, and (2) a mesic fescue grassland (*Festuca-Stipa* range type) community on a loam textured Orthic Black Chernozem soil. All sites were within 15 km of one another to facilitate use of a common manure source. Many native areas in the region have been converted into tame pastures. The two tame pasture sites examined include: (1) a mesic meadow bromegrass (*Bromus biebersteinii* Roem & Schult)-alfalfa (*Medicago sativa* L.) pasture, seeded in the spring of 1997 on a sand-loam textured Dark Brown Chernozem, and (2) a 15 year old xeric crested wheatgrass (*Agropyron cristatum* L.)-alfalfa pasture on a loam textured Dark Brown Chernozem. The Crested Wheatgrass-Alfalfa and Meadow Bromegrass-Alfalfa sites will hereafter be referred to as the Crested Wheat and Meadow Brome sites, respectively. On the native sites litter was observed to be 1-2 cm thick. Soil and vegetation characteristics at each site are summarized in Tables 3.1 and 3.2, respectively. Soil profile descriptions are summarized in Appendix 1.

Manure application treatments were established using a randomized block design with 4 sites, two in each type of forage land (tame pasture and native rangeland). Each site was internally uniform with respect to physical site conditions (e.g.; slope, aspect, and topographic position) and initial vegetation (see Appendix 1), and was established on vegetation in good to excellent range condition. Ten treatments at each site consisted of combinations of 5 different target rates of LHM (10, 20, 40, 80, and 160 kg.ha^{-1}-NH_4) applied at each location with 2 methods of application (surface and injection), applied once from April 12-13, 1999. There was also a control treatment, and two dry injection treatments (0 kg.ha^{-1}-NH_4) one in spring, and one in fall (summarized in Appendix 2). The dimensions for each treated plot were 7 x 50 meters, oriented perpendicular to the slope of the site. A one meter buffer strip was maintained between all treatment plots.

3.2.2. Manure Treatments

The Prairie Agricultural Machinery Institute (PAMI) of Humboldt, Saskatchewan was contracted to apply the manure, as they possessed unique injection equipment capable of achieving highly accurate LHM application rates, as required by the study. LHM was applied using a 3-meter 'Green-Trac' applicator drawn with a 90 kW (120 horsepower) Case IH Magnum FWA Model 7220 tractor. The applicator is a pressurized tank with a distributor system that delivers LHM through a system of hoses to injector shanks that lie directly behind single vertical disk coulters. During application, coulters cut 10 cm into the soil and the shanks with injector boots apply the LHM directly into the furrows behind the coulters. For this experiment, coulter spacing was always 25 cm. When LHM was surface applied, the coulter system was raised above the ground to provide adequate clearance (approximately 10 cm), with the LHM then top-dressed. This technique differs markedly from traditional splash-plate methods. Splash-plate applications generally occur higher above the ground surface (often greater than two meters) and create more agitation (i.e.: increased volatilization and evaporation) than the method we used, which was more suitable to small plot research trials. Machine speed and orifice diameters within the distributor were adjusted to obtain the various application rates, with pre-treatment manure sampling and calibration (using water) used to determine the necessary application speeds.

Preliminary samples of LHM were collected and analyzed for nutrient content to derive the appropriate bulk volume application rates [see Code of Practice for the Safe and Economic Handling of Manures (1995)]. Levels of bulk manure application varied with target application rates of ammonium-N (10, 20, 40, 80, and 160 $kg.ha^{-1}$), with actual bulk manure application rates ($liters.ha^{-1}$) adjusted for the ammonium as determined by preliminary manure analysis (see Table 3.3). The LHM source was the first lagoon of a three-pit, non-agitated, uncovered lagoon of a 4000-head hog operation. The project cooperators use a non-agitated lagoon system as it reduces volatilization of odorous compounds and subsequent nutrient loss. Because all equipment and application rates were calibrated using samples from the non-agitated lagoon system, pits were not agitated prior to, or during LHM removal for treatment application. All LHM for plot application was removed from the lagoon with a vacuum truck. The intake was always set in the same place near the center of the lagoon using an intake hose suspended from a float that allowed the hose opening to extract LHM from one meter below the lagoon surface, and the tank on the application system was continuously agitated. Additionally, the 10 $kg.ha^{-1}$ rate could not be achieved under normal operating conditions due to an excessive machine (tractor) speed requirement. Thus, the 10 $kg.ha^{-1}$ rate was attained by diluting manure through a 1:1 mix with water (Table 3.3).

Previous research has indicated that hog manure is highly variable in composition, depending upon characteristics such as its age, level of dilution, nature of the storage facility, location of extraction from the lagoon, solid component, and odor treatment (Lorimor et al. 1997, Bayne 1997). As a result, it was necessary to have accurate data on actual nutrient input levels into each treatment. At the time of application, separate samples were collected from each truckload of manure applied to plots. After collection, all manure samples were immediately stored inside an electric cooler at 4 °C, and then shipped to the lab the same day. Samples were tested for uniformity in moisture content, electrical conductivity (EC), pH; organic-N, NO_3-N, NH_4-N; as well as total phosphorus, sulfur, potassium, calcium, sodium, and magnesium; results and lab analysis methods are summarized in Table 3.4.

3.2.3. Static Sorber Ammonia Traps

Static sorber ammonia traps were set up on the study area, two per manure treatment plot. Traps were constructed and set up similar to the method used by Marshall and DeBell (1980) and Nason et al. (1988), who examined ammonia losses from urea applied to forest understories. However, due to the different nature of the treatments in this study, some modifications were necessary to facilitate use of the static sorber traps on rangeland (see Figure 3.1). Marshall and DeBell (1980) set up traps by first pounding a connector ring into the ground, and applying urea pellets after the soil was allowed to equilibrate. Once urea pellets were applied, the static sorber traps were put in place by fitting them into the connector rings to form a tight seal. With the application of LHM to rangeland, it was not possible to pre-install connector rings, primarily due to the soil disturbance associated with the injection treatment and use of heavy equipment. Injection passes by heavy equipment would dislodge or destroy the rings. In attempting to make sampling alike on all plots, rings were not installed on any plots that received LHM. Rather than using connector rings, traps were firmly pressed and twisted into the soil surface, approximately 0.5 cm. Traps were secured in place using weights applied to the top of each trap, which also served to maintain a tight seal with the soil surface.

Construction of sorber traps involved the use of commonly available materials. Traps were made from 11L plastic pails, 27 cm in diameter, and 23 cm deep. A 1.25 cm brass cuphook was installed in each pail, with the hook centered above the bottom on the inside of the pail. The sorbers were constructed from 2.5 cm thick polyethylene foam, and were 15 cm wide by 7.5 cm tall. Sorbers were saturated with 75mL of 0.7 M (2.2 N) phosphoric acid in glycerol solution and allowed to drain under gravity until they contained approximately 50 mL of solution. Phosphoric acid (H_3PO_4) was used because it reacts with volatilized ammonia (NH_3) to form ammonium phosphate ($NH_4H_2PO_4$) in the sorber sponge, which can be extracted with deionized water and analyzed for ammonium-N in solution. Glycerol was used to prevent desiccation of static sorber sponges. The sorbers were then stored in airtight containers until installation. Sorber sponges were held in place inside the traps by clamping one edge of the sorber with a 2.5 cm office clamp, which was then hung upside down from the cup hook inside the pail. Two replicate traps were set up within 30 seconds of the LHM application equipment passing through each treatment plot. Traps were set up randomly within the treatment plot, but were always oriented centrally over the midpoint between two parallel application lines or injection furrows. Each trap was labeled with the time of placement, and remained in place for exactly 48 hours. The period was similar to the time exchange intervals used by Nason et al. (1988), and coincided with the disappearance of visible LHM moisture at the ground surface. Daytime high temperatures ranged between 12-15 °C, while overnight low temperatures ranged between 3-4 °C. Once traps were removed from the ground surface, sorber sponges were immediately placed in plastic Ziploc bags, and any remaining air squeezed out before the bags were sealed. Precipitation was negligible during LHM application, static sorber trap set-up, and the 48-hour monitoring period that followed.

Ammonia extractions were done by extracting the static sorber sponges with three washings of 100 mL of deionized water, made up to 300 mL. Extractions from the three washings were combined and analyzed for ammonium concentration in solution, using a Technicon (1973) Auto-Analyzer II. Replicate sub-sample ammonia levels were averaged per plot prior to statistical analysis.

3.2.4. Statistical Analysis

Data were analyzed using an analysis of variance (ANOVA) as a split plot (Steel and Torrie 1980) to test the effects of the two types of forage land (tame pasture and native range), as well as the five LHM application rates and two application methods. Mean comparisons were conducted on all significant main treatment effects and their interactions using Tukey's mean comparison (Steel and Torrie 1980). Significant rate effects were further evaluated using a series of contrasts to fully characterize their nature (Steel and Torrie 1980). All differences were considered significant at $p<0.05$, unless otherwise noted.

3.3. Results

Rate and method of LHM application significantly affected ammonia loss from treated plots ($p<0.001$; Table 3.5). Forage type also affected ammonia loss, although at a significance level of $p<0.06$ (Table 3.5). In addition to these main effects, forage type interacted significantly with both rate and method of application ($p<0.0001$ and 0.051; respectively; Table 3.5).

Contrasts of LHM application rate with ammonia loss indicated the increases in ammonia loss were linearly ($p<0.0001$) associated with rates of LHM on both native range and tame pasture (Figure 3.1). However, the interaction of rate with forage type resulted from relatively greater increases in ammonia loss on tame pasture, particularly at rates of 80 and 160 kg.ha^{-1}-NH_4-N (Figure 3.2), with overall ammonia loss on tame pasture nearly 3.5 times that from native rangelands (Table 3.6). At the highest application rate of LHM, measured ammonia losses were four times greater on tame pasture, than on native pasture (Figure 3.2).

The use of coulter injection rather than dribble broadcast during LHM application generally reduced estimated ammonia loss from sampled plots by as much as 55% (Table 3.6). The greatest NH_3-N losses were found on surface broadcast treated plots within tame pastures (Table 3.6), accounting for the significant method by forage type interaction. Thus, it appears that injecting LHM reduced ammonia volatilization, and was particularly effective on tame pastures.

3.4. Discussion

There was an average loss of 3.35 kg.ha^{-1} of NH_3-N on the tame pastures at the 160 kg.ha^{-1} rate (*vs.* 0.79 kg.ha^{-1} NH_3-N on native range), indicating LHM application to native rangeland, rather than tame pasture conserved N. It should also be noted that the surface broadcast application method used (i.e. dribble broadcast 20 cm above the ground) in this experiment likely underestimated the amount of NH_3 that would be volatilized using conventional splash-plate application technologies as there is a reduction in agitation, atomization and air travel-time exposure. Although it was suspected that some differences could have existed between the mesic (Fescue Grassland and Meadow Brome) and xeric (Mixed Prairie and Crested Wheatgrass) sites, little difference was detected in mean ammonia loss between the two [0.77(±0.17) and 0.69 (±0.17) kg.ha^{-1} N, respectively]. These results suggest forage type rather than current moisture status influenced ammonia loss across the study area.

Ammonia losses increased linearly with rate of applied LHM, indicating the relative risk of ammonia loss remained constant regardless of application rate. However, greater absolute losses at higher rates of application may increase the likelihood of other problems, such as the risk of exceeding localized odor tolerances by surrounding landowners and residents. The linear ammonia losses were similar to other studies involving fertilizer (Fan and MacKenzie 1993; Nason et al. 1988; Harper et al. 1983; Fenn and Kissel 1973; Ernst and Massey 1960) and liquid manure (Moal et al. 1995; O'Halloran 1993; Sommer et al. 1991; Brunke et al. 1988; Beauchamp et al. 1982) or biosolids (Harmel et al. 1997) conducted in North America.

The overall amount of ammonia volatilized, even at high LHM application rates (maximum of 4.8% of total applied NH_4) is a relatively small fraction of the applied N. Other studies have indicated that NH_3 losses may be as high as 99% of total applied NH_4^+ (O'Halloran 1993; Lauer et al. 1976). Differences in the amount of ammonia loss between studies, however, may be due to differences in manure type, composition, length of storage times, and handling methods. In addition, differences may exist based on the types of vegetation and soils investigated, along with the inherent weather conditions during and after application. It should also be noted that the method used to assess ammonia losses in this study (static sorber traps) is not as accurate relative to more elaborate but expensive procedures such as the integrated horizontal flux technique (McGinn and Janzen 1998). For example, sheltering the soil surface directly below the trap from wind is likely to minimize measured ammonia loss by convection or drying. Ernst and Massey (1960) found that ammonia losses were directly related to increasing soil pH and temperature for urea applied to the soil under laboratory conditions and that the loss of NH_3 was closely related to the rate of soil drying and its initial moisture content. Sommer et al. (1991) also found that ammonia losses increased with increasing wind speeds. This effect may be offset, however, by the sorber trap functioning as a local ammonia sink, capable of drawing down ambient airborne ammonia, thereby potentially encouraging continued losses of ammonia from the soil surface. As a result, interpretation of the data is probably most reliable between comparative treatment types rather than of absolute numbers, and further validation would be needed to assess how closely the measured ammonia losses represent those that could be expected under actual field conditions. The benefits of the sorber traps are in their ease of setup and application, and the relatively low cost of materials, labour, and laboratory analysis (total cost of approximately $800 Cdn for 100 samples).

Although ammonia losses were consistently lower on native range relative to tame pasture, the significant rate by forage type interaction reflects the increasing absolute (actual) difference in ammonia loss between forage types through greater rates of application (Figure 3.1). These differences may be due to the relative abundance of litter and mulch on the surface of native rangelands compared with tame pastures. The latter areas have been cultivated and re-seeded in the last 15 years, reducing the amount of litter and increasing the fraction of exposed soil (Table 3.2). The removal of litter will increase wind velocity at the soil surface, thereby increasing the potential for water evaporation and ammonia volatilization after LHM application. However, given that wind was likely absent under the sorber traps, other factors may account for the differences in volatilization.

Native rangelands are uncultivated and have extensive litter and mulch layers (Weaver and Rowland 1952), which contribute to rapid moisture infiltration (Naeth et al. 1991) and water conservation (Facelli and Pickett 1991). In the current investigation, removal of this layer and exposure of soil on tame pastures was observed to result in both soil crusting, and subsequent manure ponding following LHM application, particularly at greater application rates, because the mulch layer promotes infiltration, retards evaporation, increases organic matter at the soil surface, provides soil surface insulation (preventing crusting), and promotes root and rhizome growth in the upper soil layers (Weaver and Rowland 1952). This ponding would increase the opportunity for ammonia volatilization to occur immediately following application. Interestingly, the removal of wind by the sorber traps suggests the differences in ammonia loss between native and tame forage types in this study may have been underestimated, as wind may have increased ammonia dispersal from exposed ponded manure on tame sites due to evaporation (O'Halloran 1993, Brunke et al. 1988).

Different application methods also influenced observed ammonia losses, with lower ammonia losses on injected plots than dribble broadcast plots. This difference is likely attributable to the direct placement of manure into the soil matrix below the ground surface (up to 10 cm) aiding adsorption of NH_4 onto cation exchange complexes, reducing opportunities for N contact with air, a necessary precursor for ammonia volatilization. LHM emergence onto the soil surface was observed during coulter application only when application rates reached 42 000 $L.ha^{-1}$, with the greatest emergence at 84 000 (the 160 $kg.ha^{-1}$-NH_4 application rate). Overall measured ammonia losses were cut nearly in half using coulter injection (Table 3.6). This reduction represents a potential savings in terms of plant nutrients, with associated benefits probable in terms of air quality (e.g., odor). However, any actual reduction in ammonia loss must ultimately be assessed against the added cost of the application equipment and the time (and labor) needed to apply the manure. The low added capture of N using injection (i.e.: 2 $kg.ha^{-1}$ at the highest rate) suggests that in the current economic climate, the greatest benefits of this technology may be in odor control and pollution reduction, rather than nutrient retention. For example, higher power requirements (i.e.: fuel costs) and greater risk of soil compaction due to a higher draft requirement for injection equipment with self-contained manure tanks may potentially limit the use of injection technologies. However, it is also important to recognize that the dribble broadcast method used here was markedly different from traditional splash plate techniques. Splash plate application increases air-manure contact through increased manure atomization (Thomas 2001; Bittman et al. 1999; Sawyer et al. 1990; Long et al. 1975), as well as increases runoff potential (Gangbazo et al. 1995). Thus, N conservation through coulter application is likely to be even greater compared to conventional splash plate application. Other intermediate methods of LHM application (e.g.: punch aeration with broadcast) may also have economic and practical benefits, but require testing as well.

The fact that no method by rate of application interaction was observed indicates that the benefits of using injection technology appear to apply uniformly across all application rates. There was, however, a significant method by forage type effect, with greater reductions in ammonia loss from using coulter injection on tame pasture rather than native rangeland. On tame pastures with reduced litter and crusted soil, the use of incorporation methods such as low-disturbance injection may reduce the potential for ammonia volatilization, by creating points of entry and absorption for LHM to the soil matrix and reducing surface residence time (i.e. ponding).

Litter on native rangelands may also aid in N retention due to its tendency to conserve soil moisture (Willms et al. 1986). Increased moisture allows for rapid adsorption of NH_4^+ (Tisdale et al. 1993). Native rangeland plant communities likely have more developed root systems and associated rhizospheric microbial populations (Dormaar and Willms 1990), which in turn, may produce more organic matter and reduce soil bulk density, as well as serve as a fairly rapid sink following application. This may aid in NH_4 adsorption by roots and cation exchange complexes and absorption by soil as the more developed root systems of native plant communities increase soil porosity and create larger root channels that LHM can percolate into. Large, diverse microbial populations may immobilize ammonium, acting as slow-release fertilizer for later plant use following microbe decomposition. On the native sites, particularly the Mixed Prairie the entry of LHM into the soil may have been reduced because of the litter layer, which was 1-2 cm thick in some areas.

In contrast, tame pastures are primarily monocultures or simple polycultures developed for the sole purpose of economic biomass production, and are not necessarily self-sustaining. That is, they typically require inputs such as fertilizer, cultivation, or re-seeding for rejuvenation. These inputs, coupled with the simple composition of the plant community, may prevent the advanced development of complex or diverse microbial populations or root systems that aid in retaining nitrogen from the LHM in the rhizosphere where it can benefit plant production (Dormaar and Willms 1990). The use of an incorporation method such as low-disturbance injection may also reduce NH_3 volatilization by placing NH_4-containing LHM in contact with the soil, or more importantly, soil moisture, microbes, and plant root systems.

3.5. Conclusion

This field experiment demonstrated several promising outcomes in the overlapping spheres of waste management and rangeland science. Static sorber traps offer a low cost, simple, and practical tool to successfully compare ammonia loss trends from LHM applied to native rangeland and tame pasture. Results from this field study indicate there is a clear positive linear relationship between increasing LHM application rates and associated ammonia loss. In addition, ammonia losses were greater on tame pasture than native rangeland, with the greatest effect evident at application rates at or above 80 $kg \cdot ha^{-1}$-NH_4-N. Coulter injection of LHM decreased ammonia losses, particularly on tame pasture. Although economic factors will likely drive the adoption of injection technologies, other factors such as socio-environmental concerns may become increasingly important driving forces behind future waste management plans for producers. Additional research is needed to quantify the actual ammonia losses on different lands (e.g., soil types) with different methods of application and/or disposal, for use in more detailed cost-benefit analyses, and perhaps more improved or sophisticated methods for measuring NH_3 volatilization. Overall, these results indicate innovative application technologies have implications for the reduction of odor, conservation of soil nutrients, and the integration of hog production with range and pasture management.

3.6. Literature Cited

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Table 3.1: Mean (SD) soil characteristics in the 0-20cm depth for each of the native and tame sites as sampled in September 1998, prior to manure application.

	Sites			
	Native Rangeland		Tame Pasture	
Constituent	Xeric Mixed Prairie: Dark Brown Chernozem (n=5)	Mesic Fescue Grassland: Black Chernozem (n=5)	Xeric Crested Wheat: Dark Brown Chernozem (n=5)	Mesic Meadow Brome: Dark Brown Chernozem (n=5)
[1] NH_4-N*	1.22 (0.72)	1.26 (0.54)	1.52 (0.77)	1.14 (0.37)
[2] NO_3-N*	0.72 (0.66)	0.22 (0.22)	2.96 (2.15)	2.94 (1.11)
[2] PO_4-P*	2.4 (0.6)	3.6 (0.9)	9.0 (2.6)	9.0 (2.8)
[2] K*	471 (60)	334 (64)	337 (96)	213 (93)
[3] SO_4-S*	9.98 (9.78)	4.24 (1.61)	5.04 (2.57)	2.48 (0.80)
[4] Exch. Ca**	8.0 (3.51)	8.46 (2.19)	10.8 (5.52)	8.46 (2.63)
[4] Exch. Mg**	3.44 (0.79)	3.24 (1.39)	4.02 (1.40)	1.44 (0.54)
[4] Exch. Na**	0.44 (0.67)	0.12 (0.07)	0.84 (0.67)	<0.1 (0)
[4] Exch. K**	0.89 (0.13)	0.69 (0.14)	0.64 (0.20)	0.47 (0.22)
[5] E.C. (dS/m)	0.34 (0.16)	0.12 (0.03)	0.56 (0.41)	0.13 (0.022)
[5] pH	6.6 (0.2)	6.3 (0.2)	7.0 (0.7)	6.6 (0.2)
[6] O.M. %	3.86 (0.67)	4.94 (1.22)	3.22 (0.82)	3.22 (0.97)
[7] Db***	1.28 (0.04)	1.09 (0.03)	1.28 (0.08)	1.28 (0.14)
[8] Total Sand %	50.8 (1.3)	45.0 (0.6)	49.2 (0.9)	62.4 (0.2)
[8] Total Silt %	29.9 (1.2)	38.3 (0.6)	29.4 (1.1)	20.4 (0.2)
[8] Total Clay %	19.3 (0.4)	16.7 (0.1)	21.5 (0.9)	17.2 (0.0)

[1] Extractable by 2M Potassium Chloride Solution (McKeague 1978)
[2] Extractable by Modified Kelowna Extract (Ashworth and Mrazek 1995)
[3] Extractable by 0.001M Calcium Chloride Solution (McKeague 1978)
[4] Exchangeable by Ammonium Acetate at pH 7.0 (McKeague 1978)
[5] 1:2 Soil:Water Method (McKeague 1978)
[6] Organic Matter by Loss on Ignition (McKeague 1978)
[7] Bulk Density for mineral soils, cores taken with powered core sampler, corrected for coarse fragments (McKeague 1978).
[8] Particle Size Analysis using the Hydrometer Method (McKeague 1978).
* Units are $mg.kg^{-1}$
** Units are $meq.100g^{-1}$
*** Units are $Mg.m^{-3}$

Table 3.2: Mean canopy cover percent (± SE) for the dominant plant species present on native rangeland and tame pasture sites as sampled in July and August of 1999. Adapted from (Blonski 2001).

