INFLUENCE OF SLOPE POSITION AND HOG MANURE INJECTION ON FALL SOIL P AND N DISTRIBUTION IN AN UNDULATING LANDSCAPE

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ABSTRACT. Investigation of how soil nutrients are distributed over the landscape in the fall is a prerequisite to identify critical source areas (CSA), which contribute soil nutrients to surface waters through snowmelt runoff. The objectives of this study are to investigate: (1) the distribution of soil nutrients in the landscape before soil freeze-up, and (2) how manure application in the fall affects this distribution. The study site, located in an undulating landscape in the Canadian prairies, is a closed drainage basin with moderate to fine textured soil. The basin received hog manure in fall 2001 and fall 2003. The landscape was classified into the shoulder, backslope, and footslope using a digital elevation model (DEM). Soil samples, collected from each landform segment in fall 2003 and fall 2004, were analyzed for available soil phosphorus (ASP), nitrate (NO₃⁻), and ammonium (NH₄⁺). In the undulating landscape, ASP levels had a distribution pattern of backslope < shoulder < footslope in fall 2003. The NO₃⁻ levels increased from the shoulder to the footslope. The NH₄⁺ levels did not vary between the shoulder and the backslope, while the footslope had significantly higher NH₄⁺ than the other two landform segments. Manure application appeared to change these distribution patterns of ASP, NO₃⁻, and NH₄⁺ temporally. However, one year after manure application, the manure effect was only seen for ASP. The soil moisture level at the footslope was significantly different from that of the other landform segments in fall 2004. The shoulder and backslope were homogeneous in terms of soil moisture for both fall seasons.

Keywords. Critical source areas, Fall soil nutrients, Hog manure, Landscape positions.

Contributions of phosphorus (P) and nitrogen (N) through snowmelt runoff from agricultural fields to surface water bodies are primarily controlled by the interaction of P and N source factors (such as fall soil P and N, nutrients released from crop residues, and manure applied in the fall) with transport factors (snowmelt runoff) (Gburek and Sharpley, 1998). Therefore, prevention of nutrient (i.e., P and N) loss with snowmelt runoff from agricultural fields should target the source areas that combine high soil P and N levels with high snowmelt runoff potential. In order to implement control measures that reduce or prevent the nutrient losses to the surface waters with snowmelt runoff, the spatial variability of soil nutrients (i.e., soil P and N) across the landscape in the fall should be known.

Most agricultural fields in the Canadian prairies are characterized by hummocky or undulating features (Pennock et al., 1987). In landscapes with this form of topography, water redistribution is the fundamental control of nutrient cycling, soil productivity, and crop yield (Pennock et al., 1987). Lower slope segments (e.g., footslopes) typically have the greatest soil water and nutrient content, and thus generally produce the highest crop yield (Halvorson and Doll, 1991). Redistribution of water, solute, and solids from upper slope (e.g., shoulder) to lower slope (e.g., footslope) segments due to gravity is considered to be the major pedogenic process associated with variable topography (Hairstion and Grigal, 1994; Pennock et al., 1994). Pennock et al. (1987) described that higher soil moisture contents are expected in convergent landscape elements relative to divergent elements and generally follow the sequence of shoulder < backslope < footslope. Increases in soil water and N contents in the downslope direction have been frequently documented (Ruhe, 1975; Schimmel et al., 1985; Butler et al., 1986). Stevenson et al. (1995) found 32% higher soil moisture contents at the footslope relative to the shoulder in the thick Black soil zone near Birch Hills, Saskatchewan, Canada.

