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Solute Transport in Eroded and Rehabilitated Prairie Landforms. 1. Nonreactive Solute

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Information regarding solute and water transport as affected by soil properties, topography, and climatic conditions is required to improve and validate transport models. This study evaluated the dissipation of bromide applied to the soil surface in the fall and spring to undisturbed (eroded) and rehabilitated landforms, in which topsoil was moved from depositional areas to the eroded upper slope. Despite large changes in soil properties, the amount and center of mass of bromide remaining in the top 1 m of soil was the same in undisturbed and rehabilitated plots. Approximately 60% of the fall-applied bromide was lost during the winter and early spring, presumably due to leaching and runoff. The center of mass of spring-applied bromide remained at depths of <30 cm. At the end of the experiment, 33% of the spring-applied bromide was detected in soil and 56% in corn plants. These results suggest that little bromide was leached out of the root zone in the spring and that plant uptake was a major route of bromide dissipation during the growing season.

KEYWORDS: Bromide; frozen soil; leaching; plant uptake; soil-landscape rehabilitation; slope

INTRODUCTION

The hummocky landscapes of the northern North American prairies are highly productive, but prone to erosion. Soils in this region have been tilled for ~100 years, during which tillage and water erosion have combined to result in a complex redistribution of soil in hilly landforms. In eroded upper slope positions, organic carbon contents are low throughout the profile and subsoil material is close to the soil surface, often incorporated into the tilled layer. Topsoil accumulation in areas of decreasing slope results in relatively high organic carbon and nutrient concentrations throughout the upper profile and a large depth to the C horizon (*1*). One approach to increase the overall productivity of eroded landscapes is soil-landscape rehabilitation, in which topsoil is moved from areas of net soil accumulation (areas of decreasing slope) to areas of net soil loss (convex landscape positions). Such intralandform soil movement can result in increased uniformity in soil properties across the landform and increased productivity in areas of soil addition (*2*).

In eroded landforms, soil chemical and physical properties that influence water infiltration, retention, and runoff are highly variable with landscape position (*1−3*). Landscape position affects the dynamics of water flow and sediment transport (*4*). Bromide is widely used as a hydrologic tracer because it undergoes little sorption or transformation in the soil-water environment. Many field and laboratory studies have used bromide as a tracer of water movement to indicate the importance of soil physical properties and water application rates and timing on vertical water transport through bare soil. These studies have indicated that bromide transport in structured field soils can be highly variable, impacted by soil texture and the presence of preferential flow paths (*5*, *6*).

Movement of bromide downslope from the area of application has been reported (*7*, *8*). Several studies have evaluated the influence of landscape position on bromide transport in soil. These studies found that at the same sampling time, the depth of surface-applied bromide leaching was deeper in the footslope than in the backslope and shoulder slope positions (*3*, *7*). The increased leaching in the footslope was attributed to the higher hydraulic conductivity of the surface soil and lower clay content of subsurface soils in the footslope compared to upper slope positions (*3*, *7*). In a grassed watershed, deeper transport of bromide was observed in the drainage way than in the backslope (*8*). In each of these studies, differences in bromide transport were only observed when cumulative rainfall was >500 mm.

Plant uptake of bromide has been implicated in its dissipation when used as a tracer (*9−11*). Bromide is readily taken up by plants and is extensively translocated to the shoot and leaves of corn (*12*) and other plants. Bromide taken up by plants tends to remain in inorganic form (*11*) except for a small fraction that can be methylated by some plants (*13*). There is some evidence of active bromide uptake by corn (*14*), so plant uptake of bromide may serve as an upper limit for the passive uptake of other solutes.

Information regarding the spatial variability of solute and water transport as affected by soil properties, topography, and climatic conditions is required to improve and validate transport models, especially because most of the available information is for soils in the southeastern United States where there are no freeze/thaw cycles. Information is needed for the northern Corn Belt, where many prairie potholes have been drained and cultivated for agricultural production. Prairie potholes exhibit a complex hydrology including large overland flow during snowmelt and