		Native Range		Tame Pasture	
Growth Form and Species Name	**Scientific Name**	**Mixed Prairie**	**Fescue Grassland**	**Crested Wheat**	**Meadow Brome**
Graminoids					
Crested Wheatgrass	*Agropyron cristatum* (L.) Gaertn.	-	-	56.4 (8.8)	5.2 (3.1)
Russian Wildrye	*Elymus junceus* Fisch.	-	-	3.4 (2.6)	-
Meadow Brome	*Bromus biebersteinii* Roem & Schult	-	-	-	17.8 (4.5)
Wheatgrass spp.	*Agropyron* spp.	0.6 (0.3)	0.4 (0.9)	-	1.0 (1.4)
Junegrass	*Koeleria macrantha* (Ledeb.) J.A. Schultes f.	11.2 (3.2)	0.2 (0.4)	-	-
Needle and Thread	*Stipa comata* Trin. & Rupr.	5.7 (6.4)	-	-	-
Western Porcupine Grass	*Stipa curtiseta* (A.S. Hitchc.) Barkworth	5.5 (6.8)	4.2 (2.3)	-	-
Plains Rough Fescue	*Festuca hallii* (Vassey) Piper.	3.7 (5.4)	42.5 (6.7)	-	-
Blue Grama	*Bouteloua gracilis* (HBK) Lag.	1.6 (1.0)	0.03 (0.1)	-	-
Hooker's Oatgrass	*Helictotrichon hookerii* (Scribn.) Henr.	3.7 (3.8)	1.5 (1.4)	-	-
Western Wheatgrass	*Agropyron smithii* Rydb.	4.3 (3.7)	1.0 (1.0)	-	-
Sedge spp	*Carex* spp.	13.5 (3.6)	7.5 (3.6)	-	-
Forbs					
Alfalfa	*Medicago sativa* L.	-	-	15.6 (8.6)	59.4 (8.6)
Common Peppergrass	*Lepidum densiflorum* Schrad.	-	-	0.9 (0.9)	2.8 (1.4)
Wild Buckwheat	*Polygonum convolvulus* L.	-	-	-	2.1 (1.7)
Cut-leaved Anemone	*Anemone multifida* Poir.	5.8 (2.3)	1.1 (0.9)	-	-
Low Goldenrod	*Solidago missouriensis* Nutt.	0.6 (0.9)	0.5 (0.5)	-	-
Ascending Purple Milk Vetch	*Astragalus striatus* Nutt.	0.4 (0.7)	-	-	-
Mallow	*Sphaeralcea coccinea* (Pursh.) Rydb.	1.0 (0.7)	-	-	-
Common Yarrow	*Achillea millefolium* L.	0.1 (0.4)	1.8 (2.3)	-	-
American Vetch	*Vicia Americana* Muhl.	-	3.0 (2.8)	-	-
Slender Milk Vetch	*Astragalus flexuosus* Dougl. *Ex* G.Don	1.2 (1.3)	1.2 (0.2)	-	-
Shrubs					
Pasture Sage	*Artemisia frigida* Willd.	10.2 (4.4)	0.7 (0.9)	-	-
Prairie Rose	*Rosa arkansana* Porter	0.03 (0.2)	1.3 (1.8)		
Litter		81.3 (5.7)	99.5 (0.8)	87.8 (7.0)	78.7 (6.4)
Bare Soil		0.3 (0.3)	0	10.7 (7.3)	19.7 (6.5)

Table 3.3: Target and Actual LHM Application Rates and Associated Water Depth Equivalents for Fall and Spring Applications.

Season & Target Application Rate (kg.ha^{-1} –NH_4-N)		Actual Application Rate (kg.ha^{-1} –NH_4-N)	LHM Application Rate Volumes (L.ha^{-1})	Calculated Water Depth Equivalent (mm)
Fall	**10**[1]	9.3	13 000	1.3
	20	18.6	13 000	1.3
	40	37.1	27 000	2.7
	80	74.2	53 000	5.3
	160	148.4	107 000	10.7
Spring	**10**[1]	9.5	11 000	1.1
	20	19.0	11 000	1.1
	40	37.9	21 000	2.1
	80	75.8	42 000	4.2
	160	151.6	84 000	8.4

[1] Water Depth Equivalents and Application Rate Volumes for the 10 and 20 rates (kg.ha^{-1}- NH_4-N) are the same because the Target Application Rate of 10 (kg.ha^{-1}- NH_4-N) was achieved by mixing LHM and water at a 1:1 ratio.

Table 3.4: Results of the manure analysis during application by truckload (n=7), April 1999.

Constituent	Mean (SD)$_{1-6}$	Min.$_{1-6}$	Max.$_{1-6}$	Sample 7*
[1]**Moisture %**	99.34 (0.06)	99.30	99.46	99.76
[3]**NH_4-N %**	0.21 (0.00)	0.21	0.21	0.10
[3]**NO_3-N %**	0.01 (0.00)	0.01	0.01	<0.01
[2]**Kjeldahl N %**	0.23 (0.01)	0.22	0.23	0.10
[2]**Organic N %**	0.01 (0.01)	0.01	0.02	0.00
[4]**Total K %**	0.11 (0.00)	0.11	0.12	0.05
[4]**Total P %**	0.03 (0.01)	0.02	0.03	0.01
[3]**SO_4-S %**	<0.01 (0.00)	<0.01	<0.01	<0.01
[4]**Ca %**	0.01 (0.00)	0.01	0.01	0.01
[4]**Mg %**	<0.01 (0.00)	<0.01	<0.01	<0.01
[4]**Na %**	0.04 (0.00)	0.04	0.04	0.02
[5]**pH**	7.67 (0.05)	7.60	7.70	7.80
[6]**EC (dS.m^{-1})**	17.62 (0.10)	17.50	17.70	8.87

*Sample 7 was diluted with water to reduce the manure concentration for treatments receiving LHM at 10 kg.ha^{-1}, as this low rate could not be achieved through normal operating conditions.

[1] Samples dried at 104 °C for 3 hours (Gardner 1986).

[2] Nitrogen determinations by Kjeldahl (Strong Acid Block Digestion) (Keeney and Bremner 1966)

[3] Extracted with a weak $CaCl_2$ solution (0.001 M) mixed with KCl (100 ppm K) (Maynard and Kalra 1993).

[4] Samples taken to dryness, ashed, then digested with HCl, and then read by ICP (Metals in Plants 1990)

[5] pH electrode used directly on sample (McKeague 1978)

[6] EC electrode used directly on sample (Rhoades 1982)

Table 3.5: Summary of significant manure treatment effects on measured ammonia losses in 1999.

Factor	*df*	*Mean Square*	*F-Value*	*Probability*
Forage Type*	1	1030.33	16.36	0.056
Error 1	2	63.00	----	
Rate	4	856.10	42.57	<0.0001
Method	1	286.17	14.23	0.001
Rate x Method	4	29.59	1.47	0.252
F. Type x Rate	4	340.62	16.94	<0.0001
F. Type x Method	1	87.32	4.34	0.051
F. Type x Rate x Method	4	8.03	0.40	0.807
Error 2	18	20.11	----	
TOTAL	**39**			

* Refers to Tame *vs.* Native sites.

Table 3.6: Measured mean ammonia-N* losses (± SE) in kg.ha^{-1} for 48-hours following LHM application on different vegetation types with varying manure application methods.

		Manure Application Methods		
		Injected	**Surface Broadcast**	**Combined Methods**
Vegetation Type		**Mean**	**Mean**	**Grand Mean[2]**
Native Range	Mixed Prairie	0.31 (0.18)	0.52 (0.18)	0.41 (0.12)
	Fescue Grassland	0.14 (0.18)	0.31 (0.18)	0.40 (0.12)
	Native Mean	**0.23[1] (0.11)^{c}**	**0.42 (0.11)^{bc}**	**0.32 (0.14)^{B}**
Tame Pasture	Crested Wheatgrass	0.65 (0.18)	1.26 (0.18)	0.96 (0.12)
	Meadow Brome	0.95 (0.18)	1.67 (0.18)	1.31 (0.12)
	Tame Mean	**0.80 (0.11)^{b}**	**1.47 (0.11)^{a}**	**1.13 (0.14)^{A}**
Grand Mean[2]		**0.51 (0.09)^{B}**	**0.94 (0.09)^{A}**	

[1] Within vegetation type by application method, those means with different lower case letters differ significantly at $p<0.05$.

[2] Within each of vegetation type and application method, grand means with different upper case letters differ significantly at $p<0.06$.

* Ammonia extracted from static sorber sponges with de-ionized water. Extractions were analyzed for ammonium concentration in solution, using a Technicon (1973) Auto-Analyzer II.

Figure 3.1: Schematic of static sorber ammonia trap

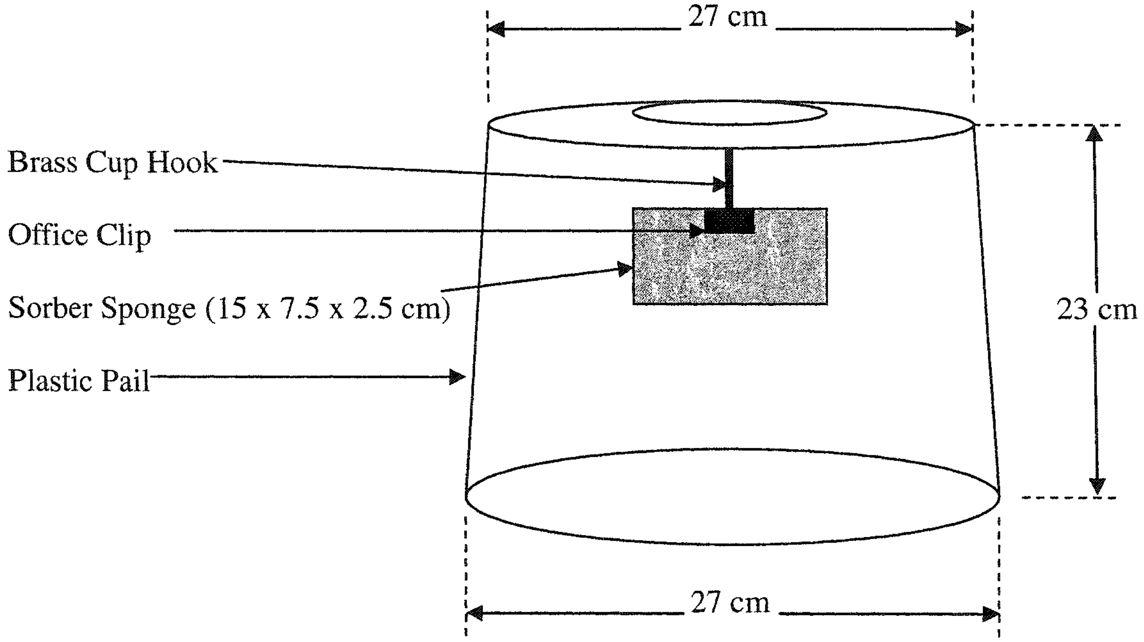
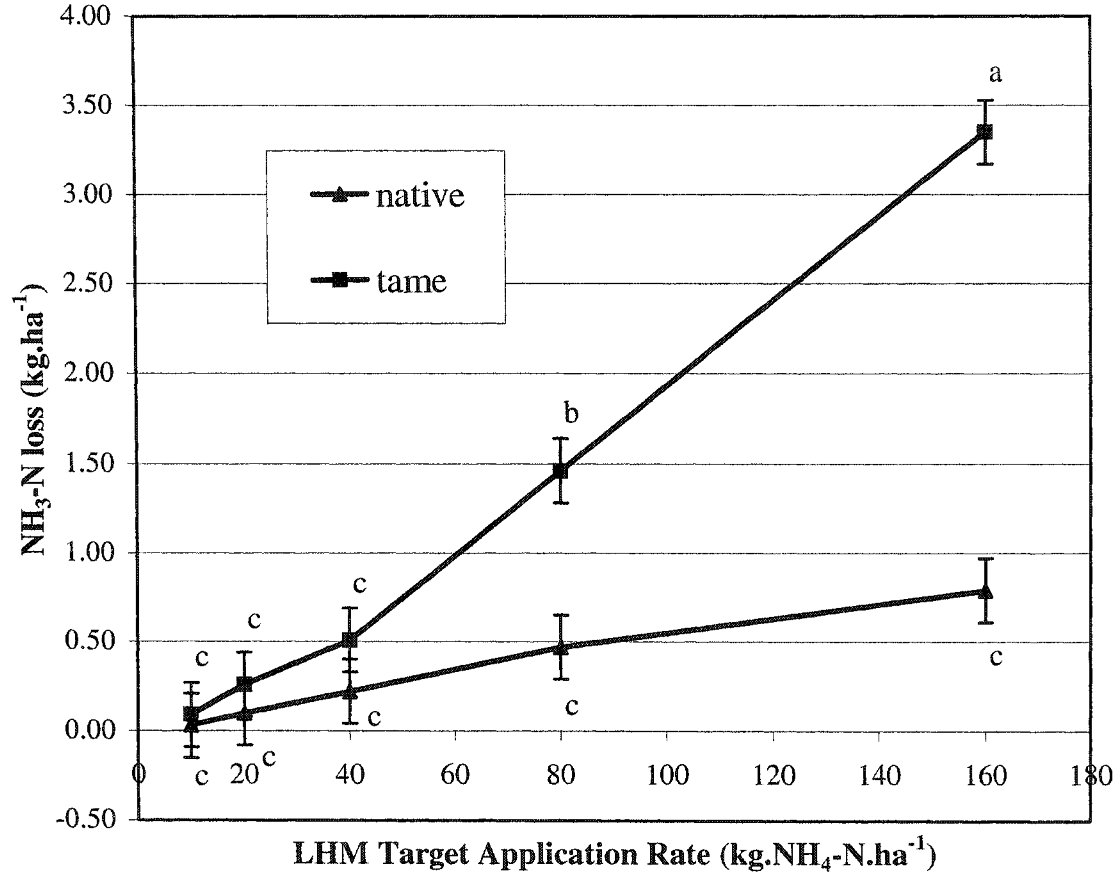


Figure 3.2: Measured NH_3-N* losses (kg.ha^{-1}) (± SE) on tame and native sites following LHM application at 5 different rates in April 1999.



* Ammonia extracted from static sorber sponges with de-ionized water. Extractions were analyzed for ammonium concentration in solution, using a Technicon (1973) Auto-Analyzer II.

CHAPTER 4

Soil Nutrient Responses Following LHM Application to Forage Land

4.1. Introduction

Significant increases in hog production have taken place in Alberta over the past several years and include expansion of large-scale hog production facilities into semi-arid regions of Alberta (CAESA 1991). Such geographic trends may prevent conflict over aesthetics and odor. Future expansion may be governed by increasing public concern for environmental issues, including the disposal of liquid hog manure (LHM). Recent changes in the livestock industry have resulted in increased confinement feeding and larger concentrations of livestock (Jackson et al. 2000; Adeola 1999; Janzen et al. 1999; McKenna and Clark 1970). These changes have been a result of both economic factors and regulations aimed at reducing the pollution effect of livestock operations, especially under the influence of a public's growing concern and awareness for environmental safety (Innes 2000, Jongbloed and Lenis 1998). Manure applications must be made in a manner that does not contribute to soil, water, and/or air pollution while remaining compatible with efficient crop production (Evans et al. 1977). Profit maximization from the use of manures is rapidly leading large-scale producers to the concept of manure management at minimum cost and below a certain 'nuisance' level (McKenna and Clark 1970).

Traditional sinks for LHM have been cultivated lands, which are not readily available in semi-arid areas. From a cost-efficiency perspective, alternative lands must be considered for LHM application given that it is unrealistic to transport manure, especially LHM, long distances. As more hog operations move into semi-arid regions, socially and environmentally appropriate methods of LHM disposal will be required. The widely available, but potentially less productive, native rangelands and tame pastures adjacent to these operations, could provide an alternative sink for LHM. This activity would also convert manure from a troublesome liability into a valued asset The major benefit of applying LHM to forage crops is nutrient recovery through increased plant production and forage quality (Gangbazo et al. 1999).

Relatively little is known about the influence of LHM application on tame pasture and/or native rangeland. In Alberta, this lack of information is at least partly due to a strong historical focus for LHM use on cultivated croplands. Differences in manure compatibility with permanent cover crops versus annually cultivated fields are to be expected. Thus, manure application guidelines [see the Code of Practice for Responsible Livestock Development and Manure Management (2000)] for the province of Alberta are developed with a strong emphasis on crops that may change annually with crop rotation. In addition, because the Code is based upon cultivated cropping systems, it largely addresses recommendations for cultivated regions of the province. Native rangelands are often located in drier areas, so biomass production is lower, with subsequently lower nutrient demand. Furthermore, on rangeland, a large part of plant nutrients is recycled to the soil as urine/manure. Also, the moisture status of many rangelands, due to their location, is often lower/drier. Hence, movement of LHM into and through the soil may differ from moister areas – establishing the need to study LHM application on rangelands.

In contrast, the Code (2000) does not address soil zones that may coincide with various permanent cover crops, especially native pasture. As expansion of the hog industry continues, particularly into the drier, less arable, and less populated areas of the province, a growing proportion of the manure generated will need to be applied to these forage lands. In addition to these areas consisting predominantly of native rangeland and tame pasture, there are large portions that are under public control (e.g.: within grazing reserves and leases). Environmental issues are a key driver of management decisions in these areas, and may be regulated by government legislation in the near future (Neeteson 2000). These trends highlight the need for research to evaluate how LHM can be safely and effectively applied to forage lands without creating adverse effects within the soil environment. Consequently, this research was conducted to provide more detailed information on the immediate and longer-term effects of LHM application to soils under native rangeland and tame pasture and to aid in determining the potential compatibility of swine production with other land uses, including the production of perennial tame and native forages.

Previous research has shown the significance of varying rates of fertilization (Vetsch et al. 1999; Ledgard et al. 1996; Rehm et al. 1995; Campbell et al. 1994) and manure addition (Schmidt et al 2001 and 2000; Randall et al. 2000; Gupta et al 1997; Lory et al. 1995; Schmitt et al. 1994; Trehan and Wild 1993; Sawyer et al. 1990; Schmitt et al. 1992) to cultivated lands, with others demonstrating the effects of different rates of fertilizer (e.g., Kowalenko and Bittman 2000) and manure addition to tame forages (Lowrance et al. 1998; Bittman et al. 1997; Sanderson and Jones 1997; Schmitt et al. 1994, Westerman et al. 1987; Burns et al. 1987) or tame forages and annual crops

(Gangbazo et al. 1999 and 1995a). The majority of information regarding the effects of varying rates of manure application, however, pertains to solid manure applied to annual croplands. Little information exists on the effects of nutrient additions, especially in the form of liquid manure, to native rangelands (Power and Alessi 1971).

Overall, the majority of studies that examine various manure application methods have also investigated cultivated areas (Sawyer et al. 1990). Manure additions to pasture and range are limited to surface broadcast or low disturbance injection with no incorporation. While some studies have examined the effects of manure incorporation into cultivated lands or tested various injection methods into tame pastures (Lory et al. 1995), little comparative information exists on the effects of different manure application methods (injected *vs*. surface broadcast). In addition, there have been no studies that evaluate the potential benefits of using injection at varying rates of LHM on either tame pasture or native rangeland. Thus, there is a need to examine the effects of different manure application methods on forage lands (Fee 1996; Vellidis et al. 1996; Sawyer et al. 1990).

The purpose of this chapter is to report on original research conducted to assess the soil nutrient changes associated with applying LHM to semi-arid native rangeland and tame pasture in central Alberta. The goal of this research was to evaluate soil nutrient changes with: (1) varying LHM application rates, (2) different methods of application (dribble-broadcast *vs*. sub-surface injection), and (3) different seasons of application (fall *vs*. spring). A secondary goal was to compare soil changes under different types of forage land including native rangeland and tame pasture.