In semi-arid regions, topographic differences are responsible for much of the variability in soil fertility and crop yield (Rennie and Clayton, 1960; Malo and Worcester, 1975). The crop demand for nutrients such as N and P may vary across the landscape, largely as a function of differences in water availability and the level of nutrients. Gregorich and Anderson (1985) found that the greater moisture levels, greater infiltration, and subsequent greater vegetation growth of the lower slope positions, along with the redistribution of soil to lower slope segments, resulted in increased organic carbon (OC) and available N and P content at these segments. Similar findings were reported by Anderson.
Variation of plant-available N (PAN) has been recorded at different landscape segments (Jowkin and Schoenau, 1998), and this variation is mainly controlled by the spatial variation in net N mineralization (Qian and Schoenau, 1995). The PAN also varies with management practices such as tillage and the use of leguminous crops. Although the response of N mineralization to different management practices has been considered by numerous researchers, little of this work has been done on variable landscapes. Dharmakeerthi et al. (2005) reported that most of the variation in PAN within a season in the landscape was accounted for by the variation of OC content. They further reported that the spatial pattern of PAN was temporally stable, suggesting a temporal consistency in the spatial patterns of factors influencing PAN. Solohub et al. (1996) reported that the pre-seeding, bicarbonate-extractable P showed a significant landscape effect in Black Chernozemic soils developed on a rolling lacustrine landscape at Birch Hills, Saskatchewan. The P levels were greatest in the lower levels and depressional positions followed by the footslopes, while the shoulder contained the least sodium bicarbonate extractable P. Cahn et al. (1994) observed that NO₃⁻ and PO₄-P data, collected across the landscape, were highly skewed due to several outlying values. They suggested that the high values may represent sites of high microbial activity or localized accumulation of nutrients.

Most of these studies had been focused on the spatial distribution of soil nutrient and moisture of soil depths greater than 50 mm at the beginning of or during the growing season. However, spatial distribution of fall soil nutrients in the top 50 mm layer is the most important factor that determines the quality of snowmelt runoff. The nutrient distribution observed at seeding or during the growing season will not necessarily be the same as that occurring in the fall because of active processes such as soil erosion, nutrient addition to the soil, or nutrient uptake by plants and micro-organisms during the growing season. Therefore, a study that focuses on the fall distribution of soil nutrients in the landscape before soil freeze-up is important to understand and to manage the quality of snowmelt runoff water.

Investigation of how soil P and N are distributed in the fall landscape will provide information vital for understanding and identification of critical source areas (CSA) that affect the quality of snowmelt runoff. Assessment of spatial distribution of soil nutrients is further important in making land use decisions, varying fertilizer application, identifying mapping units, designing field experiments, and scaling up field studies to regional scales (Soil Survey Staff, 1975; Pennock et al., 1987; van Kessel et al., 1993; Fiez et al., 1995; Stevenson et al., 1995). Therefore, the primary objectives of this study are: (1) to investigate the distribution of soil nutrients (soil P and N) across the landscape in the fall, and (2) to study how fall-injected hog manure affects the amount and distribution of soil nutrients. This study focused only on available P and N, which are crucial nutrients in terms of crop production and surface water quality.

**MATERIALS AND METHODS**

**SITE CHARACTERISTICS**

The experimental site was a small drainage basin, approximately 0.8 ha, with an average slope of 2.7%. This site was chosen within one farm field as being representative of the local landscape. The site was located (52° 02′ N, 106° 06′ W) 55 km east of the city of Saskatoon, Saskatchewan, Canada. The area has an undulating landscape with local small hilltops and depressions consisting of fine-textured lacustrine material over till. Snowmelt runoff accumulates in the central depression (fig. 1). Subsequent infiltration of the accumulated runoff generally takes between two and four

Figure 1. Experimental watershed with the locations of sampling points (circles refer to sampling points for the footslope, triangles for the backslope, and squares for the shoulder; dotted lines show the transects).
Figure 2. Schematic diagram of relative locations of landform segments with surface water flow on the surface. The size of arrows indicates the depth of water flow at that point on the surface (adapted from Pennock, 2003).

weeks depending upon the volume. The soil is classified as an Orthic Dark Brown Chernozem (Typic Haploborol) of the Elstow association (Acton and Ellis, 1978), consisting of medium to moderately fine-textured, moderately calcareous, clayey glacio-lacustrine deposits (ADF, 2002). Soil texture of the upper 150 mm of soil is clay loam to silty clay.