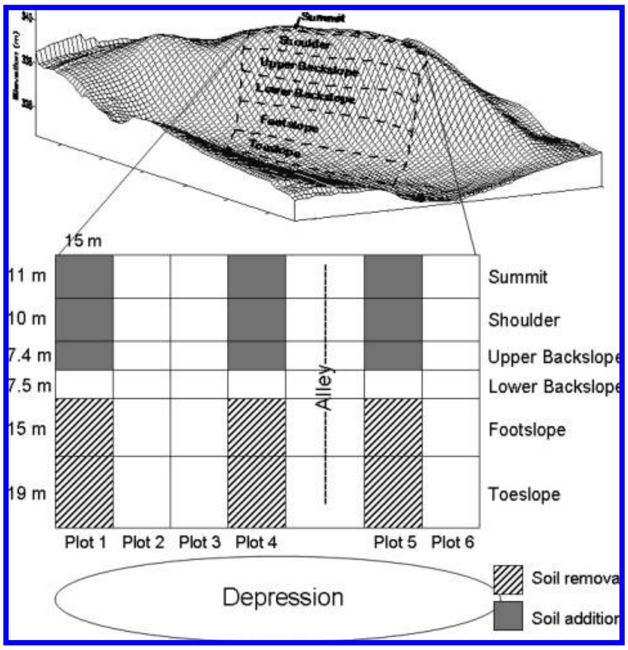

Figure 1. Schematic diagram of study site, including designation of landscape positions. Plots 1, 4, and 5 are rehabilitated; plots 2, 3, and 6 are undisturbed.

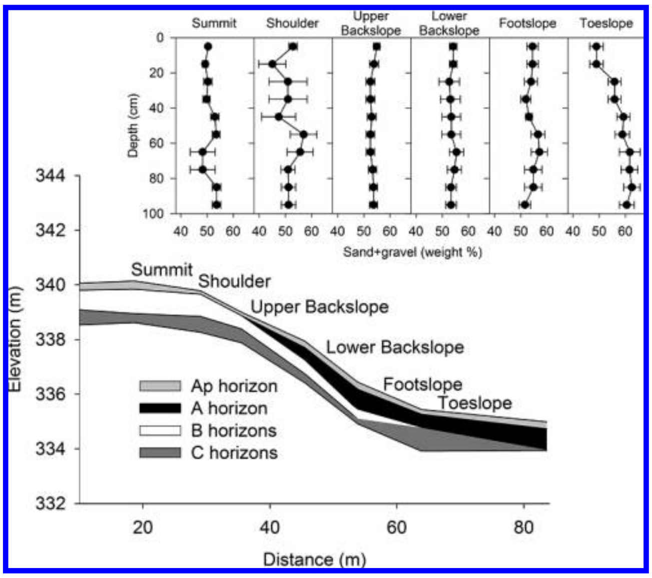

Figure 2. Soil horizons and sand + gravel content as a function of landscape position and depth prior to soil movement. Soil horizons are for a single transect in plot 3. Sand + gravel contents were determined by horizon and converted to a depth basis. Values are the mean of six plots ± standard error.

shallow subsurface flux of water upslope from wetlands with temporal shifts in hydraulic gradients (*15*). In these studies, we evaluated the dissipation of the nonreactive solute bromide (discussed in this paper) and a reactive solute, the herbicide metolachlor (discussed in a companion paper, ref *16*), in a highly variable eroded landform and in adjacent portions of the landform that were rehabilitated. These field studies provide unique information on solute movement under the same climatic conditions in landforms with nearly identical topography, but vastly different soil properties.

MATERIALS AND METHODS

Site. Experiments were conducted in west central Minnesota (45.65° N, 95.83° W) in a 0.8 ha portion of a 28 ha (70 acre) field. This site was characterized as part of a related experiment (*2*). The site consists of a ridge and a surface-drained wetland that was separated into six replicate plots extending from the summit to the toeslope. Each plot was segmented into six landscape positions, which are designated as subplots: summit, shoulder, upper backslope, lower backslope, footslope, and toeslope (**Figure 1**). Subplots were 15 m wide and ranged from 7.4 m (upper backslope) to 19 m (toeslope) in length (up/downslope direction).

Soils were formed in calcareous till. In upper slope positions, erosion has removed the mollic and cambic horizons from the soil profile. Throughout the upper slope and backslope, the B and C horizons are very high in calcium carbonate. In the footslope and toeslope, 46 cm of depositional material overlies the original A horizon, so that A-horizon material extends from the surface to a depth of > 68 cm (**Figure 2**). In the lower slope, B and C horizons are gleyed as a result of water logging.

Three of the plots were rehabilitated in November 2005 by removing accumulated topsoil from the lower slope (footslope and toeslope) and adding that soil to the eroded upper slope (summit, shoulder, and upper backslope, **Figure 1**). The area of soil removal was the same as the area of soil addition in each plot, so 15−20 cm of soil was removed from the lower slope and 15−20 cm of soil was added to the upper slope. The remaining three plots remained in their eroded condition and are designated undisturbed (**Figure 1**).

Agronomic Practices. This site that has been cultivated for ~100 years, with annual moldboard plowing for most of its cultivated history. For at least 10 years prior to this study, tillage consisted of fall chisel plowing following corn (*Zea mays*) crop and spring tillage following soybean (*Glycine max*) and wheat (*Triticum aestivum*) crops. The site was cropped to soybean in the growing season preceding this study.