Specific objectives of the research were to:

(1) Quantify changes in soil nutrients following liquid hog manure on pasture and rangeland. This will help facilitate the establishment of practical, safe, and sustainable soil conservation guidelines regarding the timing, rate, and method of LHM application on soils supporting pasture and rangeland vegetation,

(2) Assess the rate of depletion of available soil nutrients within different soil and vegetation types following different LHM application rates, timings, and methodologies,

(3) To target a perennial cover crop land base (i.e.: pasture and rangeland) in a semi-arid region for the utilization of LHM, and in the process increase the potential land area considered suitable for the sustainable application of LHM.

4.2. Materials and Methods

4.2.1. Study Area and Design

Manure application treatments were conducted on tame pasture and native rangeland in south-central Alberta, near Little Fish Lake, 40 kilometers east of Drumheller, Alberta (51°22' N, 112°13' W). Study sites are located near the transition from the Mixed Grass Prairie to the Aspen Parkland ecoregion (Strong and Leggat 1992), although many native rangelands have been converted into tame pastures. Sites were selected because they represent a wide range of common soil and growing conditions in Alberta: from Dark Brown to Black soils (*Canadian System of Soil Classification* 1987). The region has a continental climate, with warm summers and cool winters, and a semi-arid mean annual precipitation of 394 mm. This data is the long-term (30 year) average compiled from the nearest weather station at Craigmyle, Alberta, 30 kilometers north of the study area. The study area is also representative of the type of areas wherein hog production is known to be particularly high (CAESA 1991). Native rangeland in the region is representative of a diverse mix of plant communities, from xeric Mixedgrass Prairie to mesic Fescue Grasslands, respectively.

The two native study sites were: (1) an upland bench (Mixedgrass Prairie) consisting of a *Stipa-Agropyron* range type on a loam textured Dark Brown Chernozem soil, and (2) a mesic fescue grassland (*Festuca-Stipa* range type) community on a loam textured Black Chernozem soil. In contrast, the 2 tame pastures were: (1) a mesic meadow bromegrass (*Bromus biebersteinii* Roem & Schult)-alfalfa (*Medicago sativa* L.) pasture, seeded in the spring of 1997 on a sand-loam textured Dark Brown Chernozem and (2) a 15 year old xeric crested wheatgrass (*Agropyron cristatum* L.)-alfalfa pasture on a loam textured Dark Brown Chernozem. The Crested Wheatgrass-Alfalfa and Meadow Bromegrass-Alfalfa sites will hereafter be referred to as the Crested Wheat and Meadow Brome sites, respectively. Soils and vegetation characteristics at each site for 1998-99 can be found in Tables 4.1 and 4.2, respectively. Soil profile descriptions are summarized in Appendix 1.

Manure application treatments were established using a randomized block design with 4 sites, two in each type of forage land (tame pasture and native rangeland) at two moisture regimes (xeric and mesic). Each site was internally uniform with respect to physical site conditions (e.g.; slope, aspect, and topographic position) and initial vegetation, and was established on vegetation in good to excellent range condition (i.e., not overgrazed). Each site was fenced (~150 x 35 meters) after treatment to exclude livestock grazing in order to avoid confounding vegetation responses to treatments with subsequent grazing activities (e.g.: defoliation, compaction, manure additions) during the growing season, with grazing permitted only in late summer and fall after vegetation sampling (Blonski 2001).

Within each site, there were 20 manure treatments; a single randomly assigned untreated control, and a dry injection pass in each of the seasons (spring and fall) treatments (n=23). Treatment plots were 6 meters wide x 35 meters in length. Ten treatments consisted of combinations of 5 different levels (10, 20, 40, 80, and 160 $kg.ha^{-1}$-NH_4) of liquid hog manure (LHM) applied during the fall (October 5-7, 1998), with 2 methods of application (surface and injection). The other 10 treatments used the same 5 rates and 2 application methods, but were applied the following spring (April 12-13, 1999). Fall treatments were conducted after plant growth had ceased. Spring treatments were carried out after spring thaw, but prior to plant growth. Control and dry pass treatments are summarized in Appendices 3-7.

4.2.2. Manure Treatments

The Prairie Agricultural Machinery Institute (PAMI) of Humboldt, Saskatchewan was contracted to apply the manure with unique injection equipment capable of achieving highly accurate LHM application rates, as required by the study. LHM was applied using a 3-meter 'Green-Trac' applicator drawn with a 90 kW (120 horsepower) Case IH Magnum FWA Model 7220 tractor. The applicator is a pressurized tank with a distributor system that delivers LHM through a system of hoses to injector shanks that lie directly behind single vertical disk coulters. When injecting, coulters cut into the soil to a maximum of 10 cm (although actual depth may have ranged from 7.5-10 cm, due to rough terrain) and shanks with injector boots that applied manure at the same depth directly into the furrows (1 cm in width) left by the disks. For this experiment, coulter spacing was always 25 cm, with 12 equally spaced openers. When LHM was surface applied the coulter and shank system was raised above the ground to provide adequate clearance (approximately 10-20 cm), with the manure then top-dressed. The width of the top-dressed bands was typically 7-10 cm for the three lower rates, while bands actually touched one another and completely covered the ground surface at the 2 highest rates. It should be noted that this differs from traditional surface broadcasting methods for LHM, whereby manure is sprayed against a splash plate. Splash plate applications are higher from the ground surface (approximately two meters) and create more agitation (i.e.: increased atomization and susceptibility to drift) than the method we used, which was more suitable to small plot research trials. Machine speed and orifice diameters within the manure distributor of the Greentrac were adjusted to obtain the various application rates, with pre-treatment manure sampling and calibration used to determine the necessary speeds. A one meter buffer strip was maintained between all treated plots.

Preliminary samples of liquid hog manure were collected from the source lagoon and analyzed for nutrient content to derive the appropriate bulk volume application rates [see Code of Practice for the Safe and Economic Handling of Manures (1995)]. Amounts of bulk manure application varied with target application rates (of NH_4-N) of 10, 20, 40, 80, and 160 $kg.ha^{-1}$, with actual application rate volumes (Table 4.5) adjusted for the NH_4-N as determined by preliminary manure analysis (see Tables 4.3 and 4.4). The 10 $kg.ha^{-1}$ rate could not be achieved under normal operating conditions due to an excessive machine (tractor) speed requirement. Thus, the 10 $kg.ha^{-1}$ rate was attained by reducing the concentration of manure, established through a 1:1 mix of LHM and water (Table 4.5).

Previous research has indicated that hog manure is highly variable in composition, depending upon characteristics such as its age, level of dilution, nature of the storage facility, and odor treatment (Lorimor et al. 1997; Bayne 1997). As a result, it was necessary to have accurate data on actual nutrient input levels into each treatment. The LHM source was taken from the first lagoon of a three-pit, non-agitated, uncovered lagoon of a 4000-sow hog operation. Manure was removed from the lagoon with a vacuum truck. The intake was always set in the same place near the center of the lagoon using an intake hose suspended from a float that allowed the hose opening to extract LHM from one meter below the manure lagoon surface. At the time of application, separate samples were collected from each truckload of manure applied to plots. Samples were tested for moisture content, electrical conductivity (EC), pH; organic-N, NO_3-N, NH_4-N; as well as total phosphorus, SO_4-S, potassium, calcium, sodium, and magnesium; results and methods are summarized in Tables 4.4 and 4.5.

4.2.3. Soil Sampling

Soil samples were collected (via soil coring) across each study site at two different depths; shallow (0-20cm) and deeper (20-40 cm) in the soil profile, at each of 3 time periods:

(1) Fall 1998: just prior to manure application (and before freeze-up), to provide a benchmark of starting soil nutrient levels. See Table 4.1 for methods of analyses.

(2) April 16-18, 1999: after fall and spring manure application, but before plant growth, and

(3) April 21-22, 2000: 12 months later (after spring thaw), to represent soil nutrient levels one growing season post-treatment. It should be noted that attempts were made to conduct soil sampling on April 15, 2000 (exactly one year later), but were unsuccessful due to an unexpected snowstorm.

Deeper soil samples (20-40 cm) were used in an attempt to track the vertical movement of mobile nutrients within the soil profile. To limit the cost of soil analysis, only 5 samples were randomly taken from each of the 4 blocks during the first (pre-treatment) sampling period (n= 4 x 5 x 2 depths = 40). This provided an approximation of how variable the endemic soil characteristics were within individual sites (e.g.: blocks).

At the second and third sampling periods, each treatment plot was sampled separately (n= 23 x 2 times x 2 depths = 92 per block). Plots were sampled by collecting 10 cores (0-40 cm) that were then bulked into one composite sample for each of the 0-20 cm and 20-40 cm depths, respectively, for future analysis. As a result, there were 2 composite samples per plot, one representing the shallow soil layer and one representing the deep soil layer.

All pre-growth (post-treatment) soil coring was done during a 3-day period (April 16-18, 1999), beginning four days after manure application to the spring treatments. Soil coring was performed using a hydraulic press-corer from Alberta Agriculture, Food, and Rural Development. The corer was side-mounted on a ¾ ton truck. Soil cores were taken using a 2.5 cm diameter coring tube. Soil cores were divided into two layers (1) from 0-20cm and (2) 20-40 cm. On some treatments in the Mixed Prairie site the top 1-2 cm (approximately) was removed from the core so as to avoid contamination from litter, surface deposited soil, and the heavy layer of fibrous roots or club moss.

During soil sampling care was taken to avoid the middle and edges of each plot. Edges were avoided to prevent sampling an area that may have been outside applicator passes. Sampling from the middle of plots was also avoided in the event there was too much or too little overlap of the two applicator passes. Cores were taken randomly throughout the length of each plot. Given the coulter spacing and soil core size, this pattern ensured equal and representative sampling of all areas of the treatment. No cores were taken directly on top of injection furrows. This was done to prevent sampling soil that may have been compacted; contained large air pockets, or that had been admixed from soil higher in the profile. Drying of soil samples commenced in the field by leaving storage bags open in a cool sheltered place. Soil samples were shipped within 48 hours back to the lab.

Once field sampling was completed, soil samples were prepared using methods from Nyborg et al. (1992). Samples were air dried in tin pans at 25-30 °C ambient room temperature, 1-2 cm deep. Once soil samples were dried, they were prepared for chemical extraction by sieving and grinding each sample in a 2-mm motorized tumbling sieve. Sieved samples were then stored in labeled, airtight plastic bags.

All 1999 soil samples were analyzed for soil pH and electrical conductivity using 1:2 dried soil-water (M/M) ratio (McKeague 1978). A solution of 2 M potassium chloride was used to extract NH_4-N [exchangeable], NO_3-N [water soluble], and PO_4-P [water soluble] (McKeague 1978). Exchangeable-K^+, Na^+, Ca^{2+}, Mg^{2+} was extracted using NH_4Ac at pH 7 (McKeague 1978). In 1999, Norwest Labs analyzed soil samples for extractable SO_4-S using 0.1 M calcium chloride solution (McKeague 1978) and inductively coupled plasma (ICP) analysis. Soil samples from 1999 were also analyzed for metals at Norwest Labs using hot block digestion (EPA Method 3050B, 1990) using a strong acid (nitric acid) and ICP for final analysis. However, due to the high cost of metals analysis, only samples from the 10, 40, and 160 $kg.ha^{-1}$-NH_4 target rates of LHM application were analyzed (see Appendix 8). Soil samples taken in 2000 were only analyzed for parameters that showed statistically significant results on the 1999 samples. Hence only pH, EC, NH_4-N [exchangeable], NO_3-N [water soluble], and PO_4-P [water soluble], using the same methods used for the 1999 samples. Soil profile descriptions were done for each site using soil pits and/or adjacent road cuts. Sampling was also conducted for the determination of both corrected bulk density by core method, and particle size analysis by hydrometer method (McKeague 1978), see Table 4.1.

4.3. Statistical Analysis

Soil data from 1999 were analyzed from the randomized block design using an ANOVA to test for main treatment effects [i.e.: 2 seasons of application (fall *vs*. spring), 5 rates of application (10, 20, 40, 80, and 160 $kg.ha^{-1}$-NH_4), and 2 application methods (sub-surface injection VS. dribble broadcast)] and their interactions. A split-plot design was used to test for soil depth effects and its interaction with the main manure treatments (Steel and Torrie 1980). Depths were considered the sub-plot within each whole plot. Although a secondary objective in this study, it was considered important to test for the potential interaction of site effects with the main treatments, as this may aid in their interpretation. To accomplish this, separate ANOVA's were conducted to ascertain the interaction effects of site by rate and site by method, by adding each term into the main model, one at a time. Post-hoc mean comparisons were conducted on all significant main treatment effects and their interactions using Tukey's mean comparison (Steel and Torrie 1980). All differences was considered significant at $p<0.05$, unless otherwise noted. All data were checked for normality and homogeneity of variances using the Shapiro-Wilkes test (Steel and Torrie 1980). All data were found to be normal, and variances homogeneous.

Results of the statistical analyses (ANOVA) from 1999 were used to help identify those soil nutrient/chemical parameters to re-analyze for the 2000-sampling period. That is, any soil parameter that showed statistically significant treatment effects from 1999 were re-analyzed using the 2000 samples to check for a residual soil effect (i.e.: NH_4-N, NO_3-N, PO_4-P, pH, and EC. Chemical or nutrient parameters that were analyzed in both 1999 and 2000 were also examined for the differences between time periods (2000-1999) in order to evaluate chemical and nutrient changes (i.e.: an anticipated decrease) between the year of application and one growing season later.

4.4. Results

4.4.1. Ammonium and Nitrate

Both ammonium-N and nitrate-N were greater during1999 in the 0-20 cm depth with increasing rate of LHM application (Table 4.6, Figure 4.1). However, by April of 2000, (one growing season later) no significant differences in either NO_3-N or NH_4-N remained across any applied LHM rates (Table 4.6). The actual change in either NO_3-N or NH_4-N between 1999 and 2000 also reflected these patterns, with both nitrate-N and ammonium-N declining significantly (Table 4.6; data not shown).

In 1999, NO_3-N showed a significant rate by site interaction (Table 4.6). The greatest increase in nitrate-N after LHM application occurred within the meadow brome site with differences most evident at LHM rates of 80 or 160 $kg.ha^{-1}$-NH_4-N (Figure 4.2). In contrast, the two native rangeland sites increased relatively little in NO_3-N at all rates of LHM (Figure 4.2). Although ammonium-N showed no such rate by site effect in either year of sampling, the change in ammonium-N between sampling periods was significant ($p<0.05$; Table 4.6). There was a trend of declining NH_4-N, particularly at high rates of LHM application, with greater reductions appearing at higher rates on native sites (Figure 4.3).

Nitrate-N levels, but not ammonium-N, demonstrated significant method, and depth by method effects in the spring of 1999 prior to plant growth ($p<0.01$; Table 4.6). Soil nitrate was greater on injected rather than broadcast treatments in the surface 20 cm of soil (Table 4.7). This increase continued to be evident in April of 2000, one growing season later (Table 4.6; Table 4.7). In contrast, no differences in nitrate-N were observed among different application methods in either year at depths below 20 cm (Table 4.7).

Although no rate by method effect was found (Table 4.6), visual assessment of the nitrate data trends in relation to these factors suggested that an important difference might have occurred at the 80 $kg.ha^{-1}$-NH_4-N rate in April of 1999 when nitrate-N was greater following injection (Figure 4.4). The lack of a significant overall effect in 1999 is likely the result of the limited differences among treatments at the 160 $kg.ha^{-1}$-NH_4-N rate.

Although season of application had little impact on observed soil nitrogen levels, ammonium-N did respond to rate by season in April 1999 (Table 4.6), as did the change in soil ammonium-N from 1999 to 2000. Although, visual assessment of this interaction indicated that fall applied manure plots had less soil ammonium-N in April of 1999 than the spring treatments, but only at rates below 160 kg.ha^{-1}-NH_4-N (Figure 4.5). Changes in ammonium-N between years also exhibited a significant rate by season interaction ($p<0.001$, Table 4.6) with the greatest decline on fall-applied plots (Figure 4.5), validating the notion that the seasonal differences were treatment-caused and not spurious. With higher nutrient application rates, there is a greater potential for decline in soil nutrients.

4.4.2. Phosphate-P

Similar to nitrogen, soil phosphate-P responded significantly to different rates of LHM after application in 1998 and 1999 ($p<0.001$; Table 4.6). Increasing rates of LHM resulted in less extractable soil phosphate at and above 80 kg.ha^{-1}-NH_4-N (Table 4.8). A significant season effect on soil-P was also evident in 1999 ($p<0.05$; Table 4.6), with spring application resulting in greater levels of detectable phosphate-P than with application the previous fall, prior to plant growth (Table 4.8).

One year after LHM application, in April 2000, residual rate effects continued to be evident in soil phosphate-P, and were accompanied by a significant rate by season effect ($p<0.001$; Table 4.6, Figure 4.6). Examination of this interaction indicated that it was largely caused by contrasting phosphate-P levels between spring and fall treatments at the 40, 80, and 160 kg.ha^{-1}-NH_4-N rates (Table 4.6, Figure 4.6): fall applied LHM appeared to result in lower phosphate-P levels with the exception of 80 $kg.ha^{-1}$-NH_4-N. Changes in phosphate-P between 1999 and 2000 had significant rate, season and rate by season effects. Greater phosphate-P levels in 1999 were generally followed by a greater reduction in soil phosphate-P one year later (Figure 4.6).

Despite the absence of any significant rate by depth effects in 1999 and 2000, the change in soil phosphate-P between 1999 and 2000 was significantly affected by this interaction ($p<0.05$; Table 4.6). In the 0-20 cm soil depth, greater reductions in phosphate-P occurred at LHM rates below 80 $kg.ha^{-1}$-NH_4-N (Table 4.8). However, in the 20-40 cm depth, greater reductions were limited to intermediate LHM treatments (20 and 40 $kg.ha^{-1}$-NH_4-N). The lack of significant rate by depth effects in the two years of sampling and the fact that the only difference occurred at the lowest rate suggests this interaction may be spurious.

Although there was no significant effect on phosphate-P associated with different methods of LHM application, there was a significant interaction between method and site in 1999 ($p<0.05$, Table 4.6). On native sites, phosphate-P levels were generally greater within injected treatments. Phosphate-P levels on the injected and surface broadcast treatments were 0.19 and 0.18 $mg.kg^{-1}$ for the Fescue Grassland site, and 0.20 and 0.17 $mg.kg^{-1}$ for the Mixed Prairie site, respectively. Conversely, soil phosphate-P levels were greater within surface applied treatments on tame sites. Phosphate-P levels on the injected and surface broadcast treatments were 0.17 and 0.21 $mg.kg^{-1}$ for the meadow brome site and remained similar (0.19 $mg.kg^{-1}$) for the crested wheatgrass site.

4.4.3. Sulfate and Exchangeable Cations

At all sites but the meadow brome pasture, available sulfur (SO_4-S) was analyzed from all soil samples collected in April 1999. At the meadow brome site, preliminary analysis of samples from the 10, 40 and 160 kg.ha^{-1}-NH_4-N rates indicated sulfate was undetectable in all soil samples, and as a result, sulfate was not analyzed from the remaining treatments. No statistically significant differences were found among any of the main treatments or their interactions (Table 4.9), even with the omission of soil samples from the meadow brome site. The lack of significant results immediately after treatment precluded the need to assess residual sulfate levels in 2000.

Similar to sulfate-S, exchangeable cations (Ca, Mg, K, and Na) were analyzed and tested for statistical significance in 1999, with few significant differences due to treatments in any of the main treatment effects or their interactions. However, there was a significant site effect for exchangeable Mg, K, and Na and a significant depth effect for exchangeable Ca, Mg, K, and Na (Table 4.9), which are inherent soil characteristics. The lack of many initial significant differences once again eliminated the need for analysis of cations among treatments in 2000.

4.4.4. pH

Rate of LHM application significantly affected soil pH in 1999 following treatment ($p<0.05$, Table 4.10), with a trend towards maximum pH at intermediate LHM rates. For instance, pH at the 10, 20, 40, 80, and 160 kg.ha^{-1}-NH_4-N rates of application averaged 7.1, 6.9, 7.3, 6.9, and 7.0, respectively. There was also a significant three-way interaction in 1999 between application rate, method and season ($p<0.05$, Table 4.10).

This complex interaction appeared to be caused by increasing rates of LHM application, with differences among both methods and seasons of application (Figure 4.7). In general, pH increased more on fall applied manure treatments up to 40 kg.ha^{-1}-NH_4-N, and subsequently declined to levels similar to the spring treatments. The complex nature of the interaction and very irregular pattern of differences between different methods and seasons, however, suggests this 3-way interaction may be a spurious effect arising from natural variability in soil pH and limited sample sizes. In addition, it should be noted that the total amount of change in soil pH among all treatments was minimal, ranging from a minimum of 6.6 (at the spring-injected 80 and spring-surface 20 kg.ha^{-1}-NH_4-N rates) to a maximum of 7.4 (at the fall-surface 40 kg.ha^{-1}-NH_4-N rate) (Figure 4.7), which is similar to the low variability found during pre-treatment site testing (Table 4.1).

The rate effect observed pertaining to soil pH was only significant in 1999 (Table 4.10), whereas a rate by method effect was observed in April 2000 ($p<0.01$, Table 4.10). Given that there was only a main effect due to rate in 1999, it is difficult to explain why there would be an interaction between rate and method. Figure 4.8 indicates that this effect was attributable to an isolated difference between the injected and surface applied treatments at the lowest application rate of 10 kg.ha^{-1}-NH_4-N. Consequently, the true nature and importance of this effect is debatable.