A meteorological station, installed at the site, recorded air temperature and rainfall data for our study. For comparison purposes, climatic normals (1971-2000) from the town of Viscount (51°57′ N, 105°37′ W), about 30 km to the east of the site, were used (Environment Canada, 2005). The mean annual air temperature at Viscount is 2.5°C, with a monthly mean of −16.8°C in January and 18.1°C in July (1971-2000). Monthly air temperatures are below 0°C from November through March; therefore, a hydrological year is defined starting on 1 November and ending on 31 October (Hayashi et al., 1998). A hydrological year consists of a winter (November to March), a spring (April and May), a summer (June to August), and a fall (September and October). The mean annual precipitation at Viscount is 412 mm, of which 84 mm occurs in the winter, 184 mm during the summer, and 63 mm during the fall.

This study focuses on data collected in fall 2003 and fall 2004. The field, within which the study watershed was located, received agitated hog manure in fall 2001 for the first time and again in fall 2003 (2 October 2003). The application rate of 56.2 m³ ha⁻¹ (approximately 125 kg N ha⁻¹ and 36 kg P ha⁻¹) was based on the common hog manure application rate in the province. Manure was applied in an east to west direction by a commercial operator. Knife openers injected the manure to a depth of 100 to 120 mm, and a compaction wheel closed the injection slots. With the exception of manure application, the seeding operation was the only other soil disturbance in the reduced tillage system in use at the study site. An air seeder with a sweep opener was used for seeding. After seeding, the soil was subsequently harrowed and packed. In 2003, canary seed (Phalaris canariensis) was grown in the site, while wheat (Triticum aestivum L) was grown in 2004. Crops had been removed from the site at the time of manure application and sampling. The average stubble height was about 150 mm.

This article presents the results of nutrient (P and N) analysis of soil samples collected from the top 50 mm layer in fall 2003 and fall 2004. The study period was characterized by a relatively dry summer and fall in 2003 (143 and 45 mm, respectively) and a normal summer (183 mm) in 2004 followed by a dry fall (32 mm).

**TOPOGRAPHIC ANALYSIS AND LANDFORM SEGMENTATION**

The site was surveyed using a laser theodolite. The topographic survey, taken at approximately 10 m spacing, was used to interpolate a DEM for the site. A kriging interpolator was used for surface interpolation. The morphological attributes (i.e., aspect, plan curvature, profile curvature, and gradient) for each cell of the DEM were calculated using the programs of Martz and de Jong (1988). The terrain attributes (definitions are given in table 1) were then used to place each cell into a discrete landform element class using pre-defined ranges of morphological and positional terrain attributes (Pennock, 2003). The landscape was then classified into the landform segments utilized in this study: shoulder, backslope, and footslope (fig. 2).

**SAMPLING**

Six sampling transects were established, radiating outwards from the central depression (fig. 1) to the shoulder in the directions of NE, E, SE, SW, W, and NW. Three sample locations per transect were picked so that each landform segment was represented. Soil samples were collected on 1 October 2003, before manure application (bma), on 18 October 2003 after manure application (ama), and once in