Fertilization consisted of 130 kg ha^{-1} N as anhydrous ammonia applied in the fall and granular fertilizer (27−70−40) applied on May 10, 2007, at a rate of 240 kg ha^{-1}. Corn (DeKalb 4492) was planted on May 12, 2007, at a seeding rate of 79000 seeds ha^{-1} with a row spacing of 76 cm.

Soil Properties. Landscape position has a strong influence on soil properties in undisturbed plots, with the toeslope having significantly higher surface soil OC and EC than any other landscape position (**Table 1**). Surface soils in the summit, shoulder, upper backslope, and lower backslope of undisturbed plots are depleted in OC and have elevated IC contents (data not shown) due to the incorporation of calcareous subsoil material into the tilled layer. In undisturbed plots, surface soil OC concentrations in the lower slope are approximately 4 times (toeslope) and 2 times (footslope) that in the upper backslope (**Table 1**). Deep accumulation of topsoil in the lower slope results in soil OC concentrations that are higher throughout the profile in lower slope positions than in eroded upper slope positions of undisturbed plots. Surface soil textures were sandy clay loam in the summit, shoulder, and upper backslope; sandy loam in the lower backslope and footslope; and loam in the toeslope. In the toeslope, sand and gravel comprised a lower weight fraction of the soil at depths of < 20 cm than at depths of > 20 cm (**Figure 2**). The toeslope is an area of net soil deposition by tillage and water erosion (*2*); these processes have likely enriched the silt- and clay-sized fractions of the surface soil in the toeslope of undisturbed plots.

Following soil movement during rehabilitation, surface soil properties in the upper slope were similar to those for the footslope and toeslope (**Table 1**). In rehabilitated plots, upper slope surface soil OC increased by a factor of 2−3 compared to undisturbed plots. We observed no increase in soil compaction in rehabilitated plots as measured by bulk density and resistance to penetration (**Table 1**). The net effect of soil movement was that soil properties were shifted vertically upward by 15−20 cm in areas of soil removal (footslope and toeslope) and shifted downward by 15−20 cm in areas of soil addition (summit, shoulder, and upper backslope), with a large increase in surface soil OC and nutrients from the addition of 15−20 cm of high-organic-matter material to rehabilitated plots (**Table 1**) (*2*).

Removal of 15−20 cm of soil from the footslope and toeslope did not significantly change surface soil OC, EC, soil strength, or bulk density (**Table 1**). Removal of 15−20 cm of soil from the toeslope increased the mean particle size of the surface soil in this landscape position by removing the fine-textured material at the soil surface (**Figure 2**).

Table 1. Selected Surface Soil (0−15 cm Depth) Properties for Each Landscape Position[a]

soil property	summit	shoulder	upper backslope	lower backslope	footslope	toeslope
organic carbon (g kg^{-1})						
rehabilitated plots	38 ± 3 a	34 ± 2 a	32.9 ± 0.8 a	18 ± 2 a	23 ± 3 a	35 ± 3 a
undisturbed plots	17.4 ± 0.5 b	13 ± 2 b	11 ± 4 b	15 ± 4 a	22 ± 2 a	39 ± 1 a
electrical conductivity (μS cm^{-1})						
rehabilitated plots	374 ± 11 a	328 ± 14 a	299 ± 7 a	238 ± 7 a	267 ± 12 a	410 ± 7 a
undisturbed plots	253 ± 7 b	229 ± 6 b	215 ± 18 b	225 ± 13 a	268 ± 5 a	439 ± 14 a
resistance to penetration (MPa)						
rehabilitated plots	0.24 ± 0.06 a	0.27 ± 0.06 a	0.25 ± 0.06 a	0.37 ± 0.07 a	0.25 ± 0.04 a	0.28 ± 0.04 a
undisturbed plots	0.22 ± 0.04 a	0.24 ± 0.05 a	0.24 ± 0.04 a	0.29 ± 0.06 a	0.23 ± 0.05 a	0.22 ± 0.04 a
bulk density (g cm^{-3})						
rehabilitated plots	1.32 ± 0.03 a	1.30 ± 0.09 a	1.3 ± 0.1 b	1.37 ± 0.05 a	1.37 ± 0.03 a	1.06 ± 0.07 a
undisturbed plots	1.39 ± 0.05 a	1.36 ± 0.07 a	1.39 ± 0.06 a	1.40 ± 0.09 a	1.38 ± 0.03 a	1.15 ± 0.03 a
gravimetric water content on Nov 7 (%)						
rehabilitated plots	19.4 ± 0.4 a	18.9 ± 0.7 a	25 ± 2 a	16.2 ± 0.6 a	17.9 ± 0.4 a	24 ± 2 a
undisturbed plots	14.3 ± 0.2 b	13 ± 1 b	12.5 ± 8 b	13.6 ± 0.1 a	16.9 ± 0.4 a	21 ± 1 a
gravimetric water content on May 17 (%)						
rehabilitated plots	22 ± 3 a	19.5 ± 0.8 a	20 ± 1 a	16 ± 2 a	16 ± 2 a	27 ± 2 a
undisturbed plots	17.0 ± 0.4 a	15.6 ± 0.5 b	13.4 ± 0.9 b	1.46 ± 0.2 a	17 ± 1 a	23.1 ± 0.9 a