4.4.5. Electrical Conductivity

Electrical conductivity (EC) showed few differences among treatments in both 1999 and 2000 (Table 4.10). In April 1999 following treatment, rate of LHM application significantly increased EC ($p<0.01$). With the exception of the 80 kg.ha^{-1}-NH_4-N treatment, EC generally increased with greater LHM to a peak at 160 $kg.ha^{-1}$-NH_4-N (Figure 4.9). The rate effect lasted only a single year, however, with negligible differences by the spring of 2000 (Table 4.10).

One additional effect observed in 2000, was a significant two-way interaction between the season of application and soil depth ($p<0.05$; Table 4.10). Examination of this interaction revealed the fall treatment had greater EC levels at shallow depths than spring treatments. For example, measured mean EC at the 20-40 cm interval was 2.9 $dS.m^{-1}$ (SE 0.4) among the fall treatments, but averaged 2.0 $dS.m^{-1}$ (SE 0.2) with spring application. In the 0-20 cm soil interval, EC was lower but similar for both seasons (1.2 $dS.m^{-1}$ for fall and 1.3 $dS.m^{-1}$ for spring).

4.4.6. Heavy Metals – Manganese (Mn) and Cadmium (Cd)

While the abundance of several heavy metals of potential concern was quantified in the soil samples collected in April 1999, there were few that exhibited significant treatment effects. Of those examined, cadmium and manganese were the only two that displayed statistically significant treatment or interaction responses. It should be noted that in 1999, there was a significant method by season interaction for both elements ($p<0.05$, Table 4.11). Assessment of these results suggested that surface application in the fall resulted in lower cadmium and manganese levels than any other treatment combination (Table 4.11).

Manganese similarly demonstrated significant method ($p<0.01$, Table 4.11), as well as season by method interaction effects ($p<0.05$, Table 4.9). The significant method effect arose from less manganese within surface applied LHM plots; while the interaction indicates the discrepancy between injected and surface treatments was evident only on plots treated in the fall (Table 4.11). Manganese was further influenced by a significant rate by method interaction (*$p<0.01$*, Figure 4.10). Mean manganese concentrations were greater for injected treatments than surface applied plots, for both spring and fall applied LHM. A significant rate by season interaction also occurred for manganese (*$p<0.01$*, Figure 4.10). Mean soil-Mn levels tended to be greater on spring-applied treatments, but only on the 40 and 160 kg.ha^{-1}-NH_4-N rates.

4.5. Discussion

4.5.1. Ammonium and Nitrate

As the rate of LHM application increased, there was a linear increase in soil inorganic-N. This is consistent with both manure application studies and fertilizer trials (Schmidt et al. 2000; Lowrance et al. 1998; Sanderson and Jones 1997; Ledgard et al. 1996; Westerman et al. 1987). Despite the semi-arid conditions of the study area, plant growth appeared to have depleted NO_3-N and NH_4-N after one year's growth, with no carryover. This relatively rapid depletion may be partially due to favorable plant growth during the first growing season following LHM application. In a parallel investigation, increasing rate of LHM application increased plant biomass yield, crude protein content, and crude protein yield at all four sites (Mixed Prairie, Fescue Grassland, Crested Wheat, and Meadow Brome) during the first growing season (summer of 1999) following LHM applications (Blonski 2001). In addition, Blonski (2001) noted a carryover effect into the second growing season (summer 2000), which was limited to increased plant crude protein yield at the highest rate of LHM application on all four sites. These effects account for a large portion of the N removed from the soil after supplementation via LHM application. There may have also been the potential for immobilization, especially on the two native sites, which may have well-developed microbial populations capable of rapidly sequestering nutrients during periods of abundance (Dormaar and Willms 2000b).

Inorganic nitrogen did not move into lower soil depths (e.g.: 0-20 cm *vs.* 20-40 cm) immediately after application, except at the highest rate of LHM (e.g.: 160 $kg.ha^{-1}$-NH_4-N). Despite abnormal rainfall in 1999 (58% above average), there was also no incremental increase in inorganic-N at the deeper soil depth (20-40 cm) over the two years of the study, indicating there appears to be minimal risk of ground water contamination following one time LHM application.

Variable rate effects among sites may be due to greater organic matter and microbial biomass within the native sites that would rapidly monopolize and immobilize excess nitrogen. This pattern is consistent with studies done by Dormaar and Willms (2000a, 2000b, 1990) and Dormaar et al. (1995). Changes in detectable soil ammonium were different over the two years of the study, with the greatest reduction on the native sites. Variation in soil texture (e.g.: NH_4^+ can bind to clay, hence soils with higher clay content may fix some ammonium) and organic matter content among sites (Table 4.1), and/or microbial immobilization may collectively contribute to the observed differences. Although it appears that the native rangelands examined are equally capable of rapidly utilizing the N contained in the LHM, even at high rates, the decision to apply manure to these areas should take into account other factors as well, including impacts on the plant community.

The use of injection increased soil N, particularly nitrate-N, but only at shallow depths. Further examination of this effect indicated that while there were weak positive responses in soil NO_3-N and NH_4-N at all LHM application rates, the single greatest response occurred at 80 $kg.ha^{-1}$ NH_4-N. The lack of a response at the highest rate may be because, at the time of application, all injected treatments at the 160 $kg.ha^{-1}$ rate experienced some spillover of LHM onto the ground surface. That is, the high volume of LHM being injected exceeded the coulter furrow size and soil hydraulic conductivity, causing some LHM to flow onto the ground surface before infiltration. This process mimicked the behavior of LHM on surface applied treatments, which may have led to increased volatilization of ammonia, and may partly account for the similar N-levels among methods at the160 $kg.ha^{-1}$ rate. Decreasing LHM application volumes or increasing coulter depth could alleviate problems associated with nitrogen loss.

Another possible reason for the lack of a difference between methods at the highest application rate could be due to plant N uptake. By mimicking surface applied treatments, the injected high rate treatment may have experienced more rapid N use by vegetation. That is, range and pasture vegetation typically has a greater concentration of fine roots in the soil layer nearest to the surface, which could enhance the uptake of nitrogen near the soil surface. Fine roots were removed from the soil samples upon sieve preparation for lab analysis. At the injected 160 $kg.ha^{-1}$ rate, rapid uptake by roots at the surface would reduce the difference in N between injected and surface applied treatments (Dormaar et al 1995; Coupland and Johnson 1965). Overall, these results suggest that the use of injection when applying LHM at 80 $kg.ha^{-1}$-NH_4-N could convey potential NO_3-N savings of approximately 5.5 kg-$N.ha^{-1}$ within the soil (to a depth of 40 cm, assuming an average soil bulk density of 1.25 $Mg.m^{-3}$). This savings translates to approximately $0.84.$ha^{-1}$ at the 80 $kg.ha^{-1}$-NH_4-N rate, assuming N-fertilizer (46-0-0) valued at $300.$Mg^{-1}$.

Residual-N effects from injection were evident in 2000. One year after LHM application there was still a residual positive effect of injection on soil nitrate-N. This occurred despite favorable plant growth the previous year. Based on soil inorganic-N levels, injection of LHM could be recommended because of a limited, but non-detrimental, carryover of available-N one growing season after supplemental nitrogen additions from LHM application.

Season of LHM application had no effect on soil NO_3-N, but did have an effect on ammonium-N, which was generally lower in April 1999 on fall-applied treatments at all rates except 160 $kg.ha^{-1}$-NH_4-N. The reduction at rates below 160 $kg.ha^{-1}$-NH_4-N was likely due to nitrification during the late fall and winter. No simple explanation exists for the unexpected response at the 160 $kg.ha^{-1}$ rate, where the fall treatment was visibly greater, but not statistically. Although this could be interpreted as a chance effect, this is doubtful because of the greater associated decrease in soil ammonium over the following year on this treatment. The lack of an overall season effect indicates LHM application can be conducted at either time period.

4.5.2. Phosphate-P

Mean soil phosphate levels were greatest on plots treated at the 20 and 40 $kg.ha^{-1}$ rates. This occurred in both the fall and spring treatments, with overall levels generally greater on spring treatments. This is likely due to mineralization, immobilization, or plant uptake on fall applied LHM treatments. The non-linear results may be due to sequestration by microbial populations or root absorption. At higher rates of LHM microbial populations or roots may assimilate more available-P due to the additional nitrogen and greater associated plant growth, although this may not occur immediately following application. At intermediate application rates, plant growth may not be sufficiently altered to trigger P assimilation (Dormaar and Willms 2000b).

There was also a significant interaction between method and site, with greater phosphate levels apparent on the tame plots that received surface applied LHM. This difference could be due to two factors, the first being nutrient placement and rhizosphere proximity, and the second, plant adaptations to nutrient availability. Plants cannot utilize nutrients that they cannot reach. LHM that is surface applied on tame pastures may be less accessible to plant roots for uptake because these areas include more bare soil with no established plants (Table 4.2). In addition, native plant systems have been found to possess larger and better-distributed root systems (Coupland and Johnson 1965) that can capitalize on and store nutrients such as phosphate during periods of relative surplus (Black and Wight 1979). In the event that LHM containing even higher levels of phosphate are applied to range or pasture in the future, it may be advisable to use injection methods in order to take advantage of the rhizospheric capabilities of these agro-ecosystems.

The LHM applied in this study contained little organic matter due to the method of removal from the lagoon and lack of prior agitation. Consequently, the LHM contained little associated organic-P, a nutrient of typical concern when LHM is applied to land. Instead, the main form of phosphorus in the manure was inorganic orthophosphate. It should also be noted that although the amount of phosphate as applied in this experiment was detectable, the observed levels were low enough not to be of agronomic importance or environmental concern. The low levels of phosphate-P detected in post-treatment sampled soils may also be due to the method of determination used, that being 2M KCl solution, which would only determine water-soluble phosphorus, whereas most commercial soil lab tests would determine extractable-P. It should be noted that pre-treatment soil analysis methods determined extractable-P, rather than water-soluble P. Nonetheless, the amount of P added in the LHM used was low due to non-agitation of the lagoon before LHM removal for treatment applications, leaving NH_4-N as the land-limiting constituent in this study.

4.5.3. Sulfate and Exchangeable Cations

Since there were no important statistical findings to illustrate any significant main or interaction treatment effects for rate, method, or season, based upon the samples taken in 1999, analyses for sulfate or exchangeable cations was unwarranted in 2000, especially due to the fact the amounts of sulfate and cations applied in the LHM were low, and insufficient to cause changes in the soil. Thus, analyses were not conducted on any samples from the April 2000 sampling period.

The lack of significant treatment or interaction effects is not surprising as the LHM used in this study contained low amounts of these constituents. It should be noted that a frequent concern regarding manure application is the potential accumulation of associated salts (Tisdale et al. 1993). Hence, it is advisable to take manure samples and have them tested in order to determine the soil's nutrient status and determine the land-limiting constituents (Gangbazo et al. 1995b) of any parcel of land to receive LHM, and apply accordingly. Under the conditions of this investigation it appears sulfate and/or exchangeable cations would not be the limiting constituents when determining guidelines for LHM application to these forage lands, at least for one or a few applications.

4.5.4. pH

Changes in soil pH following LHM application are a frequent concern to producers, as they may limit or alter plant growth (AAFRD 1996). Although soil pH demonstrated a significant rate effect and a rate by method by season interaction in 1999 following application, as well as a significant rate by method effect in 2000, pH levels did not show any drastic changes. Following application of LHM, pH levels varied only slightly (e.g.: 6.7-7.3), with the most extreme values occurring on treatments that received intermediate rates of LHM. These findings suggest the significant effects, particularly those of the more complex interactions, may be questionable.

Perhaps more importantly, the observed pH values were within the pH range typically considered neutral to plant growth (pH=6.5-7.5) (Tisdale et al. 1993; AAFRD 1996) and therefore pose no threat to reducing production or causing dissociation of heavy metals that may be found within soil complexes (pH<5.5 needed). As a result, the significant effects detected are of limited biological and/or agronomic significance, and may simply reflect high natural variability throughout the research sites and limited overall plot sample sizes. Problems with determining natural pH levels may have been alleviated by increasing sample numbers. Given that the observed pH levels stayed relatively neutral (even at our highest rate of application), soil pH should not create any serious problems following one-time LHM application on forage lands. In the event that repeated or successive applications are carried out on the same area or higher rates used, it would be prudent to carefully monitor pH levels with routine soil testing.

4.5.5. Electrical Conductivity

Similar to pH, changes in soil electrical conductivity (EC) can be a concern following the application of LHM, as they may create conditions that restrict plant growth. At soil depths between 0-60 cm soils with EC< 2 $dS.m^{-1}$ are non-saline, while soils with electrical conductivities of 2-4, 4-8, 8-16, and >16 $dS.m^{-1}$ are considered weakly, moderately, strongly, and very strongly saline, respectively (AAFRD 2001). The increase in EC on higher application rates may have been due to small additions of salts in the LHM or from added NH_4^+, particularly within the upper layer of soil (0-20 cm).

4.5.6. Heavy Metals – Manganese (Mn) and Cadmium (Cd)

There are several possible explanations for the relatively lower metal (Cd and Mn) concentrations found on surface applied LHM plots within the fall treatments. Compared to spring application, fall application of LHM may provide a temporal window for assimilation of metal ions into soil complexes rendering the metals less available. This is because adsorption or precipitation of metals in soils and uptake by roots limits the translocation to shoots [for most metals] and phytotoxicity from Zn, Cu, or Ni, thereby limiting metal residues in plant shoots to levels chronically tolerated by livestock and humans (Chaney 1994). The LHM that was applied contained 0.54 $mg.L^{-1}$ (ppm) of manganese and <0.0025 $mg.L^{-1}$ (ppm) of cadmium. The average soil-Mn level from all four sites was 440 ug.kg^{-1}-soil (ppb), and ranged from 313-653 ug.kg^{-1}-soil (ppb); while the average soil-Cd was 0.3 ug.kg^{-1}-soil, and ranged from 0.1-0.6 ug.kg^{-1}-soil.

Soils are considered manganese-deficient when levels are below 4 mg.kg^{-1}, levels between 9-12 mg.kg^{-1} are considered adequate, and levels above 30 mg.kg^{-1} are considered high (AAFRD 1998). The Canadian Council for Ministers of the Environment (CCME) Canadian Environmental Quality Guidelines (2002) state that soils used for agricultural purposes should not have soil cadmium levels that exceed 1.4 mg.kg^{-1}. Metals are particularly likely to be bound to the small amount of organic matter contained in the LHM used for this study. Such organic colloids would bond readily with soil colloids or clay particles (Tisdale et al. 1993). Another explanation is that surface application, especially in conjunction with the fall period, may not allow LHM to enter the soil leaving organic particles stranded at or near the soil surface and unable to make effective contact, where they may be more vulnerable to removal via runoff following episodes of precipitation or snowmelt. Plant removal and uptake of metals may also occur in the area highly concentrated with fine roots.

4.6. Management Implications and Conclusions

With the current expansion of confinement hog production into semi-arid areas of Alberta, especially into areas where cultivated lands, the traditional sink for LHM, do not occur in abundance, alternative management methods must be examined. The application of LHM to adjacent forage lands appears to be one suitable method of managing the large volume of waste accrued via intensive hog production. Based on the results of this study, a one-time application of LHM to forage lands seems feasible, as there were no detrimental effects found. Application of LHM to such nearby forage lands can provide affordable and convenient management options for hog producers while also providing nutrient supplements for forage production. Injection of LHM serves to conserve nutrients and may reduce odors associated with nutrients contained within the LHM, due to greater soil-LHM contact because of placement within the soil. This certainly seems to be a favorable option compared with conventional land spreading of LHM with splash plate applicators on tanker trucks. Injection or low agitation surface application would likely not only serve to reduce odors at application time, but would allow producers greater consistency and control over the application of LHM. In addition, producers would be afforded more consistent monitoring of nutrient status on pastures receiving supplemental nutrients from LHM application. Because of the large permanent land base of forage lands near hog production facilities in SE Alberta, the integration of hog production and range and pasture management is feasible. A large land base would provide greater options regarding the timing, frequency, and rates of application. While there is always a concern when nutrients are applied to native range, due the concern with encroachment by undesirable plant species in the presence of excess nutrients, there are still many areas with tame pastures to accommodate manure disposal. Infrequent or consistent rotational applications of LHM at relatively low rates over large areas of perennial forage land may be the best option to prevent or reduce any negative effects that may be caused by nutrient or manure applications to agro-ecosystems. Lower application rates and reduced agitation may also serve to reduce or accommodate social concerns about intensive livestock production. Integrated hog production and range and pasture management in conjunction with public acceptance may be possible. In regard to this study, reapplication is also warranted, as long as land-limiting constituents are not exceeded. Finally, this study showed that the use of injection equipment is an agronomically and physically feasible option for application of LHM, even on native prairie or tame pasture. However, methods that require reduced energy requirements for injection may be necessary in order to be economically feasible.

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Table 4.1: Mean (SD) soil characteristics in the 0-20cm depth for each of the native and tame sites as sampled in September 1998, prior to manure application.

	Sites			
	Native Rangeland		**Tame Pasture**	
Constituent	**Xeric Mixed Prairie: Dark Brown Chernozem (n=5)**	**Mesic Fescue Grassland: Black Chernozem (n=5)**	**Xeric Crested Wheat: Dark Brown Chernozem (n=5)**	**Mesic Meadow Brome: Dark Brown Chernozem (n=5)**
[1] **NH_4-N***	1.22 (0.72)	1.26 (0.54)	1.52 (0.77)	1.14 (0.37)
[2] **NO_3-N***	0.72 (0.66)	0.22 (0.22)	2.96 (2.15)	2.94 (1.11)
[2] **PO_4-P***	2.4 (0.6)	3.6 (0.9)	9.0 (2.6)	9.0 (2.8)
[2] **K***	471 (60)	334 (64)	337 (96)	213 (93)
[3] **SO_4-S***	9.98 (9.78)	4.24 (1.61)	5.04 (2.57)	2.48 (0.80)
[4] **Exch. Ca****	8.0 (3.51)	8.46 (2.19)	10.8 (5.52)	8.46 (2.63)
[4] **Exch. Mg****	3.44 (0.79)	3.24 (1.39)	4.02 (1.40)	1.44 (0.54)
[4] **Exch. Na****	0.44 (0.67)	0.12 (0.07)	0.84 (0.67)	<0.1 (0)
[4] **Exch. K****	0.89 (0.13)	0.69 (0.14)	0.64 (0.20)	0.47 (0.22)
[5] **E.C. (dS.m^{-1})**	0.34 (0.16)	0.12 (0.03)	0.56 (0.41)	0.13 (0.022)
[5] **pH**	6.6 (0.2)	6.3 (0.2)	7.0 (0.7)	6.6 (0.2)
[6] **O.M. %**	3.86 (0.67)	4.94 (1.22)	3.22 (0.82)	3.22 (0.97)
[7] **Db*****	1.28 (0.04)	1.09 (0.03)	1.28 (0.08)	1.28 (0.14)
[8] **Total Sand %**	50.8 (1.3)	45.0 (0.6)	49.2 (0.9)	62.4 (0.2)
[8] **Total Silt %**	29.9 (1.2)	38.3 (0.6)	29.4 (1.1)	20.4 (0.2)
[8] **Total Clay %**	19.3 (0.4)	16.7 (0.1)	21.5 (0.9)	17.2 (0.0)

[1] Extractable by 2M Potassium Chloride Solution (McKeague 1978)

[2] Extractable by Modified Kelowna Extract (Ashworth and Mrazek 1995)

[3] Extractable by 0.001M Calcium Chloride Solution (McKeague 1978)

[4] Exchangeable by Ammonium Acetate at pH 7.0 (McKeague 1978)

[5] 1:2 Soil:Water Method (McKeague 1978)

[6] Organic Matter by Loss on Ignition (McKeague 1978)

[7] Bulk Density for mineral soils, cores taken with powered core sampler, corrected for coarse fragments (McKeague 1978).

[8] Particle Size Analysis using the Hydrometer Method (McKeague 1978).

* Units are mg.kg^{-1}

** Units are meq.100g^{-1}

*** Units are Mg.m^{-3}

Table 4.2: Mean canopy cover percent (± SE) for the dominant plant species present on native rangeland and tame pasture sites as sampled in July and August of 1999. Adapted from (Blonski 2001).