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>Elevation above sea level or a local datum (m).</td>
</tr>
<tr>
<td>Gradient</td>
<td>Slope between the land surface and a horizontal plane at a given point (m m⁻¹, degree or percent).</td>
</tr>
<tr>
<td>Aspect</td>
<td>The compass direction that the slope segment is facing (degree).</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>Downslope curvature of a slope segment. By convention, convex curvatures are assigned positive values and concave curvatures negative values (degree m⁻¹).</td>
</tr>
<tr>
<td>Plan curvature</td>
<td>Across-slope or contour curvature of the slope segment. By convention, convex curvatures are assigned positive values and concave curvatures negative values (degree m⁻¹).</td>
</tr>
</tbody>
</table>
the following year on 14 October 2004. Manure was not applied in fall 2004. At each sample location, four soil samples were taken randomly within a 2 m² area. Sampling errors were minimized through the careful soil sample collection. At each sample location, three soil samples were collected and bulked for analysis of soil moisture and soil nutrients. Each soil sample consisted of the soil from a 330 mm (long) × 100 mm (wide) and 50 mm (deep) block that had been carefully delineated and then removed with a spade. The dimensions of the soil sample were chosen to ensure representative inclusion of one manure injection slot and the area between injection slots. The depth of soil sampled (0 to 50 mm) represents an environmental rather than agronomic sampling depth; it is an average effective depth of surface soil-runoff interaction for a range of soils, rainfall intensities, slopes, and soil management characteristics (Sharpley, 1995). Representative hog manure samples were collected at the time of application and were analyzed for manure N and P (table 2). Nearly 61% of the total N (TN) in the hog manure was in the available form of NH₄⁺, while 20% of total P (TP) was in the available form. Daniel et al. (1994) and Schoenau et al. (2000) reported similar results with liquid hog manure.

**LABORATORY ANALYSIS**

All soil samples were air-dried and sieved (to less than 2 mm) before analysis. The available P (ASP) of soil samples and hog manure samples were determined using modified Kelowna extraction (Qian et al., 1994), and NO₃⁻ and NH₄⁺ were determined using 2M KCl extraction (Keeney and Nelson, 1982). Soil samples collected in fall 2004 were also analyzed for TN, TP, OC, and total C (TC). The TN and TP of both soil and hog manure samples were determined by sulfuric-acid-peroxide digestion at 360 °C (Thomas et al., 1967), followed by colorimetric determination of N as NH₄⁺ and P as orthophosphate using Technicon automated colorimetry. The OC and TC were determined using a Leco Carbonator automated combustion carbon analyzer and the method of Wang and Anderson (1998). Inorganic C was calculated by subtracting OC from TC. Soil moisture contents were determined in fresh soil samples collected in fall 2003 and fall 2004 by oven-drying (105 °C for 24 h).

**DATA ANALYSIS**

The ASP, NH₄⁺, NO₃⁻, and soil moisture values for each landform segment were initially grouped into box plots, which allow both the median and dispersion of values to be visually assessed. The results were tested for normality using the Shapiro-Wilk statistics using the Proc Univariate function of SAS (SAS, 1999). As the data from each landform segment were used to compare ASP, NH₄⁺, NO₃⁻, and soil moisture values between landform segments. The results were evaluated using one-way analysis of variance (ANOVA) using a least significant difference multiple comparison test to assess the significance of the difference between pairs of landform segments. The significance level (α) was set at 0.05.

**RESULTS AND DISCUSSION**

**SOIL CHARACTERISTICS**

Means of TN, TP, TC, and OC of the surface 50 mm layer of soil collected in fall 2004 increased from the shoulder to the footslope (table 3). Previous studies (Honeycutt et al., 1990; Pennock and Corre, 2001; Landi et al., 2004) reported that OC increases from the shoulder to the footslope and related this trend to long-term transport of fine OM and lateral movement of clay from higher elevations. The OC content may also be related to the biomass productivity, which is affected by moisture redistribution in the landscape. Although OC levels in our study increased from the shoulder to the footslope, only the OC at the footslope was significantly different from other landform segments. The lack of significant difference between the shoulder and the backslope indicated that these two segments were homogeneous with respect to OC. Therefore, the OC level could be represented by the sequence shoulder = backslope < footslope, rather than by the sequence shoulder < backslope < footslope, as observed in the previous studies (Honeycutt et al., 1990; Pennock and Corre, 2001; Landi et al., 2004).

Amounts of inorganic C (less than 1% of soil mass) were relatively low and were not significantly different between slope segments. Hence, the distribution of TC was largely influenced by the OC content and had the same distribution pattern (shoulder = backslope < footslope).