[a] Values are the mean of three replicate plots ± standard error. Lower case letters indicate significant differences between rehabilitated and undisturbed plots (Tukey test, α = 0.05) for each soil property at each landscape position.

Soil temperature was monitored continuously at a depth of 5 cm using temperature logging devices (Onset Computer Corp., Pocasset, MA) in plots 1, 2, 5, and 6. Rain gauges were installed at the site. Snowfall was monitored at the University of Minnesota West Central Research and Outreach Center, located 8 km from the study site.

Bromide Application. Potassium bromide (60 kg of KBr ha^{-1}, 40 kg of Br ha^{-1}) was applied to separate portions of three undisturbed plots and three rehabilitated plots in the fall (November 7, 2006) and in the spring (preemergence, May 17, 2007). Bromide solution was applied at 190 L ha^{-1} using a hooded sprayer with a 3 m wide boom and flat-fan nozzles at 0.21 MPa. Bromide was not incorporated. The bromide application rate was monitored in each subplot using empty Petri dishes. Bromide application resulted in surface soil (0−10 cm) bromide concentrations of $24 \pm 1\ \mu\text{g g}^{-1}$, which were consistent across landscape positions ($p > 0.05$) for both the fall and spring applications. Petri dishes and surface soil samples collected in untreated areas contained no detectable bromide.

Soil and Plant Sampling. Soil cores were collected to a depth of 1 m immediately before bromide application and throughout the growing season. Soil cores were collected 0, 14, 175, 203, and 226 days after fall application (November 7 and 21, May 1 and 29, and June 21) and 0, 7, 22, and 41 days after spring application (May 17 and 24, June 8 and 27). One soil core was collected in each subplot (36 cores per sampling). A 5.7 cm diameter Hoffer probe was used to collect a core from 0 to 10 cm. Brass rings were used to retain the opening and to avoid the contamination of soil > 10 cm deep with surface soil. A 3.2 cm soil probe with a polyethylene terephthalate glycol (PETG) copolyester linear was used to collect a core from 10 to 100 cm using a tractor-mounted Giddings hydraulic system. Soil samples from 0 to 10 cm were transferred to a plastic bag; soil cores were capped on each end. All samples were stored on ice until transport to the laboratory, where they were stored at −10 °C until processing. Each hole was backfilled with soil, and the sampling location was marked to avoid resampling at the same location.

Crop plants in each landscape position of each plot were harvested and analyzed for bromide. Three corn plants were harvested from each subplot on June 26, 2007 (231 days after fall bromide application and 40 days after spring bromide application), by cutting at the soil surface. Plants from each treatment were composited, dried at 64 °C for 3 days, and stored at room temperature until further analysis.

Sample Processing and Analysis. Frozen soil cores (in liners) were sectioned into segments of 10−20, 20−40, 40−60, and 60−100 cm depth using a miter saw with a carbide blade. A subsample was reserved for gravimetric water content determination.

Soil samples were dried and sieved to 0.5 mm. A 2 g aliquot of dry soil was placed in a plastic centrifuge tube and extracted with 20 mL of 0.1 N $NaNO_3$. Plant material was ground to pass a 0.84 mm screen, dried at 70 °C for 24 h, and moved to a desiccator to cool. An aliquot (200 mg) of each sample was weighed into a small porcelain crucible, 1.5 mL of 0.5 M KOH was added, and samples were heated at 575 °C for 3 h. The ash was transferred to a plastic centrifuge tube and extracted with 20 mL of ultrapure water. Plant and soil samples were agitated on a wrist-action shaker for 30 min and centrifuged at 760*g* for 5 min, and the supernatant was filtered to remove particles of $> 2.5\ \mu$m. Extracts were frozen at −20 °C until analysis using an Alpkem RFA-300 continuous flow analyzer using RFA method A313-S630 (*17*). No bromide was detected in blanks; the instrument limit of detection was 0.2 mg L^{-1}. Recovery from spiked samples averaged 90% for soil and 88% for plant samples. Results were not adjusted for recovery.