		Native Range		Tame Pasture	
Growth Form and Species Name	**Scientific Name**	**Mixed Prairie**	**Fescue Grassland**	**Crested Wheat**	**Meadow Brome**
Graminoids					
Crested Wheatgrass	*Agropyron cristatum* (L.) Gaertn.	-	-	56.4 (8.8)	5.2 (3.1)
Russian Wildrye	*Elymus junceus* Fisch.	-	-	3.4 (2.6)	-
Meadow Brome	*Bromus biebersteinii* Roem & Schult	-	-	-	17.8 (4.5)
Wheatgrass spp.	*Agropyron* spp.	0.6 (0.3)	0.4 (0.9)	-	1.0 (1.4)
Junegrass	*Koeleria macrantha* (Ledeb.) J.A. Schultes f.	11.2 (3.2)	0.2 (0.4)	-	-
Needle and Thread	*Stipa comata* Trin. & Rupr.	5.7 (6.4)	-	-	-
Western Porcupine Grass	*Stipa curtiseta* (A.S. Hitchc.) Barkworth	5.5 (6.8)	4.2 (2.3)	-	-
Plains Rough Fescue	*Festuca hallii* (Vassey) Piper.	3.7 (5.4)	42.5 (6.7)	-	-
Blue Grama	*Bouteloua gracilis* (HBK) Lag.	1.6 (1.0)	0.03 (0.1)	-	-
Hooker's Oatgrass	*Helictotrichon hookerii* (Scribn.) Henr.	3.7 (3.8)	1.5 (1.4)	-	-
Western Wheatgrass	*Agropyron smithii* Rydb.	4.3 (3.7)	1.0 (1.0)	-	-
Sedge spp	*Carex* spp.	13.5 (3.6)	7.5 (3.6)	-	-
Forbs					
Alfalfa	*Medicago sativa* L.	-	-	15.6 (8.6)	59.4 (8.6)
Common Peppergrass	*Lepidum densiflorum* Schrad.	-	-	0.9 (0.9)	2.8 (1.4)
Wild Buckwheat	*Polygonum convolvulus* L.	-	-	-	2.1 (1.7)
Cut-leaved Anemone	*Anemone multifida* Poir.	5.8 (2.3)	1.1 (0.9)	-	-
Low Goldenrod	*Solidago missouriensis* Nutt.	0.6 (0.9)	0.5 (0.5)	-	-
Ascending Purple Milk Vetch	*Astragalus striatus* Nutt.	0.4 (0.7)	-	-	-
Mallow	*Sphaeralcea coccinea* (Pursh.) Rydb.	1.0 (0.7)	-	-	-
Common Yarrow	*Achillea millefolium* L.	0.1 (0.4)	1.8 (2.3)	-	-
American Vetch	*Vicia Americana* Muhl.	-	3.0 (2.8)	-	-
Slender Milk Vetch	*Astragalus flexuosus* Dougl. *Ex* G.Don	1.2 (1.3)	1.2 (0.2)	-	-
Shrubs					
Pasture Sage	*Artemisia frigida* Willd.	10.2 (4.4)	0.7 (0.9)	-	-
Prairie Rose	*Rosa arkansana* Porter	0.03 (0.2)	1.3 (1.8)		
Litter		81.3 (5.7)	99.5 (0.8)	87.8 (7.0)	78.7 (6.4)
Bare Soil		0.3 (0.3)	0	10.7 (7.3)	19.7 (6.5)

Table 4.3: Target and Actual LHM Application Rates and Associated Water Depth Equivalents for Fall and Spring Applications.

Season & Target Application Rate ($kg.ha^{-1}$ –NH_4-N)		Actual Application Rate ($kg.ha^{-1}$ NH_4-N)	LHM Application Rate Volumes ($L.ha^{-1}$)	Calculated Water Depth Equivalent (mm)
Fall	**10**[1]	9.3	13 000	1.3
	20	18.6	13 000	1.3
	40	37.1	27 000	2.7
	80	74.2	53 000	5.3
	160	148.4	107 000	10.7
Spring	**10**[1]	9.5	11 000	1.1
	20	19.0	11 000	1.1
	40	37.9	21 000	2.1
	80	75.8	42 000	4.2
	160	151.6	84 000	8.4

[1] Water Depth Equivalents and Application Rate Volumes for the 10 and 20 rates ($kg.ha^{-1}$- NH_4-N) are the same because the Target Application Rate of 10 ($kg.ha^{-1}$- NH_4-N) was achieved by mixing LHM and water at a 1:1 ratio.

Table 4.4: Results of the manure analysis during application by truckload (n=7), October 1998.

Constituent	Mean $(SD)_{1-6}$	$Min._{1-6}$	$Max._{1-6}$	Sample 7*
[1] **Moisture %**	99.37 (0.03)	99.33	99.41	99.78
[3] **NH_4-N %**	0.17 (0.01)	0.17	0.19	0.073
[3] **NO_3-N %**	<0.01 (0.00)	<0.01	<0.01	<0.01
[2] **Kjeldahl N %**	0.18 (0.01)	0.18	0.18	0.08
[2] **Organic N %**	0.01 (0.01)	0.001	0.014	0.007
[4] **Total K %**	0.10 (0.00)	0.093	0.10	0.035
[4] **Total P %**	0.04 (0.01)	0.03	0.04	0.02
[3] **SO_4-S %**	0.01 (0.00)	0.004	0.006	0.004
[4] **Ca %**	0.02 (0.00)	0.02	0.02	0.01
[4] **Mg %**	0.004 (0.00)	0.003	0.004	0.002
[4] **Na %**	0.05 (0.00)	0.05	0.05	0.02
[5] **pH**	7.40 (0.05)	7.4	7.5	7.6
[6] **EC ($dS.m^{-1}$)**	14.65 (0.14)	14.5	14.9	6.8

*Sample 7 was diluted with water to reduce the manure concentration for treatments receiving LHM at 10 $kg.ha^{-1}$, as this low rate could not be achieved through normal operating conditions.

[1] Samples dried at 104 °C for 3 hours (Gardner 1986).

[2] Nitrogen determinations by Kjeldahl (Strong Acid Block Digestion) (Keeney and Bremner 1966)

[3] Extracted with a weak $CaCl_2$ solution (0.001 M) mixed with KCl (100 ppm K) (Maynard and Kalra 1993).

[4] Samples taken to dryness, ashed, then digested with HCl, and then read by ICP (Metals in Plants 1990)

[5] pH electrode used directly on sample (McKeague 1978)

[6] EC electrode used directly on sample (Rhoades 1982)

Table 4.5: Results of the manure analysis during application by truckload (n=7), April 1999.

Constituent	Mean (SD)$_{1\text{-}6}$	Min.$_{1\text{-}6}$	Max.$_{1\text{-}6}$	Sample 7*
[1] **Moisture %**	99.34 (0.06)	99.30	99.46	99.76
[3] **NH_4-N %**	0.21 (0.00)	0.21	0.21	0.10
[3] **NO_3-N %**	0.01 (0.00)	0.01	0.01	<0.01
[2] **Kjeldahl N %**	0.23 (0.01)	0.22	0.23	0.10
[2] **Organic N %**	0.01 (0.01)	0.01	0.02	0.00
[4] **Total K %**	0.11 (0.00)	0.11	0.12	0.05
[4] **Total P %**	0.03 (0.01)	0.02	0.03	0.01
[3] **SO_4-S %**	<0.01 (0.00)	<0.01	<0.01	<0.01
[4] **Ca %**	0.01 (0.00)	0.01	0.01	0.01
[4] **Mg %**	<0.01 (0.00)	<0.01	<0.01	<0.01
[4] **Na %**	0.04 (0.00)	0.04	0.04	0.02
[5] **pH**	7.67 (0.05)	7.60	7.70	7.80
[6] **EC (dS.m^{-1})**	17.62 (0.10)	17.50	17.70	8.87

*Sample 7 was diluted with water to reduce the manure concentration for treatments receiving LHM at 10 kg.ha^{-1}, as this low rate could not be achieved through normal operating conditions.

[1] Samples dried at 104 °C for 3 hours (Gardner 1986).

[2] Nitrogen determinations by Kjeldahl (Strong Acid Block Digestion) (Keeney and Bremner 1966)

[3] Extracted with a weak $CaCl_2$ solution (0.001 M) mixed with KCl (100 ppm K) (Maynard and Kalra 1993).

[4] Samples taken to dryness, ashed, then digested with HCl, and then read by ICP (Metals in Plants 1990)

[5] pH electrode used directly on sample (McKeague 1978)

[6] EC electrode used directly on sample (Rhoades 1982)

Table 4.6: Summary of F-values[1] for soil NO_3-N, NH_4-N, and PO_4-P in April 1999 and 2000, as well as the change in each from 1999 to 2000 for LHM treatments conducted in October 1998 and April 1999.

Factor	NO_3-N 1999	NO_3-N 2000	NO_3-N 2000-'99	NH_4-N 1999	NH_4-N 2000	NH_4-N 2000-'99	PO_4-P 1999	PO_4-P 2000	PO_4-P 2000-'99
Season	0.37	0.76	0.05	0.06	0.93	0.35	5.09*	1.70	5.75*
Rate	12.26***	0.95	12.42***	18.60***	0.99	14.94***	8.98***	6.25***	12.50***
Method	8.56**	6.41**	3.36	3.24	0.00	3.00	0.48	0.41	0.85
Site	14.06***	13.48***	10.61***	7.94***	1.50	8.96***	0.39	0.52	0.10
Rate*Method	1.05	0.73	0.76	1.00	0.47	0.94	1.77	2.04	1.08
Rate*Season	0.10	1.94	0.52	2.93*	1.23	3.86***	0.70	6.02***	2.48*
Method*Season	0.12	1.20	0.03	2.81	0.45	1.94	1.18	0.13	0.16
Rate*Method*Season	0.08	1.33	0.30	0.75	1.18	1.46	2.22	0.64	0.29
Error 1 *[S*R*M(Site)]*									
Depth	68.92***	62.37***	15.07***	58.60***	124.53***	23.32***	4.04*	0.99	5.12*
	4.75**	0.72	3.70***	6.86***	1.47	5.50***	1.69	2.03	2.81*
Depth*Rate	8.49**	5.50*	2.54	3.36	0.75	2.57	0.01	1.59	0.91
Depth*Method	2.48	0.42	1.43	0.30	0.64	0.12	0.41	0.99	1.43
Depth*Season	0.95	0.39	1.12	0.35	0.72	0.41	1.45	1.14	1.06
Depth*Rate*Method	0.62	1.64	0.65	0.35	0.67	0.51	0.49	1.04	1.18
Depth*Rate*Season	0.61	0.87	0.07	0.75	0.03	0.66	1.71	0.75	0.18
Depth*Method*Season	0.85	0.49	1.24	0.07	0.86	0.20	0.80	0.41	0.48
Depth*Rate*Method*Season									
Error 2									
Method*Site[2]	0.63	0.49	1.24	0.97	0.51	0.57	2.84*	0.06	0.80
Rate*Site[2]	3.38**	0.45	3.98***	1.83	0.53	2.05*	0.65	0.68	0.58

[1] *, **, *** Indicates significant F-values at $p<0.05$, $p<0.01$, and $p<0.001$, respectively.

[2] Tests for Method by Site and Rate by Site were made by incorporating these single interactions into the model one at a time and testing against Error 1.

Table 4.7: Measured mean soil NO_3-N levels in mg.kg^{-1} soil for depth, and depth by method for the April 1999 and 2000 sampling periods.

		Method of LHM Application			
Sampling Time	**Depth**	**Injected**	**Surface**	**Pooled SE**	**Grand Mean**
April 1999	0-20 cm	11.09^{a1}	6.87^{b}	0.72	**8.98^{A2}**
	20-40 cm	3.00^{c}	2.98^{c}	0.72	**2.99^{B}**
April 2000	0-20 cm	6.05^{a}	4.28^{b}	0.40	**5.17^{A}**
	20-40 cm	1.99^{c}	2.08^{c}	0.40	**2.03^{B}**

[1] Within a year, Depth by Method means with different lower case letters differ significantly at $p<0.01$.

[2] Within a year, grand means for each sampling depth with different upper case letters differ significantly at $p<0.001$.

Table 4.8: Measured mean PO_4-P levels in $mg.kg^{-1}$ soil for different rates, seasons, rate by season combinations as sampled in April 1999 and changes in soil PO_4-P levels among different rates, soil depths, and rate by depth combinations from 1999 to 2000.

			Rate of LHM Application					
Sampling Date	**Factor**	**Level**	**10**	**20**	**40**	**80**	**160**	**Grand Mean^2**
April 1999	**Season**	Fall	0.19^{ab1}	0.20^{ab}	0.20^{ab}	0.13^{b}	0.14^{b}	**0.17^{A}**
		Spring	0.21^{ab}	0.24^{a}	0.24^{a}	0.17^{ab}	0.13^{b}	**0.20^{B}**
		Grand Mean^2	**0.19^{AB}**	**0.22^{A}**	**0.22^{A}**	**0.15^{BC}**	**0.14^{C}**	
April 1999 to April 2000	**Depth**	0-20 cm	-0.12^{cd1}	-0.12^{cd}	-0.14^{d}	-0.02^{ad}	-0.01^{ac}	**-0.08^{A}**
		20-40 cm	0.02^{a}	-0.14^{e}	-0.15^{e}	0.05^{a}	0.004^{ab}	**-0.04^{B}**
		Grand Mean^2	**-0.04^{A}**	**-0.13^{B}**	**-0.15^{B}**	**0.01^{A}**	**-0.003^{A}**	

[1] Within each of Season by Rate and Depth by Rate, those means with different lower case letters differ significantly at $p<0.05$.

[2] Within each of Season, Depth, or Rate, grand means with different upper case letters differ significantly at $p<0.05$.

Table 4.9: Summary of F-values[1] for exchangeable Ca, Mg, K, Na, and SO_4-S in April 1999 for LHM treatments conducted in October 1998 and April 1999.

Factor	Ca^{2+}	Mg^{2+}	K^+	Na^+	SO_4-S
Season	0.65	3.08	0.14	1.16	0.95
Rate	1.71	1.50	1.09	0.30	1.57
Method	0.68	0.58	0.01	0.29	0.65
Site	1.94	25.82***	54.19***	58.58***	2.41
Rate*Method	1.27	0.77	0.26	1.58	0.69
Rate*Season	1.32	0.44	0.65	0.48	0.94
Method*Season	0.29	0.94	1.37	1.11	0.20
Rate*Method*Season	0.98	0.91	0.11	1.47	0.60
Error 1 [S*R*M(Site)]					
Depth	50.70***	49.46***	57.90***	50.21***	8.54**
Depth*Rate	0.17	0.21	0.71	0.64	0.41
Depth*Method	0.56	0.06	0.57	0.00	0.08
Depth*Season	0.85	2.46	2.65	0.00	0.02
Depth*Rate*Method	1.06	0.65	2.18	0.41	1.35
Depth*Rate*Season	1.30	0.50	0.98	0.43	0.71
Depth*Method*Season	0.00	0.03	1.57	0.29	0.30
Depth*Rate*Method*Season	1.07	1.31	0.66	0.22	1.84
Error 2					
Method*Site[2]	0.88	0.74	2.00	1.10	1.30
Rate*Site[2]	0.62	0.90	0.79	0.47	0.63

[1] *, **, *** Indicates significant F-values at $p<0.05$, $p<0.01$, and $p<0.001$, respectively

[2] Tests for Method by Site and Rate by Site were made by incorporating these single interactions into the model one at a time and testing against Error 1.

Table 4.10: Summary of F-values[1] for soil electrical conductivity (EC) and pH in April 1999 and 2000, as well as the change in each from 1999 to 2000 for LHM treatments conducted in October 1998 and April 1999.

Factor	**EC 1999**	**EC 2000**	**EC 2000-'99**	**pH 1999**	**pH 2000**	**pH 2000-'99**
Season	1.77	2.69	0.00	0.30	0.15	0.01
Rate	3.98**	0.83	1.02	3.02*	2.02	0.80
Method	0.34	1.05	1.09	0.42	0.03	0.11
Site	11.48***	11.83***	11.16***	19.30***	19.62***	22.63***
Rate*Method	0.67	1.79	0.41	1.91	4.34**	0.71
Rate*Season	0.42	0.49	0.73	1.35	0.53	1.03
Method*Season	0.16	0.86	0.06	0.26	0.08	0.03
Rate*Method*Season	0.71	0.56	1.02	2.99*	2.37	0.32
Error 1 *[S*R*M(Site)]*						
Depth	23.02***	24.76***	1.47	106.40***	103.49***	1.17
Depth*Rate	0.85	1.73	0.22	0.31	0.70	0.23
Depth*Method	0.18	0.87	0.65	0.53	0.08	0.06
Depth*Season	0.50	4.30*	0.26	0.09	0.01	0.07
Depth*Rate*Method	0.58	0.22	0.45	0.82	1.28	0.90
Depth*Rate*Season	1.22	1.08	1.47	0.47	1.38	1.27
Depth*Method*Season	0.31	0.14	0.39	1.93	0.20	1.49
Depth*Rate*Method*Season	1.39	0.18	1.00	0.77	0.76	0.77
Error 2						
Method*Site[2]	0.96	2.24	1.51	0.92	0.26	1.04
Rate*Site[2]	1.03	1.03	0.75	0.67	0.50	0.54

[1] *, **, *** Indicates significant F-values at $p<0.05$, $p<0.01$, and $p<0.001$, respectively

[2] Tests for Method by Site and Rate by Site were made by incorporating these single interactions into the model one at a time and testing against Error 1.

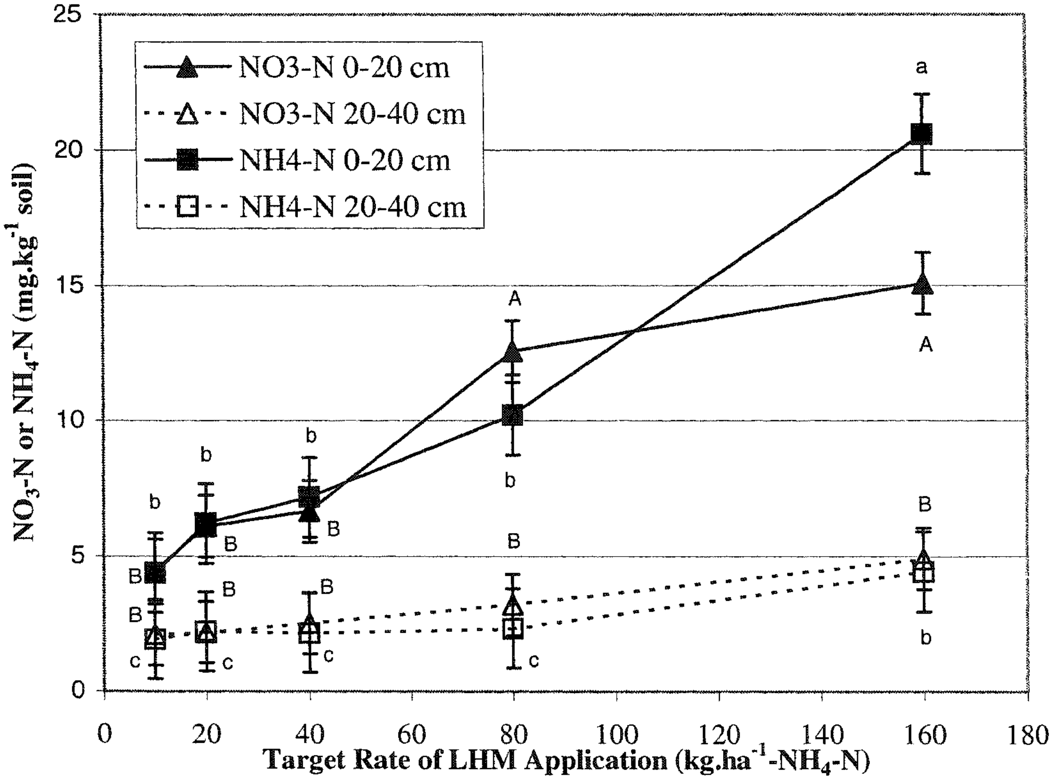
Table 4.11: Measured mean soil manganese (Mn) and cadmium (Cd) levels for season by method and method (Mn only) in ug.kg^{-1} (ppb) soil in April 1999 for LHM treatments conducted in October 1998 and April 1999.

		Manganese Method[1]			Cadmium Method[1]		
Factor		**Injected**	**Surface**	**SE**	**Injected**	**Surface**	**SE**
Season	Fall	478.67^{a}	397.08^{b}	14.18	0.30^{a}	0.23^{b}	0.02
	Spring	447.00^{a}	438.83^{a}	14.18	0.28^{a}	0.25^{a}	0.02
Grand Mean[2]		**462.83^{A}**	**417.96^{B}**	**10.03**			

[1] Within season x method for each constituent, those means with different lower case letters differ significantly at $p<0.05$.

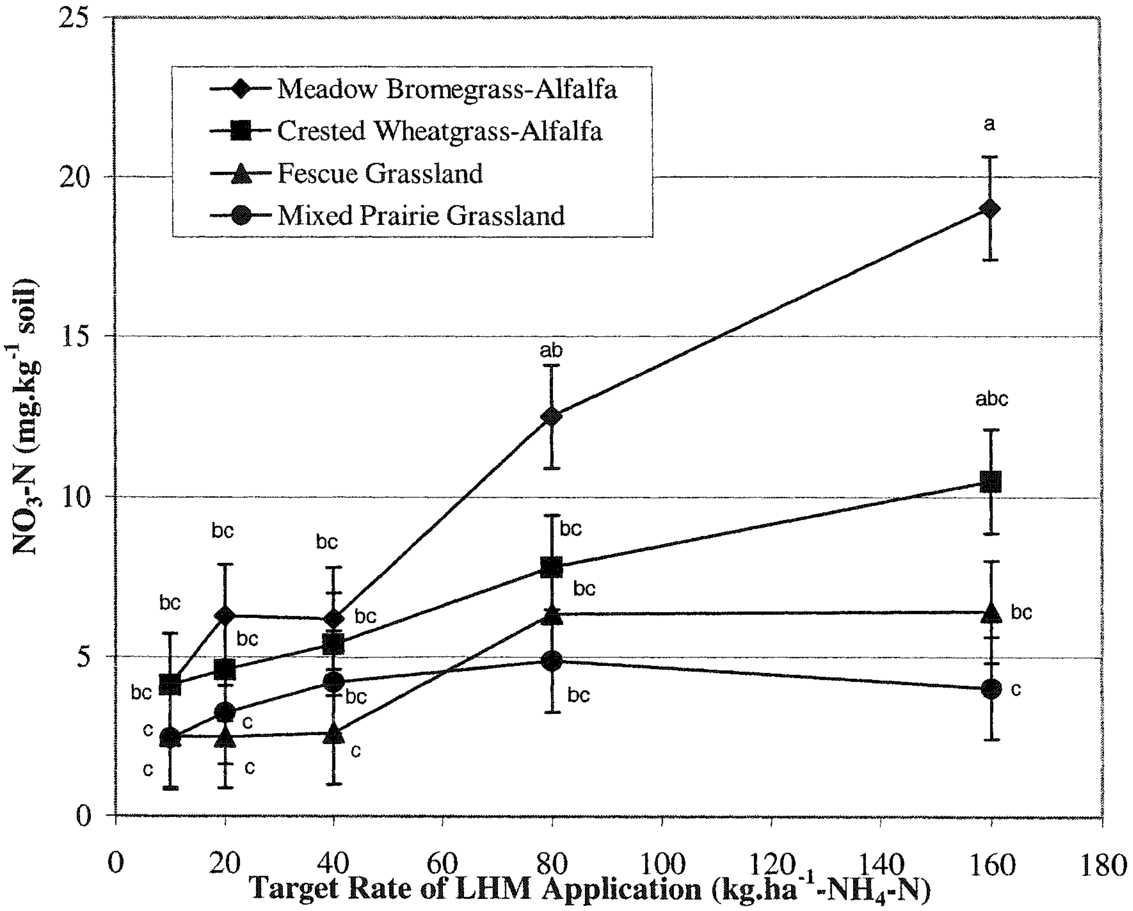
[2] Within each method, grand means with different upper case letters differ significantly at $p<0.01$.