The distribution pattern of the mean TP level was the same as that for OC and TC, increasing from the shoulder to the footslope (table 3) with no significant difference between the shoulder and backslope. However, the TN level was significantly different between all the landform segments and had the distribution pattern of shoulder < backslope < footslope in this undulating landscape. The inorganic portions of TN, expressed as the sum of NO₃⁻ and NH₄⁺ levels, was 91.5, 44.1, and 22.5 mg kg⁻¹ of soil, respectively, for the footslope, backslope, and shoulder. Variation of PAN has been previously recorded between different landform segments (Jowkin and Schoenau, 1998), and this variation has been attributed to the spatial variation in net N mineralization (Qian and Schoenau, 1995). Net mineralization is influenced by OM content and the readily mineralizable N content of OM, texture, water content, soil structure, temperature, pH, and the C/N ratio of OM. Many of these properties (OM content, texture, and water content) are known to vary across sloping landscapes (Afyuni et al., 1993; Goovaerts and Chiang, 1993; Brubaker et al., 1994; Hook and Burke, 2000).

**Table 2. Nutrient analysis from liquid hog manure samples in fall 2003.**

<table>
<thead>
<tr>
<th>Total N and P (H₂SO₄ digested)</th>
<th>Available N and P</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manure Sample</strong></td>
<td><strong>TN (mg N kg⁻¹)</strong></td>
<td><strong>TP (mg P kg⁻¹)</strong></td>
<td><strong>NH₄⁺ (mg NH₄ kg⁻¹)</strong></td>
</tr>
<tr>
<td>1</td>
<td>2255.0</td>
<td>648.0</td>
<td>1656.0</td>
</tr>
<tr>
<td>2</td>
<td>2207.0</td>
<td>648.0</td>
<td>1858.0</td>
</tr>
<tr>
<td>Mean</td>
<td>2231.0</td>
<td>648.0</td>
<td>1757.0</td>
</tr>
</tbody>
</table>

**Table 3. Means of soil TN, TP, TC, and OC (six samples for each landform segment) in fall 2004 from three landform segments.**

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Footslope</th>
<th>Backslope</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN (mg kg⁻¹)</td>
<td>2835.0 a</td>
<td>2057.0 b</td>
<td>1607.0 c</td>
</tr>
<tr>
<td>TP (mg kg⁻¹)</td>
<td>1010.0 a</td>
<td>759.0 b</td>
<td>743.0 b</td>
</tr>
<tr>
<td>TC (%)</td>
<td>5.45 a</td>
<td>4.0 b</td>
<td>3.7 b</td>
</tr>
<tr>
<td>OC (%)</td>
<td>4.63 a</td>
<td>3.4 b</td>
<td>3.0 b</td>
</tr>
</tbody>
</table>

[a] Means followed by the same letter are not significantly different at α = 0.05. Lowercase letters are used for mean comparison between columns.
**FALL SOIL MOISTURE CONTENT**

In both fall 2003 and fall 2004, the soil moisture content increased from the shoulder to the footslope (table 4). However, in 2003, they were not significantly different between landform segments. In fall 2004, the moisture content at the footslope was statistically different from those at the backslope and shoulder (table 4), but the moisture contents at the shoulder and backslope were not significantly different.

In the semi-arid climate of this region, potential evapotranspiration exceeds the growing season’s precipitation, and most of the available soil moisture is used by the crop during the growing season. However, in fall 2004, the footslope was significantly wetter than the backslope and shoulder, and this could be due to a sufficiency of growing season precipitation and above-average precipitation in August. As a result, moisture reserves at the footslope were not required by the crop. In fall 2003, the dry summer conditions depleted moisture reserves at all landform segments. Miller et al. (1988) also indicated that the spatial distribution pattern of soil moisture is absent when below-normal precipitation occurs. The other landform segments (shoulder and backslope) were not different in terms of fall soil moisture levels in either year. The low slope of this site (average slope is 2.7%) may not be steep enough to be a major effect on moisture redistribution between the upper and mid-slope positions.