Data Analysis. Bromide concentrations were determined in dried soil. The mass of bromide in each soil sample was determined from the bromide concentration in dry soil and the mass of dry soil in each sample. Because the diameter of the soil sampler used for the 0−10 cm depth increment was larger than the diameter of the soil probe used for the 10−100 cm increments, the mass of bromide per surface area (μg cm^{-2}) was calculated. The mass/surface area in the top 1 m for each soil core was normalized to the maximum value for each subplot to determine the proportion of bromide remaining in the root zone at each sampling time. The maximum was measured either on the day of application or was not significantly different from that at day 0. The center of mass of the bromide remaining in soil was calculated as the first moment of the distribution.

Treatments (fall bromide application, spring bromide application, or no bromide application) were imposed on three replicate undisturbed plots and three replicate rehabilitated plots. Landscape position was a blocking factor. ANOVA was used to evaluate the effects of landscape position and soil-landscape rehabilitation on relative bromide concentrations and the center of bromide mass. Differences were evaluated using Tukey's test (α = 0.05).

RESULTS AND DISCUSSION

Weather Conditions. Weather conditions prevailing during the study (**Figure 3**) were typical for this region. Monthly average air temperatures were within 2 °C of the 20 year average (1987−2006) except in December 2006 (4 °C warmer than the 20 year average) and February 2007 (5 °C cooler than the 20 year average). Cumulative precipitation during the study totaled 38 cm, similar to the 20 year average of 39 cm. In each month, precipitation was within 20 mm of the 20 year average except in February 2007 (precipitation 30 mm greater than the 20 year average) and April 2007 (rain 40 mm greater than 20 year average). Precipitation (90 mm) occurred as snow from December 1 through March 1, accounting for 23% of the total precipitation occurring during the study.

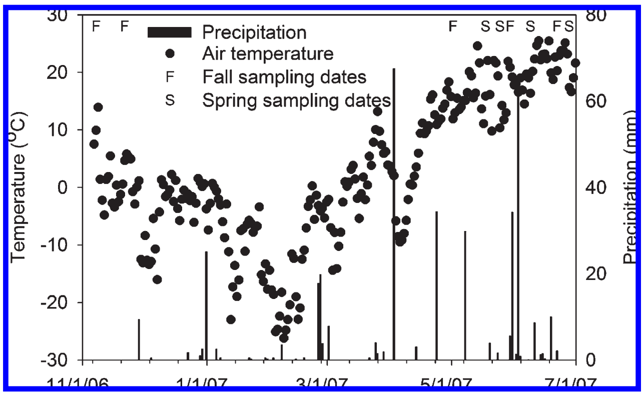

Figure 3. Precipitation and air temperature throughout the experiment. For both fall and spring applications, the day of application was the first sampling day.

The average soil temperature (5 cm depth) was 6 °C on the day of fall bromide application. In each landscape position, the surface soil was frozen from November 29 through March 11. Average daily soil temperatures remained at < 10 °C until April 20. Average daily soil temperatures ranged from 14 to 22 °C in May and from 17 to 28 °C in June.

Soil Water Content. On the days of application (fall and spring), surface soil moistures in the upper slope were significantly higher in rehabilitated plots than in undisturbed plots (**Table 1**). Surface soil moistures in the summit, shoulder, and upper backslope were 0.05−0.12 g g^{-1} higher in rehabilitated plots than in undisturbed plots on the day of fall application and 0.04−0.07 g g^{-1} higher in rehabilitated plots than in undisturbed plots on the day of spring application (**Table 1**). These differences persisted throughout most of the experiment, with the largest differential observed in the upper backslope. The largest difference in soil moisture between rehabilitated and undisturbed plots was observed in the 0−10 and 10−20 cm increments, as was expected because 15−20 cm of soil was moved during soil-landscape rehabilitation. No significant differences were observed between rehabilitated and undisturbed plots in any landscape position at depths of > 20 cm (see Table S1 of the Supporting Information).

Surface soil moistures in the lower backslope, footslope, and toeslope were generally the same in rehabilitated and undisturbed plots throughout the experiment. Throughout the experiment, soil moistures were significantly higher in the footslope and toeslope than in upper landscape positions at most depth increments (**Figure 4**; Table S1 of the Supporting Information). At each sampling time, undisturbed summit, shoulder, and upper backslope had the lowest soil moistures throughout the profile (**Figure 4**; Table S1 of the Supporting Information).

Bromide Dissipation from the Root Zone. *Fall Application.* With the exception of 203 days after application, when the lower backslope showed anomalously high relative bromide concentrations in undisturbed plots, landscape position had no significant effect on the normalized mass/surface area of bromide remaining in the top 1 m of soil. Averaged across landscape positions, the relative amount of bromide remaining in the top 1 m of soil was the same in rehabilitated and undisturbed landforms at each sampling time.