Figure 4.1: Measured mean (± SE) soil NO_3-N and NH_4-N by soil depth and rate of LHM as sampled in April of 1999*.



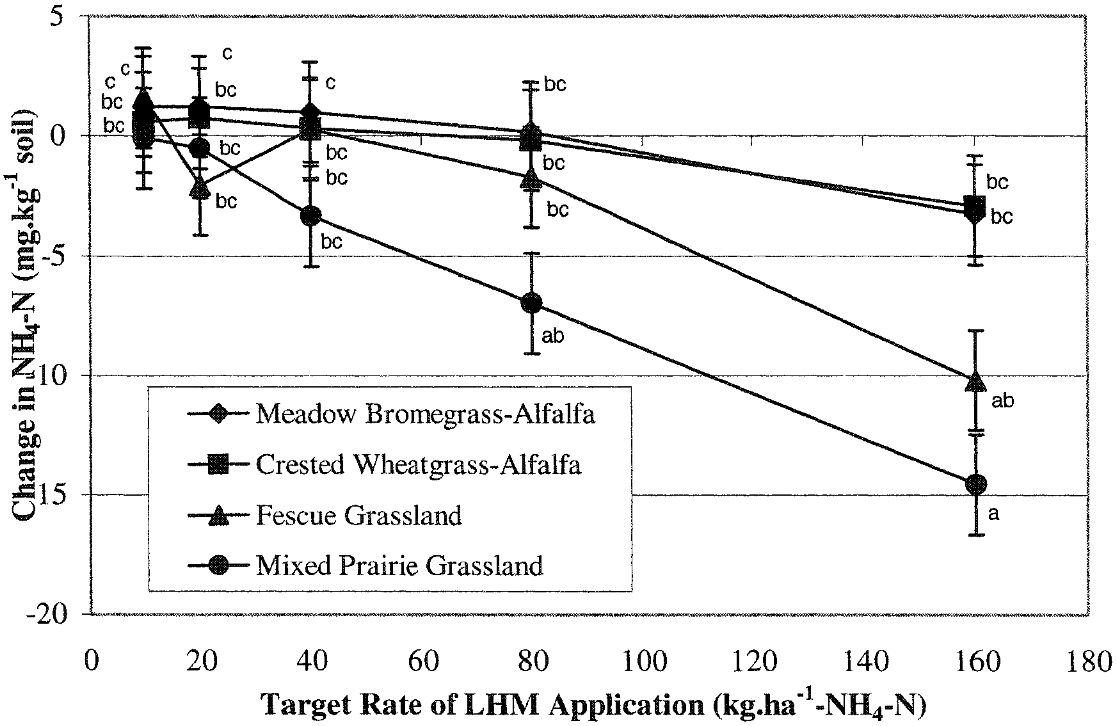
*Within each form of N (NO_3-N and NH_4-N), means with different upper case and lower case letters differ significantly at $p<0.05$, respectively.

Figure 4.2: Measured mean (± SE) soil NO_3-N in the 0-40 cm soil depth for different rates of LHM within each of the four sites during first year soil sampling (1999)*.



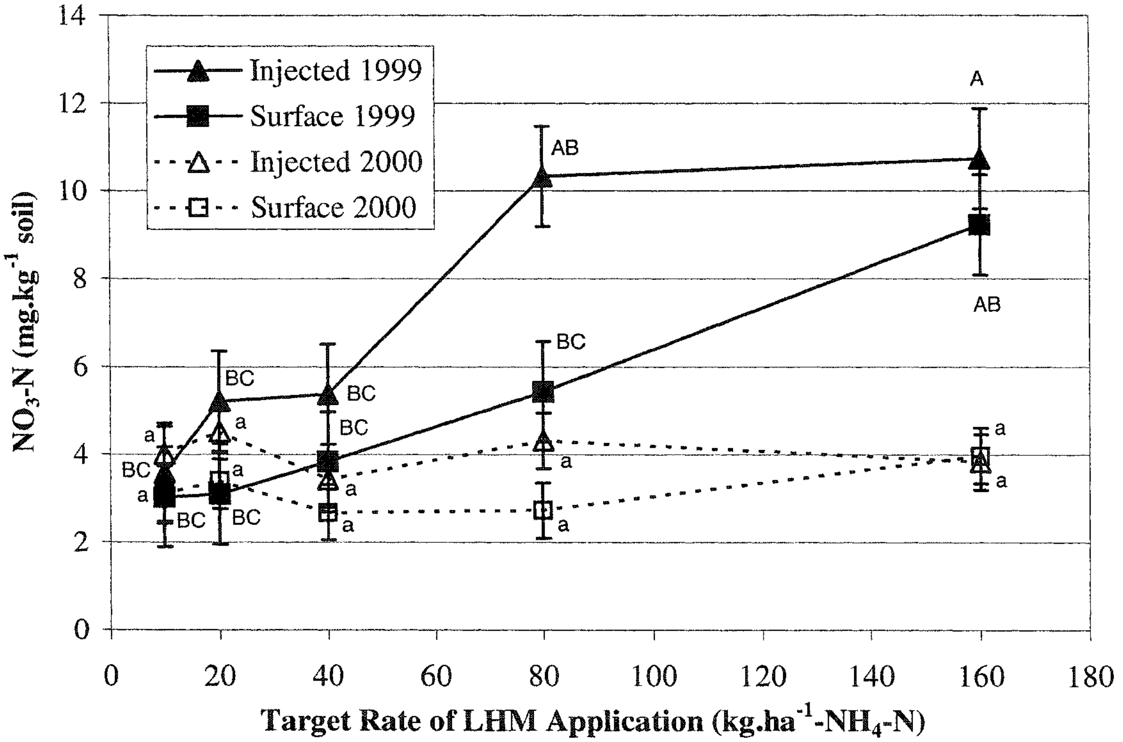
*Means with different lower case letters differ significantly at $p<0.05$.

Figure 4.3: Measured change in the 0-40 cm soil depth in mean (± SE) soil NH_4-N from April 1999 to 2000 within each rate by site combination*.



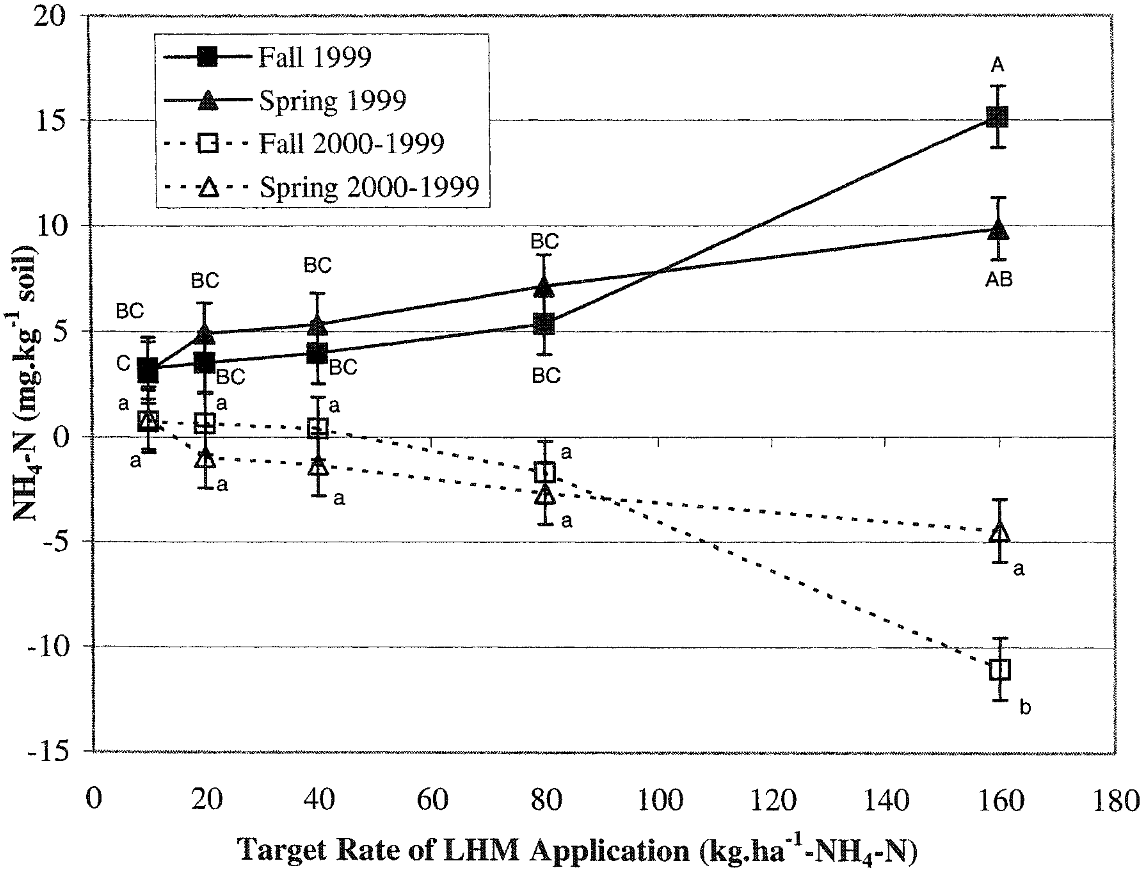
*Means with different lower case letters differ significantly at $p<0.05$.

Figure 4.4: Measured mean (± SE) soil NO_3-N in the 0-40 cm soil depth among various LHM application method and rate combinations during the April 1999 and 2000 soil sampling periods*.



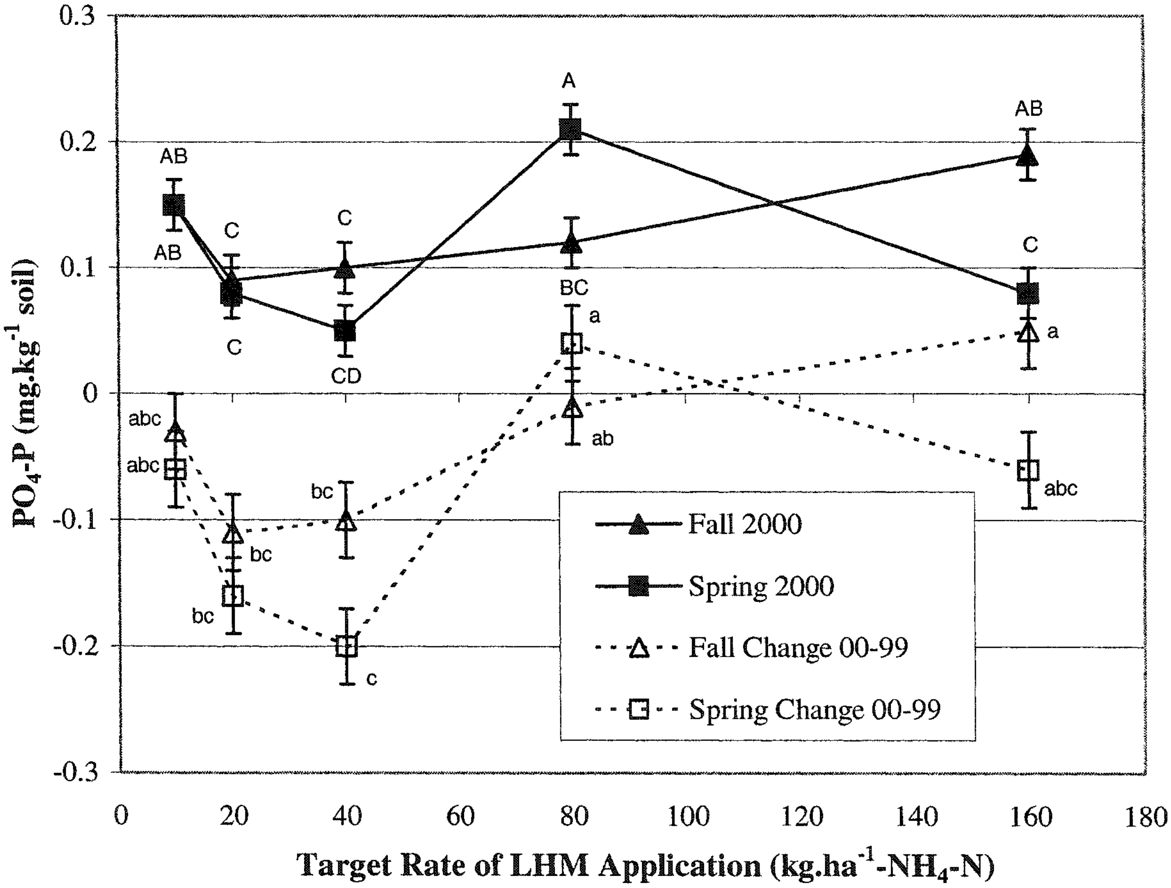
*Within each sampling date, means among rate by method combinations with different lower or upper case letters differ significantly at $p<0.05$.

Figure 4.5: Measured mean (± SE) soil NH_4-N in the 0-40 cm soil depth for different combinations of season and rate of LHM application during April 1999, and subsequent changes from 1999 to 2000*.



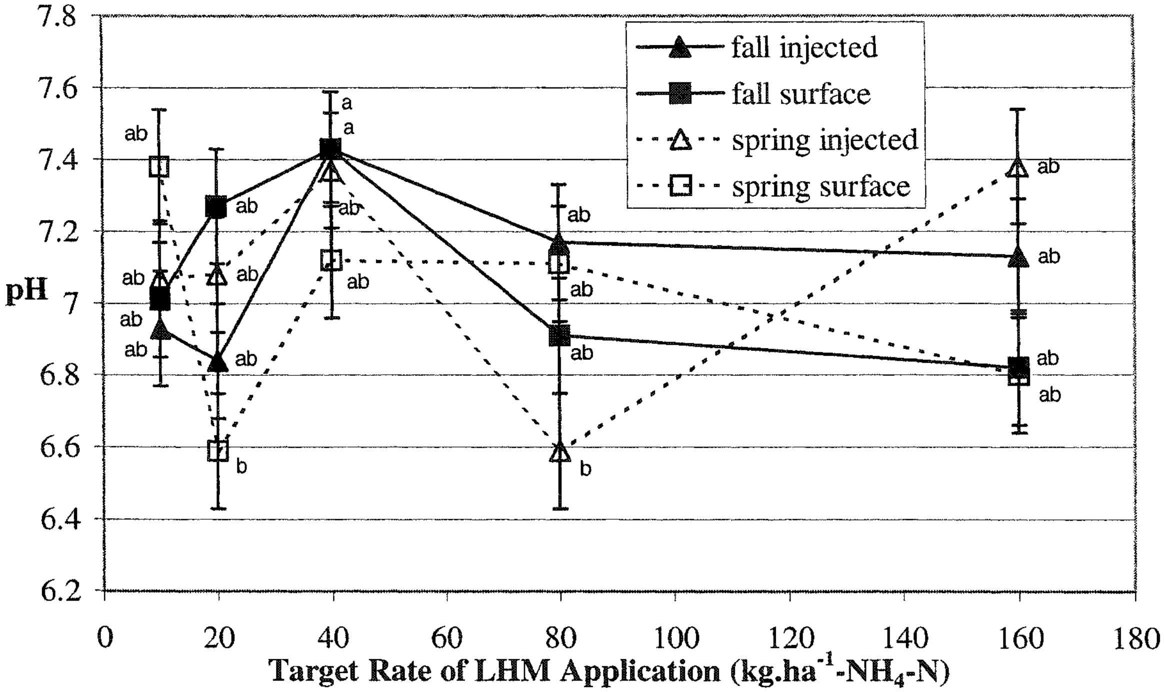
*Within each sampling period, means with different upper case and lower case letters differ significantly at *$p<0.05$*, respectively.

Figure 4.6: Measured mean (± SE) soil PO4-P in the 0-40 cm soil depth among different season of application (Fall 1998 and Spring 1999) by rate combinations in April 2000 soil sampling along with the change in PO4-P from 1999 to 2000 soil sampling periods*.



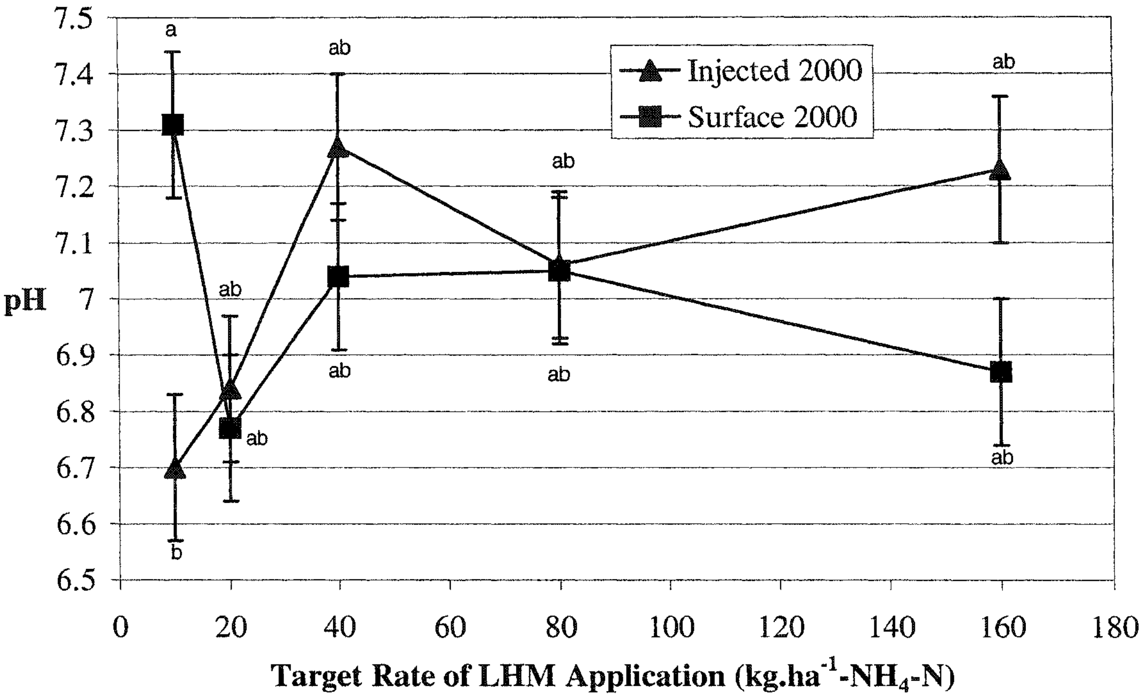
*Within each sampling period, means with different upper case or lower case letters differ significantly at $p<0.05$, respectively.

Figure 4.7: Measured mean soil pH (± SE) levels in the 0-40 cm soil depth under various season by rate by method combinations during April 1999*.



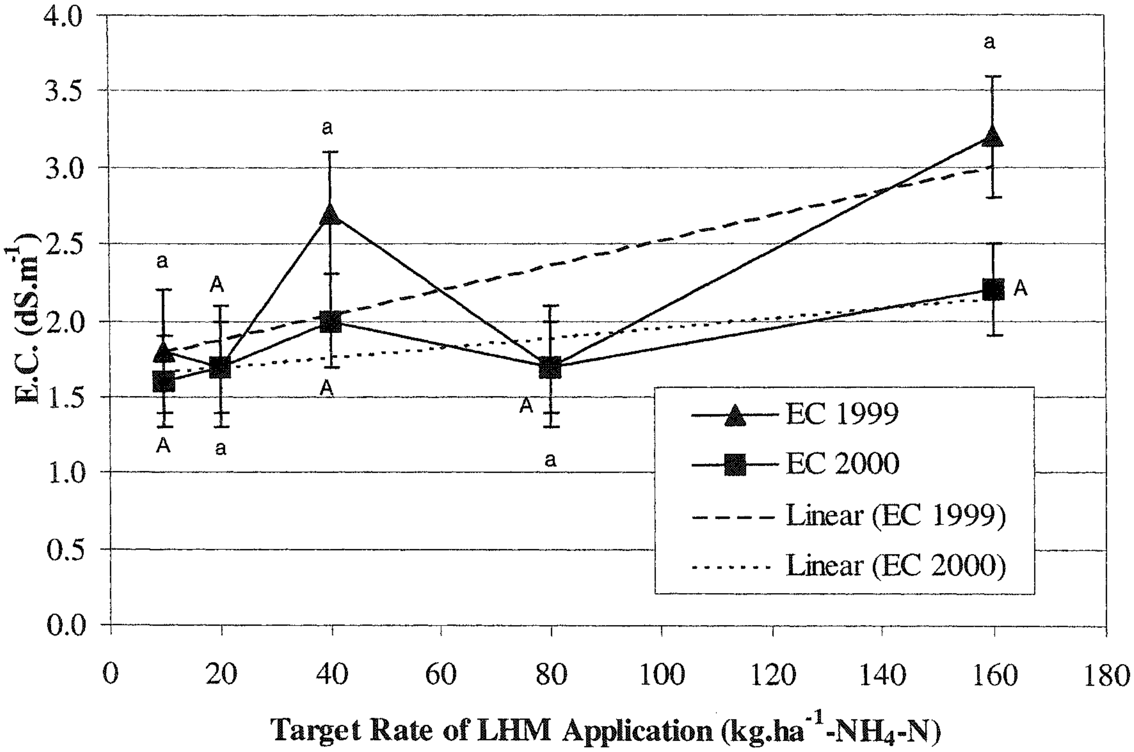
*Means with different lower case letters differ significantly at *p<0.05*.