**SOIL NITRATE (NO\textsubscript{3}\textsuperscript{−})**

The mean fall 2003 NO\textsubscript{3}\textsuperscript{−} levels (bma) increased from the shoulder to the footslope (shoulder < backslope < footslope) (fig. 3, table 5), as was observed with OC and TN (table 3). As NO\textsubscript{3}\textsuperscript{−} is readily mineralized from soil OM, it generally reflects the pattern of OC. However, NO\textsubscript{3}\textsuperscript{−} levels between landform segments were not significantly different, and this could be due the high NO\textsubscript{3}\textsuperscript{−} variability observed within the footslope and the backslope (fig. 3) and the homogeneity of soil moisture conditions across the landscape in fall 2003.

After manure injection in fall 2003, NO\textsubscript{3}\textsuperscript{−} levels increased by 41.3, 32.0, and 16.5 mg NO\textsubscript{3}\textsuperscript{−} kg\textsuperscript{−1} of soil, respectively, for the shoulder, backslope, and footslope. The highest increase was in the shoulder, and the lowest increase was in the footslope. Only the shoulder and backslope showed a significant increase (uppercase letters in table 5). Mean NO\textsubscript{3}\textsuperscript{−} levels (ama) in fall 2003 increased from the shoulder to the footslope, but the differences were not statistically significant (table 5).

In fall 2004, the distribution pattern of NO\textsubscript{3}\textsuperscript{−} among the landform segments was the same as observed in fall 2003 bma and ama (table 5). However, the mean NO\textsubscript{3}\textsuperscript{−} levels for the landform segments were now significantly different from each other. During the 2004 growing season, N supply on the footslope and backslope must have been in excess of crop requirements. Wet and cooler summer conditions in 2004 could have been favorable for mineralization. These conditions might have created significant differences in NO\textsubscript{3}\textsuperscript{−} level between the landform segments.

By fall 2004, the shoulder and backslope had lost NO\textsubscript{3}\textsuperscript{−} while the footslope had gained soil NO\textsubscript{3}\textsuperscript{−} relative to the levels observed after the manure injection in fall 2003. Fall 2004 NO\textsubscript{3}\textsuperscript{−} levels for the shoulder, backslope, and footslope changed by −45.7, −30.0, and +10.8 mg NO\textsubscript{3}\textsuperscript{−} kg\textsuperscript{−1} of soil, respectively, since the manure injection in fall 2003. The NO\textsubscript{3}\textsuperscript{−} loss from the shoulder and backslope could be attributed to crop uptake, low organic matter mineralization, and/or NO\textsubscript{3}\textsuperscript{−} loss due to leaching and denitrification. Although crop uptake, leaching, and denitrification would have also occurred on the footslope, mineralization and N transport with runoff from upslope areas might have been sufficiently high to compensate for the losses.

Soil NO\textsubscript{3}\textsuperscript{−} levels in fall 2004 (one year after the manure injection) were not significantly different from that of fall 2003 (bma) for each landform segment (uppercase letters in table 5). The NO\textsubscript{3}\textsuperscript{−} resulting from the manure injection appeared to have been utilized by the crop, lost by...
for the shoulder, backslope, and footslope, respectively. The encompass the full range of data for the landform segments).

Figure 4. Box plots for soil NH$_4^+$ levels for different landform segments in fall 2003 (before manure application) and in fall 2004. (The line in the middle of the box is the median value, the box encloses the data points between the 25th and 75th quartiles, and the whiskers and outlier symbols encompass the full range of data for the landform segments).

denitrification, or leached below the sampling depth (50 mm).