At each landscape position, there was no change in the mass/surface area of bromide in the first 2 weeks after fall application. The relative amount of bromide remaining 2 weeks after application was > 90% in undisturbed and rehabilitated plots (**Figure 5**). During this time, no measurable precipitation fell and the average soil temperature was 2 °C (**Figure 3**). These conditions are expected to limit solute transport.

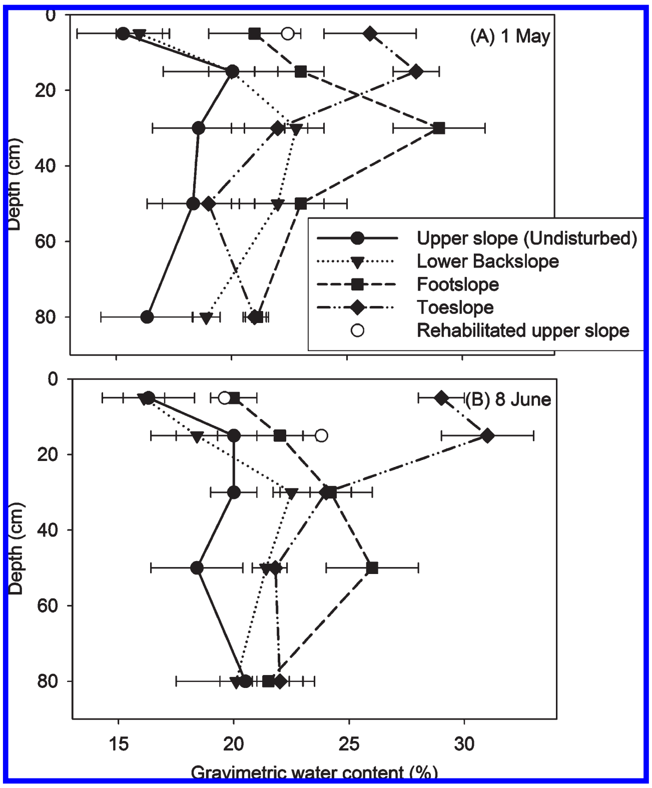

Figure 4. Soil moisture as a function of landscape position and depth. Values are mean of rehabilitated and undisturbed plots. Values for the upper slope are the mean of the summit, shoulder, and upper backslope (not significantly different). Because the upper slope of rehabilitated plots had significantly higher surface soil moisture than undisturbed plots, values for undisturbed (●) and rehabilitated plots (○) are shown separately.

Samples collected the following spring showed that most of the applied bromide had been depleted from the top 1 m during the winter. The mean relative mass/surface area of bromide remaining in the top 1 m on the first sampling day of the spring (May 1, 175 days after application) was 35% of that applied (**Figure 5**). The overwinter loss of bromide from the top 1 m of soil was ~26 kg ha^{-1}. These results are similar to previous reports of winter bromide mass loss in northern climates. Bromide loss from the top 1 m between application in September and the following spring amounted to 30 kg ha^{-1} (5% of applied) in Subarctic Alaska (*18*) and 36 kg ha^{-1} (30% of applied) in The Netherlands (*5*). During the time period from November 21 to May 1 (14−175 days after fall application), the soil was frozen most of the time and there was no opportunity for plant uptake. The depletion of bromide from the top 1 m suggests that water flux was sufficient to remove much of the applied bromide from the root zone by leaching and runoff in one season.

Fall-applied bromide continued to be depleted from the root zone throughout the growing season. By June 21, the final sampling date for the fall application, an average of 24% of the applied bromide remained in the top 1 m of the soil profile at each landscape position in both undisturbed and rehabilitated landforms (**Figure 5**).

Spring Application. Landscape position had no effect on relative bromide remaining after spring application. As was observed for the fall application, the relative amount of bromide remaining in the top 1 m of soil was the same in rehabilitated and undisturbed landforms at each sampling time following spring application.