Figure 4.8: Measured mean soil pH (± SE) levels in the 0-40 cm soil depth under various rate by method combinations in 2000*.



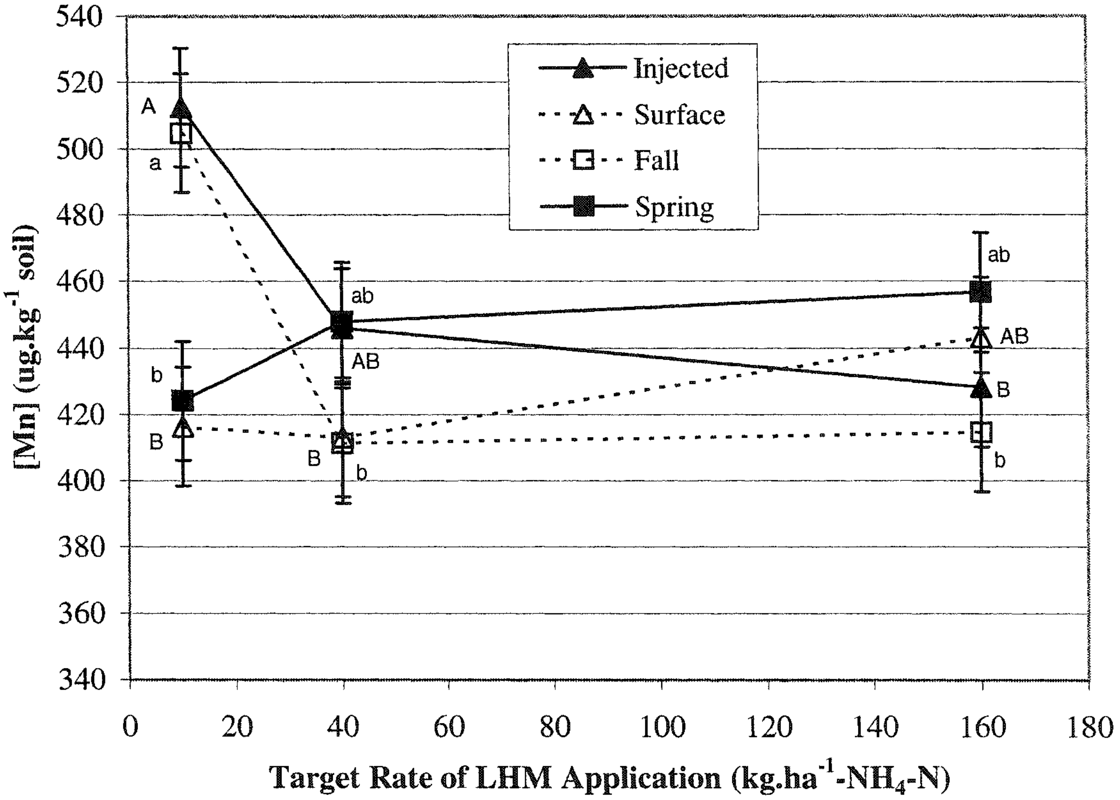
*Means with different lower case letters differ significantly at *p<0.05*.

Figure 4.9: Measured mean (± SE) soil electrical conductivity levels in the 0-40 cm soil depth under varying rates of LHM application, as sampled in April 1999 and 2000*.



*Within each sampling year, means with different upper case or lower case letters differ significantly at $p<0.05$, respectively.

Figure 4.10: Measured mean soil manganese (Mn) levels (± SE) in ug.kg^{-1}-soil in the 0-40 cm soil depth, for various method by rate and season by rate combinations in April 1999*.



* Within each of method by rate and season by rate, means with different upper case and lower case letters, respectively, differ significantly at *$p<0.05$*.

CHAPTER 5: Synthesis

5.1. Introduction

In Alberta, hog production has been increasing over the past 25 years and has included the development of large-scale intensive livestock operations (ILO's) in the southeast region of the province (AAFRD 2002). This region is less densely populated and coincides geographically with beef production (i.e. grazing of tame and native forage lands) is the predominant agricultural industry. Due to climatic and soil-based limitations (Smoliak 1986), cultivated annual cropping systems are relatively uncommon (Willms and Jefferson 1993).

Guidelines for the application of liquid hog manure (LHM) are often based on cultivated lands (*Code of Practice For Responsible Livestock Development and Manure Management* 2000), as these areas have traditionally formed the major local sink for manure produced by adjacent hog operations. As a result, relatively little quantitative information currently exists supporting guidelines for the effective and sustainable application of LHM to tame and native forage lands under semi-arid conditions. This information includes issues around the extent of nutrient buildup and depletion following application, as well as potential nutrient losses during application or prior to uptake by the perennial vegetation.

This research projected included a field experiment to investigate changes in soil nutrient and chemical changes using varied rates (10, 20, 40, 80, and 160 kg.ha^{-1}-NH_4-N), methods (subsurface injection *vs.* dribble broadcast), and seasons (fall *vs.* spring) of LHM application to tame and native forage lands. A parallel experiment was conducted on all spring applied LHM treatments to evaluate trends in soil NH_3 volatilization losses during the first 2 days following manure application.

5.2. Soil Nutrient Loading, Depletion, and Ammonia Volatilization

Overall, few chemical changes were evident in pH, EC, SO_4-S, or exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) relative to any of the main treatments, as might be expected under a limited, one-time application. Instead, the majority of observed changes were in the level of macronutrients, primarily soil-N, as other than water, ammonia nitrogen was the primary constituent of the LHM.

Similarly, limited significant responses in total nitrogen were detected due to varied seasons of one-time application. These results indicate the season of application used by producers is more likely to be determined by factors other than nutrient levels, such as producer convenience, cost of application (i.e. labor or fuel costs), climatic conditions, or public concern associated with odor during application.

Increasing rates of manure increased detectable soil-N (NO_3-N and NH_4-N) on all forage types examined, but were largely depleted after one growing season. Additionally, most soil-N remained in the upper 20 cm of soil (0-20 cm depth), with negligible movement into the lower 20-40 cm soil zone. The use of injection technology also increased levels of available soil N, particularly at high rates of manure application. Notably, these data coincided with the ammonia volatilization findings, as increasing manure (soil-N) resulted in greater ammonia losses, with the greatest losses on broadcast rather than injected treatments, and on tame rather than native sites.

The depletion of soil N during 1999 is likely due, as least in part, to high precipitation the year after LHM application, which resulted in favorable plant growth. These results indicate the various forage lands investigated are capable of effectively utilizing and/or immobilizing the nutrients after manure application, even at rates as high as 160 kg.ha^{-1}-NH_4-N. The favorable plant growth also probably helped prevent nutrient movement in the soil profile.

Given that moisture is normally a major limiting factor for plant growth in southern Alberta (Smoliak 1986), high rates (i.e. 80+ kg.ha^{-1}-NH_4-N) are likely to be most feasible when precipitation and associated plant growth do not limit nutrient uptake (Willms and Jefferson 1993). Furthermore, precipitation in this region is often highly variable, resulting in unpredictable growing conditions and opportunities for nutrient uptake (Willms and Jefferson 1993; Smoliak 1986). As a result, LHM application should strive to match nutrient addition with minimum levels of nutrient use by forage vegetation, as over-application in any one year relative to poor growing conditions could increase the possibility that nutrients exhibit movement either within the soil profile, or overland (Gangbazo et al. 1999, 1995).

The reduction in ammonia loss with LHM injection is important in that it represents both a conservation of soil nutrients, as well as a reduction in atmospheric air pollution and/or odor emissions (Beauchamp et al. 1982). Unfortunately, the actual amount of N conserved for plant growth may be considered economically marginal by producers, limiting the widespread adoption of this technology.

There were also some differences in the responses among different forage types. Injection was particularly effective at reducing ammonia volatilization on tame pastures, likely because of prominent differences in soil characteristics (e.g. litter, crusted bare ground, etc.) capable of affecting initial manure infiltration. These differences indicate injection may be more important on tame pastures than native plant communities for conserving soil N and minimizing air pollution.

5.3. Conclusions

While the application of LHM to tame and native pastures appears to be sustainable based on the lack of negative effects documented in this study, the specific conditions and methods of the experiment must be considered as limiting factors. Application of LHM only occurred once on each treatment plot, with no cumulative, split, or repeat applications taking place during the sampling period. In addition, precipitation the following summer was above average, favoring plant growth. Hence, moisture availability was not a limiting factor in nutrient uptake by vegetation. Also, information gathered from this study pertains primarily to pastures in semi-arid regions of Alberta, primarily native Mixed Prairie and Fescue Grassland, as well as tame pastures containing Crested Wheatgrass-Alfalfa or Meadow Bromegrass-Alfalfa on Orthic Dark Brown or Black Chernozem soils. While information obtained from this study may assist producers with the safe disposal of LHM, caution should be exhibited in different vegetative, soil, or climatic areas of the province due to differences in site conditions and potential nutrient depletion and distribution (Willms and Jefferson 1993).

A frequent, managerial concern with LHM application (or manure in general) is the application of additional organic matter (OM), and how it will affect soil OM content. Since the lagoon used in this study was not agitated prior to extraction of LHM, and extraction hoses were on floats in the center of the lagoon, the LHM applied to the sites contained little OM, which settles to the bottom of the lagoon. In addition to low OM, the LHM contained little associated phosphorus, which is mostly bound to OM. Thus, there was limited potential for environmental degradation or water contamination caused by excess P in this investigation, as evident in the results. The movement of phosphorus, in addition to nitrate, into water bodies is often a key concern in manure management (Gangbazo 1995; Edwards and Daniel 1993; Lauer et al. 1976). In addition to manure nutrient testing, routine soil sampling and site investigation/monitoring before and after LHM application is highly recommended to prevent over-application and subsequent environmental degradation or the loss of nutrients (Janzen et al 1999). Thus, more research is needed on establishing more comprehensive guidelines for manure application under site-specific conditions for forages and soil types. Nevertheless, the results do indicate (under the conditions of this investigation), that LHM can be safely applied to tame pasture and native rangelands, provided manure application rates are adjusted for growing conditions.

Injection of LHM, especially in the future, may serve a dual purpose in that it may assist with nutrient conservation as well as control the distribution of nutrients in soils treated with LHM, thereby reducing the risk of environmental degradation (Sutton et al. 1982). While injection technologies may not currently be cost-effective, public concern in the future about air pollution or associated odor issues may warrant voluntary or even legislated use of injection technology (Neeteson 2000; Adeola 1999; Jongbloed and Lenis 1998). Furthermore, more research is needed on how technology may be developed or adapted to the soils and vegetation types found in Alberta, particularly areas such as permanent forage lands where low disturbance application is necessary.

Based on the overall results of this research, a one-time application of LHM under appropriate climatic conditions could be recommended for semi-arid native rangeland and tame pasture. There were no findings that implicated any negative impacts of applying LHM to forage lands. Similar to when any soil amendment (i.e. fertilizer) is made, caution should be exercised when applying LHM. Routine soil and vegetation sampling as part of a site-specific monitoring and management program should be implemented (Janzen et al. 1999). While much information is available on the application of nutrients or manure to annual crops, less information exists on the effects on the application of LHM to permanent cover (perennial) crops, especially on native pastures (Gillen and Berg 1998; Choudhary et al 1996). The residual effects from N additions on grasslands are of particular importance because these appear to be more prolonged than on cultivated soils (Power and Alessi 1971). Hence, it would be advisable to use conservative application rates of LHM on native rangelands (especially if suitable tame sites are available) until additional research can be conducted to more fully quantify the effects of manure, including how it affects soil and native vegetation over the long-term.

Although benefits of injection do exist, they must be evaluated in the context of each intensive livestock operation itself (e.g., location and limitation to expansion, economics, and social constraints). While injection may not seem cost-effective within the context of current production practices and disposal methods, it may be necessary in the near future. Factors such as legislation (similar to that in parts of Europe and the

U.S.) (Innes 2000; Jackson et al. 2000; Neeteson 2000), pressure from the public, population expansion, increases in hog numbers, or the need to limit/prevent environmental degradation may make injection of LHM necessary to reduce undesirable effects of LHM application.

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APPENDIX 1: Site and soil pedon descriptions[1]

1. Mixed Prairie Site – Orthic Dark Brown Chernozem

- Rapidly drained
- Glacial till
- Anthropogenic landform
- Slope Class 2, 0.5-2.0 % slope, nearly level, southeast aspect
- Grassland pasture community

Horizon	Depth (cm)	Description
Ah	0-18	Grayish olive (2.5Y 4/2 d); loam; weak, fine granular; loose-soft; abundant, micro, vertical-oblique, inped; clear, wavy boundary; 17-19 cm thick..
Bm	18-34	Grayish olive (2.5Y 4/2 d); loam; weak, medium blocky; soft; plentiful, fine, vertical, inped-exped; few stones; clear, wavy boundary; 14-17 cm thick.
Cca	34+	Light gray (2.5Y 7/2 d); loam; weak, medium blocky; soft; plentiful, fine, vertical, exped; few stones, carbonates; gradual, wavy boundary;.

2. Fescue Grassland Site – Orthic Black Chernozem

- Well drained
- Glacial till
- Morainal landform
- Slope Class 3, 2.0-5.0 % slope, very gentle slopes, northwest aspect
- Grassland pasture community

Horizon	Depth (cm)	Description
Ah	0-24	Brownish black (2.5Y 3/1 d); loam; fine-medium granular; loose; abundant, very fine - fine, vertical, inped; few stones; clear-gradual, wavy boundary; 20-30 cm thick.
Bm	24-40	Dark grayish yellow (2.5Y 4/2 d); loam; strong, medium blocky; soft; few, fine, vertical, inped; clay films; few stones; clear-gradual, wavy boundary; 13-18 cm thick.
Cca	40+	Dark grayish yellow (2.5Y 5/2 d); loam; strong, medium-coarse, sub angular blocky; soft; very few, fine, random; few stones, carbonates; clear, wavy boundary.

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[1] Agriculture Canada Expert Committee on Soil Survey. 1987. *The Canadian System of Soil Classification*. 2nd ed. Agric. Can. Publ. 1646. 164 pp.

3. Crested Wheat Site – Orthic Dark Brown Chernozem

- Rapidly to well-drained
- Glacial till
- Anthropogenic landform
- Slope Class 2, 0.5-2.0 % slope, nearly level, south aspect
- Grassland pasture community

Horizon	Depth (cm)	Description
Ap	0-20	Grayish olive (2.5Y 4/2 d); loam; medium granular; loose; abundant, fine-medium, vertical-oblique, inped; few stones; clear-abrupt, smooth boundary; 19-21 cm thick..
Bm	20-28	Grayish olive (2.5Y 5/2 d); loam; weak, fine blocky; slightly hard; few-plentiful, fine, vertical, exped; clay films; few stones; clear, smooth boundary; 7-10cm thick..
Cca	28+	Grayish olive (2.5Y 6/2 d); loam; strong, coarse, blocky; slightly hard; very few, fine, vertical, exped; few stones, carbonates; gradual, wavy boundary.

4. Meadow Brome Site – Orthic Dark Brown Chernozem

- Very rapidly drained
- Glacial till
- Morainal landform
- Slope Class 2, 0.5-2.0 % slope, very gentle slopes, north aspect
- Grassland pasture community

Horizon	Depth (cm)	Description
Ap	0-15	Brownish black (2.5Y 3/2 d); sandy loam; weak-fine platy-granular; loose; few-plentiful, fine-medium, vertical, inped; many stones; abrupt, smooth boundary; 13-17 cm thick.
Bm	15-30	Olive brown (2.5Y 4/4 d); sandy loam; weak, fine blocky; soft; few-plentiful, fine-medium, vertical, inped-exped; clay films; many stones; clear, wavy boundary; 17-20cm thick.
Cca	30+	Yellowish brown (2.5Y 5/3 d); sandy loam; weak, medium, gravel; loose; very few, fine, vertical, inped-exped; many stones, carbonates; gradual, wavy boundary.

APPENDIX 2:

Ammonia[*] volatilization captured by static-sorber ammonia traps on dry-pass and control treatments for 48-hours immediately following simultaneous LHM application in spring 1999

Site	Rate	Method	NH_3-N Loss (kg.ha^{-1})
Crested Wheat	0	Injected	0.02
	0	Control	0.01
Meadow Brome	0	Injected	0.02
	0	Control	0.01
Mixed Prairie	0	Injected	0.02
	0	Control	0.01
Fescue Prairie	0	Injected	0.01
	0	Control	0.01

[*] Sorber traps extracted with de-ionized water and analyzed for ammonium concentration in solution, using a Technicon (1973) Auto-Analyzer II.

APPENDIX 3:
Extractable nitrogen[*] for 1999 soil sampling on dry-pass and control treatments

Site	Rate	Season	Method	Depth (cm)	NO_3-N[1]	NH_4-N[1]
Crested Wheat	0	Fall	Injected	0-20	6.66	4.32
		Spring	Injected	0-20	3.34	4.11
		Control	NA	0-20	2.88	3.67
		Fall	Injected	20-40	2.84	3.8
		Spring	Injected	20-40	2.02	1.85
		Control	NA	20-40	1.95	2.00
Meadow Brome	0	Fall	Injected	0-20	4.55	4.46
		Spring	Injected	0-20	3.47	3.15
		Control	NA	0-20	4.33	2.47
		Fall	Injected	20-40	4.50	1.78
		Spring	Injected	20-40	2.53	1.64
		Control	NA	20-40	2.26	1.52
Mixed Prairie	0	Fall	Injected	0-20	3.26	3.57
		Spring	Injected	0-20	2.44	6.62
		Control	NA	0-20	2.91	5.42
		Fall	Injected	20-40	1.41	2.49
		Spring	Injected	20-40	1.45	1.83
		Control	NA	20-40	1.94	3.08
Fescue Prairie	0	Fall	Injected	0-20	2.14	10.01
		Spring	Injected	0-20	2.32	6.02
		Control	NA	0-20	1.64	5.48
		Fall	Injected	20-40	1.57	2.40
		Spring	Injected	20-40	1.57	2.67
		Control	NA	20-40	1.37	2.23

[*] Extractable by 2M Potassium Chloride Solution (McKeague 1978)

[1] Units are $mg.kg^{-1}$

APPENDIX 4:
Extractable nitrogen[*] for 2000 soil sampling on dry-pass and control treatments

Site	Rate	Season	Method	Depth (cm)	NO_3-N[1]	NH_4-N[1]
Crested Wheat	0	Fall	Injected	0-20	3.06	3.67
		Spring	Injected	0-20	2.62	4.45
		Control	NA	0-20	2.56	4.12
		Fall	Injected	20-40	1.10	2.87
		Spring	Injected	20-40	1.57	2.67
		Control	NA	20-40	1.44	2.50
Meadow Brome	0	Fall	Injected	0-20	8.12	6.84
		Spring	Injected	0-20	5.45	5.39
		Control	NA	0-20	5.63	4.78
		Fall	Injected	20-40	2.61	2.65
		Spring	Injected	20-40	2.31	3.06
		Control	NA	20-40	2.56	1.56
Mixed Prairie	0	Fall	Injected	0-20	1.31	2.91
		Spring	Injected	0-20	1.58	4.16
		Control	NA	0-20	1.79	3.46
		Fall	Injected	20-40	1.02	2.01
		Spring	Injected	20-40	1.44	3.29
		Control	NA	20-40	1.53	3.02
Fescue Prairie	0	Fall	Injected	0-20	1.70	5.91
		Spring	Injected	0-20	6.29	3.51
		Control	NA	0-20	5.24	2.41
		Fall	Injected	20-40	1.38	3.07
		Spring	Injected	20-40	1.98	3.52
		Control	NA	20-40	1.22	2.93

[*] Extractable by 2M Potassium Chloride Solution (McKeague 1978)

[1] Units are mg.kg^{-1}

APPENDIX 5:
Extractable phosphorus* for 1999 soil sampling on dry-pass and control treatments