**SOIL AMMONIUM (NH$_4^+$)**

Before manure application in 2003, NH$_4^+$ levels increased from the shoulder to the footslope (fig. 4, table 5). However, as observed for OC (table 3), NH$_4^+$ levels on the shoulder and backslope were not significantly different from each other, while the level on the footslope was significantly different from those on the other two landform segments (table 5). The higher NH$_4^+$ level at the footslope could be due to the higher OM content, which could release more NH$_4^+$ by mineralization, and due to transport of NH$_4^+$ to the footslope from the upslope areas through runoff.

Hog manure injection significantly increased the NH$_4^+$ level in all landscape segments (table 5). On the shoulder, manure injection increased the NH$_4^+$ level by a factor of more than 60. The NH$_4^+$ levels observed after manure injection were not significantly different between the landform segments.

One year after the manure injection (fall 2004), soil NH$_4^+$ levels decreased drastically, relative to fall 2003 (ama), and were not statistically different from the values observed in fall 2003 (bma) (uppercase letters in table 5). Reduction of NH$_4^+$ levels between fall 2004 and fall 2003 (ama) could be attributed to crop uptake and/or nitrification. The NH$_4^+$ level distribution in fall 2004 across the landscape was similar to the distribution pattern observed in fall 2003 (bma). Irrespective of the soil moisture distribution pattern observed in both fall seasons, NH$_4^+$ distribution showed a consistent distribution pattern, which was similar to the soil OC distribution pattern in the landscape.

**AVAILABLE SOIL PHOSPHORUS (ASP)**

Between fall 2003 (bma) and fall 2004, the mean ASP level for each landform segment increased significantly (fig. 6, table 5). Overall (between fall 2003 bma and fall 2004), ASP increased by 15.6, 9.6, and 7.7 mg P kg$^{-1}$ of soil for the shoulder, backslope, and footslope, respectively. The increase was at least partly due to the manure injection in 2003. However, despite an increase in mean ASP on each landform segment after manure application, there was no significant difference in ASP at the footslope or backslope between the two sampling dates in 2003. The impact of the manure application was not immediately observable on all positions because only 20% of TP in hog manure applied on this field was in the available form (table 2). In addition, the manure injection depth was below the sampling depth; therefore, only manure left in the injection slot was included in the sample. The increased variability in ASP levels after manure injection would also have made statistical significance more difficult to obtain (figs. 5 and 6).

By fall 2004, the mean ASP level of each landform segment had increased significantly from the levels observed in fall 2003 (fig. 6, table 5). The delayed increase in ASP after manure application reflects liberation of ASP in soil by mineralization of applied manure, OM, and plant residues; movement of applied manure from the application depth to the surface soil; and mixing in the surface layer during seeding. It is unlikely that a loss and gain of soil P due to soil erosion (i.e., tillage and water erosion) and deposition, respectively, would be a significant process in this landscape since the average slope is 2.7% and large runoff events (more

Figure 5. Box plots for ASP levels for different landform segments in fall 2003 (before and after manure application) and in fall 2004. (The line in the middle of the box is the median value, the box encloses the data points between the 25th and 75th quartiles, and the whiskers and outlier symbols encompass the full range of data for the landform segments).