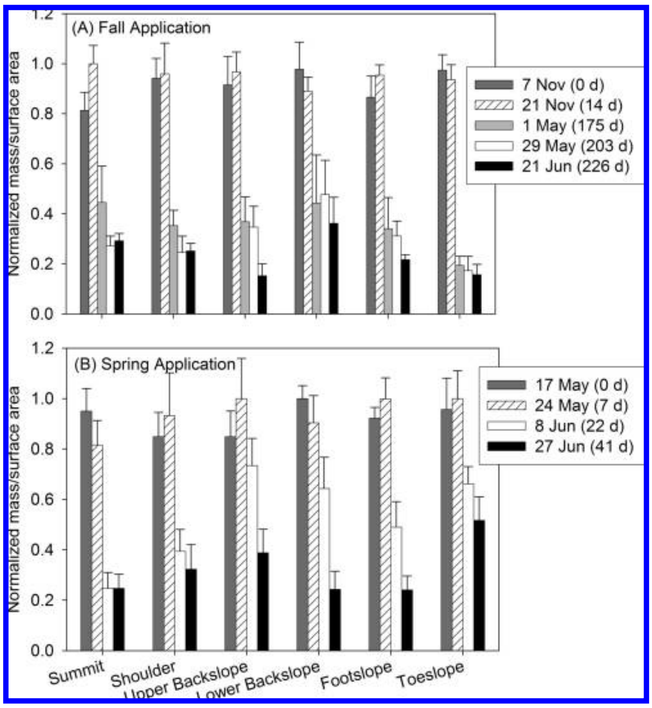

Figure 5. Dissipation of bromide in each landscape position following (**A**) fall application and (**B**) spring application. Bromide mass/surface area values were normalized to the maximum mass/surface area in each landscape position of each plot. Values are the mean of all six plots (undisturbed and rehabilitated); error bars are the standard error.

Rainfall of only ~5 mm occurred during the first 7 days after spring application (**Figure 3**), and there was no significant decrease in the mass/surface area of bromide in the top 1 m in undisturbed and rehabilitated landforms (**Figure 5**). Approximately 50−60% of the applied bromide remained in the root zone 22 days after application, and about 30−40% remained 41 days after application. Dissipation of spring-applied bromide during the first 41 days after application translates to ~27 kg ha^{-1}. Bromide mass loss of > 100 kg ha^{-1} (20−30% of applied) from soil cropped to barley was observed between early May and early July with about half the rainfall as occurred during this study (*18*).

Depth Distribution. Because little precipitation occurred shortly after application in the fall and spring, limited leaching was expected during this time. On the first and second sampling dates (on the day of application and 1−2 weeks subsequent), nearly all of the bromide was detected in the surface (0−10 cm) increment.

Approximately 212 mm of precipitation fell between the fall bromide application and the first spring sampling. Substantial leaching of bromide was observed during the winter and early spring. In samples collected in the spring following fall application, an average of 20−30% of the applied bromide was detected at depths of > 10 cm. Fall-applied bromide was detected in the 60−100 cm increment at all landscape positions except the toeslope, where no bromide was detected at depths > 40 cm (Figures S1 and S2 of the Supporting Information). In the toeslope, the maximum mass/surface area of bromide was in the 0−10 cm increment for all sampling times in rehabilitated and undisturbed plots. In other landscape positions, the maximum bromide mass/surface area was detected in the 20−40 or 40−60 cm increment in the spring following fall bromide application (Figures S1 and S2 of the Supporting Information). Only ~40% of the applied bromide was detected in the top 1 m in the May 1 sampling (175 days after application). Of the amount remaining, the mean center of mass was at a depth of 35 cm in the summit through the footslope (**Figure 6A**). This overwinter leaching is consistent with previous observations. In heavy clay soil in The Netherlands, the center of mass of bromide applied to the soil surface in the fall was at depths of > 60 cm the following April, with 400 mm of precipitation (*5*). In a loamy sand in North Carolina, the bromide center of mass increased by 30−50 cm over the winter with 672 mm of precipitation (*19*).

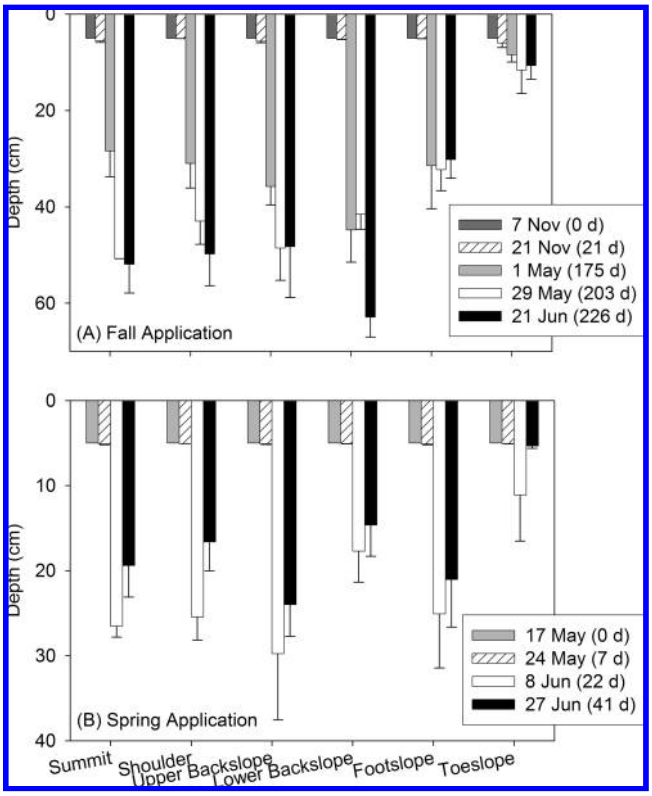

Figure 6. Center of mass of bromide remaining in the top 1 m of soil in each landscape position following (**A**) fall application and (**B**) spring application. Values are the mean of all six plots (undisturbed and rehabilitated); error bars are the standard error.