Site	Rate	Season	Method	Depth (cm)	PO_4-P[1]
Crested Wheat	0	Fall	Injected	0-20	0.25
		Spring	Injected	0-20	0.31
		Control	NA	0-20	0.22
		Fall	Injected	20-40	0.17
		Spring	Injected	20-40	0.18
		Control	NA	20-40	0.29
Meadow Brome	0	Fall	Injected	0-20	0.26
		Spring	Injected	0-20	0.32
		Control	NA	0-20	0.21
		Fall	Injected	20-40	0.28
		Spring	Injected	20-40	0.16
		Control	NA	20-40	0.3
Mixed Prairie	0	Fall	Injected	0-20	0.23
		Spring	Injected	0-20	0.53
		Control	NA	0-20	0.25
		Fall	Injected	20-40	0.27
		Spring	Injected	20-40	0.23
		Control	NA	20-40	0.32
Fescue Prairie	0	Fall	Injected	0-20	0.01
		Spring	Injected	0-20	0.15
		Control	NA	0-20	0.28
		Fall	Injected	20-40	0.09
		Spring	Injected	20-40	0.25
		Control	NA	20-40	0.24

*Extractable by 2M Potassium Chloride Solution (McKeague 1978)

[1] Units are $mg.kg^{-1}$

APPENDIX 6:
Extractable phosphorus* for 2000 soil sampling on dry-pass and control treatments

Site	Rate	Season	Method	Depth (cm)	PO_4-P[1]
Crested Wheat	0	Fall	Injected	0-20	0.13
		Spring	Injected	0-20	0.13
		Control	NA	0-20	0.05
		Fall	Injected	20-40	0.07
		Spring	Injected	20-40	0.05
		Control	NA	20-40	0.06
Meadow Brome	0	Fall	Injected	0-20	0.17
		Spring	Injected	0-20	0.07
		Control	NA	0-20	0.04
		Fall	Injected	20-40	0.18
		Spring	Injected	20-40	0.11
		Control	NA	20-40	0.12
Mixed Prairie	0	Fall	Injected	0-20	0.14
		Spring	Injected	0-20	0.09
		Control	NA	0-20	0.14
		Fall	Injected	20-40	0.23
		Spring	Injected	20-40	0.07
		Control	NA	20-40	0.1
Fescue Prairie	0	Fall	Injected	0-20	0.15
		Spring	Injected	0-20	0.13
		Control	NA	0-20	0.21
		Fall	Injected	20-40	0.15
		Spring	Injected	20-40	0.07
		Control	NA	20-40	0.11

*Extractable by 2M Potassium Chloride Solution (McKeague 1978)

[1] Units are $mg.kg^{-1}$

APPENDIX 7:
Exchangeable cations* for 1999 soil sampling on dry-pass and control treatments

					Exchangeable Cations[1]			
Site	**Rate**	**Season**	**Method**	**Depth (cm)**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**Na^{+}**
Crested Wheat	0	Fall	Injected	0-20	36.53	10.51	1.00	1.78
		Spring	Injected	0-20	11.69	4.99	1.19	0.58
		Control	NA	0-20	12.63	5.40	1.83	0.88
		Fall	Injected	20-40	64.03	18.11	0.82	4.34
		Spring	Injected	20-40	25.28	7.17	0.59	1.56
		Control	NA	20-40	14.50	7.69	1.00	1.65
Meadow Brome	0	Fall	Injected	0-20	12.16	2.75	0.79	0.10
		Spring	Injected	0-20	22.47	5.14	0.40	0.12
		Control	NA	0-20	14.03	3.89	0.40	0.16
		Fall	Injected	20-40	13.10	3.16	0.34	0.05
		Spring	Injected	20-40	24.81	4.26	0.33	0.07
		Control	NA	20-40	35.13	4.05	0.23	0.41
Mixed Prairie	0	Fall	Injected	0-20	15.91	6.03	1.19	0.97
		Spring	Injected	0-20	20.60	5.61	1.42	0.26
		Control	NA	0-20	11.22	5.61	1.00	0.49
		Fall	Injected	20-40	39.35	10.30	1.00	3.38
		Spring	Injected	20-40	40.75	8.22	1.09	1.06
		Control	NA	20-40	42.16	11.97	1.00	1.71
Fescue Prairie	0	Fall	Injected	0-20	17.31	5.61	0.87	0.12
		Spring	Injected	0-20	12.63	3.94	1.78	0.06
		Control	NA	0-20	18.25	5.61	1.46	0.75
		Fall	Injected	20-40	18.25	6.13	0.72	0.26
		Spring	Injected	20-40	19.19	3.94	1.19	0.22
		Control	NA	20-40	45.44	9.15	1.14	1.88

*Exchangeable by Ammonium Acetate at pH 7.0 (McKeague 1978)

[1] Units are $meq.100g^{-1}$

APPENDIX 8:
Heavy metals (ug.kg^{-1} soil) analyses for 10, 40 and 160 kg.ha^{-1} LHM treatments

Site	Season	Rate	Method	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth
Crested Wheat	fall	10	surface	17000	0.6	6.2	134	0.6	0.8
	fall	10	injected	14800	0.6	5.8	128	0.5	0.6
	spring	10	surface	14400	<0.3	6.1	140	0.5	0.8
	spring	10	injected	12900	0.4	4.9	122	0.4	0.6
	fall	40	surface	16200	0.4	6.6	177	0.6	0.5
	fall	40	injected	17500	0.5	5.8	148	0.6	0.8
	spring	40	surface	14700	0.6	6.3	126	0.5	0.9
	spring	40	injected	19300	0.5	6.1	131	0.6	0.9
	fall	160	surface	17000	0.6	5.9	132	0.6	0.9
	fall	160	injected	14900	0.5	5.5	136	0.5	0.5
	spring	160	surface	14300	0.5	5.1	133	0.5	1.0
	spring	160	injected	17000	0.6	6.3	151	0.6	0.7
Meadow Brome	fall	10	surface	14200	0.4	4.8	163	0.5	0.5
	fall	10	injected	11100	0.4	4.7	149	0.4	0.6
	spring	10	surface	15200	0.5	6.1	167	0.5	0.7
	spring	10	injected	15900	0.5	6.2	174	0.6	0.7
	fall	40	surface	14000	0.6	5.5	155	0.5	0.8
	fall	40	injected	15400	0.6	6.1	170	0.5	0.9
	spring	40	surface	15200	0.5	5.4	162	0.5	0.6
	spring	40	injected	14900	0.6	6.2	182	0.5	0.5
	fall	160	surface	12200	0.6	4.5	140	0.5	0.8
	fall	160	injected	13700	<0.3	4.4	174	0.4	0.7
	spring	160	surface	14500	0.6	6.6	164	0.5	1.0
	spring	160	injected	12300	0.5	5.2	137	0.5	0.8
Mixed Prairie	fall	10	surface	15800	0.7	6.4	157	0.5	0.9
	fall	10	injected	16000	0.5	6.2	188	0.5	0.7
	spring	10	surface	15600	0.6	6.9	166	0.5	0.9
	spring	10	injected	14100	0.6	6.6	153	0.5	0.6
	fall	40	surface	13700	0.7	7.1	148	0.5	1.1
	fall	40	injected	14400	0.6	6.6	164	0.5	0.6
	spring	40	surface	14200	0.8	7.5	175	0.5	1.0
	spring	40	injected	12300	0.5	4.7	167	0.4	0.6
	fall	160	surface	13500	0.5	6.5	151	0.6	0.7
	fall	160	injected	13900	0.5	6.5	143	0.5	0.9
	spring	160	surface	15700	0.8	7.7	143	0.6	1.4
	spring	160	injected	15300	0.7	6.8	155	0.5	1.0
Fescue Prairie	fall	10	surface	17200	0.6	6.0	218	0.6	0.9
	fall	10	injected	15900	0.4	5.0	239	0.5	0.8
	spring	10	surface	12700	0.6	5.3	156	0.4	0.5
	spring	10	injected	14800	0.5	4.7	223	0.5	0.7
	fall	40	surface	12600	0.4	5.5	152	0.4	0.8
	fall	40	injected	15300	0.5	5.1	202	0.5	0.8
	spring	40	surface	15600	0.5	5.6	187	0.5	0.5
	spring	40	injected	15300	0.4	5.0	210	0.5	0.7
	fall	160	surface	14900	0.5	5.3	155	0.5	0.8
	fall	160	injected	16400	0.5	4.9	184	0.5	0.6
	spring	160	surface	11800	0.5	4.4	173	0.4	0.7
	spring	160	injected	14700	0.5	5.0	204	0.5	0.5

Site	Season	Rate	Method	Cadmium	Calcium	Chromium	Cobalt	Copper	Iron
Crested Wheat	fall	10	surface	0.2	2590	18.7	6.9	13.0	16900
	fall	10	injected	0.3	1430	15.0	6.5	11.6	18000
	spring	10	surface	0.2	3250	16.3	6.6	10.4	15100
	spring	10	injected	0.2	1560	13.4	5.4	11.4	14100
	fall	40	surface	0.3	7260	18.1	6.6	22.0	16400
	fall	40	injected	0.3	2430	18.0	7.2	13.3	16200
	spring	40	surface	0.2	2050	15.5	7.2	11.2	16700
	spring	40	injected	0.3	2190	19.7	7.4	17.2	17500
	fall	160	surface	0.2	2180	17.9	6.6	13.2	16500
	fall	160	injected	0.2	2530	15.7	6.6	11.6	15000
	spring	160	surface	0.3	1840	14.1	6.1	11.5	14800
	spring	160	injected	0.3	3550	18.1	6.8	13.2	15600
Meadow Brome	fall	10	surface	0.2	2040	13.4	5.1	8.9	14100
	fall	10	injected	0.2	1810	12.1	5.0	7.5	13400
	spring	10	surface	0.2	2680	17.0	6.1	9.4	16100
	spring	10	injected	0.2	3380	17.8	6.3	10.0	16700
	fall	40	surface	0.2	2460	15.4	5.6	9.2	15800
	fall	40	injected	0.2	2860	17.3	6.1	9.9	16000
	spring	40	surface	0.2	2780	16.3	5.9	9.5	14800
	spring	40	injected	0.2	3080	16.7	6.5	10.5	16400
	fall	160	surface	0.1	2180	14.1	5.4	7.7	13900
	fall	160	injected	0.2	2160	10.6	4.5	9.6	12400
	spring	160	surface	0.2	2430	16.4	6.4	17.6	18700
	spring	160	injected	0.2	2190	13.3	5.4	7.8	14300
Mixed Prairie	fall	10	surface	0.2	2240	17.3	5.8	11.7	16900
	fall	10	injected	0.4	3040	17.9	7.2	11.7	17500
	spring	10	surface	0.4	2800	18.0	6.7	11.6	17800
	spring	10	injected	0.2	1800	14.2	6.3	12.0	19200
	fall	40	surface	0.2	3030	15.5	6.2	11.8	17200
	fall	40	injected	0.3	2660	15.8	6.0	10.7	17500
	spring	40	surface	0.3	1950	15.5	8.7	18.1	19300
	spring	40	injected	0.3	2100	12.8	4.6	11.9	13800
	fall	160	surface	0.2	2490	15.9	7.3	12.0	16000
	fall	160	injected	0.2	2240	15.7	6.4	13.9	15500
	spring	160	surface	0.2	2010	17.2	6.8	11.4	23400
	spring	160	injected	0.3	2520	16.1	6.9	10.9	17600
Fescue Prairie	fall	10	surface	0.4	2860	17.4	6.8	21.3	19500
	fall	10	injected	0.6	3270	15.0	6.2	14.8	16100
	spring	10	surface	0.3	2080	12.7	5.3	10.8	15500
	spring	10	injected	0.5	3240	14.7	5.7	17.1	17000
	fall	40	surface	0.3	2040	13.1	5.7	10.9	15700
	fall	40	injected	0.4	3000	15.2	5.9	13.8	15900
	spring	40	surface	0.3	2490	15.7	6.5	12.2	15700
	spring	40	injected	0.4	3330	15.7	6.1	13.8	15200
	fall	160	surface	0.2	2050	14.7	5.4	11.6	14800
	fall	160	injected	0.4	2430	14.5	6.3	14.6	14900
	spring	160	surface	0.3	2410	12.4	5.1	11.1	12600
	spring	160	injected	0.4	2970	14.4	5.8	13.4	14500

Site	Season	Rate	Method	Lead	Magnesium	Manganese	Molybdenum	Nickel
Crested Wheat	fall	10	surface	8.3	3120	369	0.3	18.2
	fall	10	injected	8.6	2080	653	0.5	11.3
	spring	10	surface	11.9	2740	313	0.3	15.7
	spring	10	injected	7.3	2000	354	0.4	10.8
	fall	40	surface	8.4	3560	317	0.3	19.5
	fall	40	injected	8.7	2880	454	0.3	15.5
	spring	40	surface	8.1	2370	436	0.3	12.6
	spring	40	injected	9.4	3280	419	0.3	18.1
	fall	160	surface	8.8	2890	347	0.3	16.3
	fall	160	injected	7.5	2690	362	0.3	15.0
	spring	160	surface	7.6	2070	450	0.4	11.2
	spring	160	injected	8.9	3280	355	0.3	17.9
Meadow Brome	fall	10	surface	6.6	1810	354	0.3	10.2
	fall	10	injected	6.0	1690	451	0.3	9.7
	spring	10	surface	7.1	2520	327	0.2	14.1
	spring	10	injected	7.5	2610	350	0.2	14.9
	fall	40	surface	6.8	2210	330	0.3	13.5
	fall	40	injected	7.4	2510	356	0.3	14.0
	spring	40	surface	7.2	2410	338	0.3	13.1
	spring	40	injected	8.2	2540	382	0.3	14.8
	fall	160	surface	6.3	2180	317	0.2	12.1
	fall	160	injected	6.2	1570	399	0.3	9.2
	spring	160	surface	7.9	2400	444	0.4	13.6
	spring	160	injected	6.3	2000	379	0.2	11.9
Mixed Prairie	fall	10	surface	7.5	2690	399	0.4	13.0
	fall	10	injected	8.8	3270	543	0.2	14.1
	spring	10	surface	15.6	3060	497	0.3	15.1
	spring	10	injected	7.4	2090	529	0.4	11.4
	fall	40	surface	7.5	2540	374	0.4	14.9
	fall	40	injected	7.3	2770	443	0.3	12.5
	spring	40	surface	7.8	2550	530	0.5	17.9
	spring	40	injected	6.5	2080	475	0.5	10.0
	fall	160	surface	7.8	2780	389	0.2	20.0
	fall	160	injected	8.5	2770	420	0.3	12.8
	spring	160	surface	8.4	2730	500	0.5	15.5
	spring	160	injected	7.6	2860	480	0.3	14.8
Fescue Prairie	fall	10	surface	8.7	2530	628	0.4	13.5
	fall	10	injected	7.8	2240	641	0.5	11.2
	spring	10	surface	6.2	1830	444	0.4	9.9
	spring	10	injected	12.6	2310	579	0.4	12.4
	fall	40	surface	6.5	1880	485	0.5	9.5
	fall	40	injected	7.7	2370	531	0.3	11.9
	spring	40	surface	7.8	2680	480	0.4	12.6
	spring	40	injected	7.5	2400	523	0.4	12.4
	fall	160	surface	7.3	2170	456	0.4	10.5
	fall	160	injected	8.0	2140	491	0.4	10.4
	spring	160	surface	6.5	1890	507	0.4	9.8
	spring	160	injected	7.8	2170	539	0.4	11.6

Site	Season	Rate	Method	Phosphorus	Selenium	Silicon	Silver	Strontium
Crested Wheat	fall	10	surface	406	0.9	308	<0.05	27.6
	fall	10	injected	544	0.9	369	<0.05	19.1
	spring	10	surface	459	0.8	266	<0.05	25.5
	spring	10	injected	438	0.8	422	<0.05	18.6
	fall	40	surface	375	0.7	349	<0.06	35.8
	fall	40	injected	453	1.0	318	<0.05	25.4
	spring	40	surface	455	1.0	205	<0.05	20.3
	spring	40	injected	433	0.7	304	<0.05	27.9
	fall	160	surface	433	1.1	396	<0.05	23.7
	fall	160	injected	373	1.0	322	<0.05	25.5
	spring	160	surface	510	0.9	406	<0.05	20.6
	spring	160	injected	435	0.8	412	<0.06	29.6
Meadow Brome	fall	10	surface	489	0.7	185	<0.05	16.5
	fall	10	injected	439	0.7	324	<0.05	14.0
	spring	10	surface	498	1.0	190	<0.06	18.0
	spring	10	injected	424	0.7	367	<0.06	18.4
	fall	40	surface	480	0.8	375	<0.05	17.3
	fall	40	injected	460	0.8	263	<0.05	18.3
	spring	40	surface	436	0.8	312	<0.06	17.8
	spring	40	injected	491	0.9	241	<0.05	17.9
	fall	160	surface	358	0.6	159	<0.05	16.1
	fall	160	injected	553	0.7	400	<0.05	16.5
	spring	160	surface	470	1.0	338	<0.05	17.3
	spring	160	injected	398	0.6	364	<0.05	15.2
Mixed Prairie	fall	10	surface	566	1.0	251	<0.05	23.1
	fall	10	injected	649	0.7	205	<0.05	28.2
	spring	10	surface	632	0.9	331	<0.05	26.1
	spring	10	injected	619	1.1	522	<0.05	20.5
	fall	40	surface	420	1.1	336	<0.05	32.4
	fall	40	injected	528	0.9	236	<0.05	23.8
	spring	40	surface	553	1.3	182	<0.05	21.7
	spring	40	injected	647	0.9	384	<0.05	22.8
	fall	160	surface	386	0.8	206	<0.06	23.4
	fall	160	injected	497	0.9	234	<0.05	23.1
	spring	160	surface	600	1.2	219	<0.05	21.6
	spring	160	injected	516	1.0	370	<0.05	24.2
Fescue Prairie	fall	10	surface	859	1.3	340	<0.05	30.6
	fall	10	injected	879	1.3	335	<0.05	31.8
	spring	10	surface	632	1.1	303	<0.06	19.9
	spring	10	injected	750	1.3	323	<0.05	30.7
	fall	40	surface	618	1.2	291	<0.05	19.8
	fall	40	injected	669	1.1	392	<0.05	27.8
	spring	40	surface	683	0.9	251	<0.05	25.8
	spring	40	injected	662	1.0	353	<0.06	30.3
	fall	160	surface	551	1.2	345	<0.05	21.6
	fall	160	injected	654	1.1	448	<0.05	25.5
	spring	160	surface	683	1.0	474	<0.05	22.9
	spring	160	injected	621	1.1	404	<0.05	27.8

Site	Season	Rate	Method	Thallium	Tin	Titanium	Vanadium	Zinc
Crested Wheat	fall	10	surface	0.3	0.5	206	33.1	54.7
	fall	10	injected	0.4	0.6	229	32.3	56.2
	spring	10	surface	0.4	0.6	185	29.6	48.4
	spring	10	injected	0.3	0.7	213	26.9	49.5
	fall	40	surface	<0.2	0.3	180	31.4	54.1
	fall	40	injected	0.4	0.4	211	32.3	59.5
	spring	40	surface	0.5	0.5	184	30.1	53.8
	spring	40	injected	0.3	0.5	232	35.1	61.6
	fall	160	surface	0.3	0.8	226	31.8	55.1
	fall	160	injected	0.3	0.4	195	28.6	49.1
	spring	160	surface	0.3	0.5	190	26.3	60.3
	spring	160	injected	0.5	0.5	216	31.5	56.8
Meadow Brome	fall	10	surface	0.3	0.7	245	24.5	44.4
	fall	10	injected	0.4	0.8	193	22.1	37.3
	spring	10	surface	0.8	0.5	198	30.2	44.9
	spring	10	injected	0.4	0.7	197	32.0	45.0
	fall	40	surface	0.5	0.8	211	27.6	44.4
	fall	40	injected	0.6	0.6	204	30.3	46.9
	spring	40	surface	0.5	0.6	219	28.4	46.5
	spring	40	injected	0.6	0.6	197	29.0	96.6
	fall	160	surface	<0.2	0.5	172	24.0	40.9
	fall	160	injected	<0.2	0.7	257	20.1	47.1
	spring	160	surface	0.3	0.6	178	30.2	49.2
	spring	160	injected	0.6	0.6	189	24.5	42.4
Mixed Prairie	fall	10	surface	0.5	0.5	210	32.0	55.0
	fall	10	injected	0.5	0.7	244	32.3	63.7
	spring	10	surface	0.8	0.8	218	31.0	67.9
	spring	10	injected	0.4	0.5	220	28.5	59.0
	fall	40	surface	0.8	0.5	167	28.4	50.1
	fall	40	injected	0.3	0.6	202	28.7	56.7
	spring	40	surface	<0.2	0.5	189	31.9	61.8
	spring	40	injected	0.4	0.7	184	24.2	59.8
	fall	160	surface	0.7	0.5	201	28.1	53.5
	fall	160	injected	0.4	0.7	211	29.0	53.3
	spring	160	surface	0.6	0.3	169	32.9	56.0
	spring	160	injected	0.6	0.6	195	29.3	55.8
Fescue Prairie	fall	10	surface	0.3	0.7	219	31.7	75.9
	fall	10	injected	0.4	0.6	228	27.2	84.7
	spring	10	surface	0.8	0.6	204	25.4	59.0
	spring	10	injected	0.7	0.8	194	26.0	74.8
	fall	40	surface	0.4	0.5	179	26.1	58.7
	fall	40	injected	0.6	0.6	201	27.2	69.7
	spring	40	surface	0.8	0.4	203	28.5	64.6
	spring	40	injected	0.4	0.5	188	27.5	68.3
	fall	160	surface	<0.2	0.6	204	26.0	61.9
	fall	160	injected	0.2	0.6	238	25.7	69.5
	spring	160	surface	<0.2	0.5	157	22.8	63.8
	spring	160	injected	0.2	0.5	181	25.5	73.1