Figure 6. Variation of mean ASP level in the fall across the landscape before and after manure injection and one year after manure application.
than 20 mm a day) from snowmelt or rainfall do not occur. Jones et al. (2001) reported that slopes greater than 3% increase the risk of soil erosion and can lead to increases in nutrient and sediment loading to surface waters. The ASP on the shoulder in fall 2004 was not significantly different from the level observed in fall 2003 ama, while this ASP level was significantly different from that of fall 2003 (bma). This is most likely due to the high variability of ASP levels observed immediately after manure injection in fall 2003 (fig. 5). The amount of OM mineralization should have been similar for the backslope and the shoulder since they had similar OC and moisture contents. The ASP levels varied between the landform segments (fig. 5, table 5). In fall 2003 (bma), the lowest mean ASP level (0.6 mg P kg\(^{-1}\) of soil) was at the backslope, while the highest mean ASP level (6.8 mg P kg\(^{-1}\) of soil) was at the footslope, and ASP levels increased in the sequence of backslope < shoulder < footslope. These ASP levels were significantly different between the landform segments (table 5). Available soil P levels in fall 2001 (before any manure application on this field) for the same landform segments at the site showed the same distribution pattern of backslope < shoulder < footslope (data are not reported here, as analytical methods and units to estimate ASP were different). This pattern is different from the patterns observed for soil moisture, carbon, and nitrogen and must reflect the long-term impact of agronomic practices and hydrological processes on ASP at the site. The hog manure injection in fall 2003 only significantly increased ASP on the shoulder in 2003 and resulted in a new distribution pattern (fig. 6) of mean ASP between the landform segments (backslope < footslope < shoulder). However, the mean ASP levels in 2003 (ama) were only significantly different between the backslope and the shoulder (table 5). Mean ASP levels in fall 2004 (one year after manure application) also varied between the landform segments (figs. 5 and 6, table 5) but the differences were not statistically significant. The lowest mean ASP level (10.1 mg P kg\(^{-1}\) of soil) was at the backslope, while the highest mean ASP level (19.1 mg P kg\(^{-1}\) of soil) was at the shoulder, and ASP had the distribution pattern of backslope < footslope < shoulder. This pattern was similar to the pattern observed after manure application in fall 2003 (one year before).

**CONCLUSIONS**

Soil NO\(_3^-\) levels in this landscape increased in the downslope direction (from the shoulder to the footslope) in the fall. However, in fall 2003, differences between the landform segments were not significant, perhaps because of the dry summer conditions, which resulted in homogeneous soil moisture conditions across the landscape and limited mineralization of soil OM. Even though fall manure application increased the soil NO\(_3^-\), the distribution pattern of soil NO\(_3^-\) in fall 2004 (one year after the manure application) regained the distribution pattern that was observed before manure application (shoulder < backslope < footslope). In 2004 fall, NO\(_3^-\) levels were significantly different between the landform segments because of the normal summer conditions, which resulted in different soil moisture levels between the landform segments.

Irrespective of the climatic conditions, soil NH\(_4^+\) levels showed a consistent distribution pattern for the two fall seasons. The shoulder and backslope were homogeneous in terms of NH\(_4^+\) levels in both fall seasons. However, the footslope had a significantly higher NH\(_4^+\) level than the other two landform segments. Hog manure injection increased both NO\(_3^-\) and NH\(_4^+\) levels in the top 50 mm layer. However, the increase in soil NO\(_3^-\) and NH\(_4^+\) levels after the manure application was no longer apparent in fall 2004. In addition to plant uptake, between sampling times, the NH\(_4^+\) from manure would have been volatilized or converted to NO\(_3^-\) through nitrification, and NO\(_3^-\) would have denitrified or leached below the sampling depth. For the undulating landscape in this study, ASP concentrations prior to manure application in fall 2003 varied with landform segments in the order of backslope < shoulder < footslope. Hog manure injection did not immediately increase the ASP level in the top 50 mm layer in the landform segments, except in the shoulder. One year after the manure injection, the ASP level in the top 50 mm layer of soil was significantly increased in all landscape positions. The changes in ASP level and distribution pattern after hog manure application were more persistent than changes in NO\(_3^-\) and NH\(_4^+\), as more P from the manure application would have become available through time and the resulting ASP would be retained in the surface soil.

**ACKNOWLEDGEMENTS**

We would like to thank Saskatchewan Agriculture Development Fund, Saskatchewan Wheat Pool, Saskatchewan Pork and Alberta Pork for funding; David Gallén (Environment Canada), Sandra Kuchta, Jean Chen, Shahid Sarwar, Chandima Karunanayake, and Lisa White (University of Saskatchewan) for assisting with the research; D. J. Pennock of the Department of Soil Science, University of Saskatchewan for assisting with survey instruments and surveying software; Prairie Swine Centre; and Dan Gryschuk for allowing us to work on his land.

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