Less downward movement of fall-applied bromide was observed in the spring. In the summit through the footslope, the mean center of mass of fall-applied bromide increased from 35 cm on May 1 to 45 cm on May 29 and remained at approximately 50 cm on June 21 (**Figure 6A**). The center of mass of fall-applied bromide was significantly shallower in the toeslope than in upper landscape positions on each of the spring sampling dates. In the toeslope, the mean center of mass of fall-applied bromide was at depths of ≤16 cm throughout the experiment in both undisturbed and rehabilitated plots (**Figure 6A**).

For the spring application, bromide was rarely detected in the 60−100 cm depth increment at any landscape position (Figures S3 and S4 of the Supporting Information). As for the fall application, the maximum bromide mass/surface area was always in the 0−10 cm depth increment in the toeslope. At other landscape positions, the maximum mass/surface area was detected in the 10−20 or 20−40 cm increment (Figures S3 and S4 of the Supporting Information). By 22 days after application, 20−80% of the applied bromide leached to depths of > 10 cm. The mean center of mass in the summit through the footslope of both undisturbed and rehabilitated plots was 25 cm deep at 22 days after application (8 June) and did not increase in the June 27 sampling (center of mass 19 cm deep) (**Figure 6B**). Rainfall totaling 137 mm was recorded during the 41 days after spring bromide application (**Figure 3**). These results are similar to previous reports in cropped soil with similar rainfall, in which the center of mass of surface-applied bromide was at depths of 11−19 cm with 130 mm of water input (*19*) and < 30 cm with cumulative precipitation of 140 mm (*7*).

It is expected that increased evapotranspiration resulted in less downward movement of spring-applied bromide compared to fall-applied bromide. Substantial downward movement of fall-applied bromide was observed to have occurred during the winter and early spring, but the center of mass of the bromide remaining in soil remained relatively constant once the crop was established. Loss of fall-applied bromide through leaching beyond 1 m may have depleted the mass of bromide during the winter. Detection of bromide in the depth increment 60−100 cm and the relatively deep center of mass of the remaining bromide (∼50 cm) suggest that downward water flux was sufficient to distribute bromide to at least a depth of 1 m during the winter and early spring. In contrast, the center of mass of the spring-applied bromide was shallower (< 30 cm) because increased evapotranspiration limited downward water flux.

For sampling times in the spring (following fall or spring application), the bromide centers of mass tended to be positively correlated with bulk density and negatively correlated with erosion rates, gravimetric water content, organic carbon content, and electrical conductivity. Thus, the center of mass of bromide remaining in the root zone was shallow where the surface soil moisture, organic carbon content, and electrical conductivity were high, bulk density was low, and soil was deposited by erosion—primarily in the toeslope (**Table 1**). Other studies have reported increased leaching of bromide in the lower slope compared to the upper slope (*3*, *7*, *8*), but only when cumulative rainfall was > 500 mm. At our site, the long-term average precipitation is ∼600 mm. In our studies, landscape position effects on bromide transport may have been too small to be detected by relatively infrequent sampling, and differences in leaching and overland flow as affected by soil hydraulic properties may have been overwhelmed by the effects of evapotranspiration and other processes.

Soil-landscape rehabilitation resulted in dramatic changes in soil properties in areas of soil addition, including a doubling in soil organic carbon content (**Table 1**) that resulted in significantly higher surface soil moisture (**Table 1** and Table S1 of the Supporting Information). In the upper slope (summit, shoulder, and upper backslope), the amount and center of mass of bromide remaining in the top 1 m of soil were not significantly different in undisturbed and rehabilitated plots and were not correlated with soil moisture or any of the soil properties listed in **Table 1**. Although soil-landscape rehabilitation was expected to have a large impact on water transport in this landform, we did not detect differences in bromide transport after fall or spring application in these experiments.

Plant Uptake. The proportion of the applied bromide that was taken up by plants was estimated by harvesting ≤2% of each subplot area and analyzing the plant material for bromide content. Plant bromide concentrations measured on June 26 (231 days after fall application) accounted for 9 ± 6% of the fall-applied bromide. Much of the bromide was removed from the root zone during the winter, with an average of 36% of the applied bromide remaining in the top 1 m of soil 2 weeks before planting. Plant uptake between planting (May 12) and June 26 removed about a fourth of the portion of fall-applied bromide that was present in the root zone prior to planting.

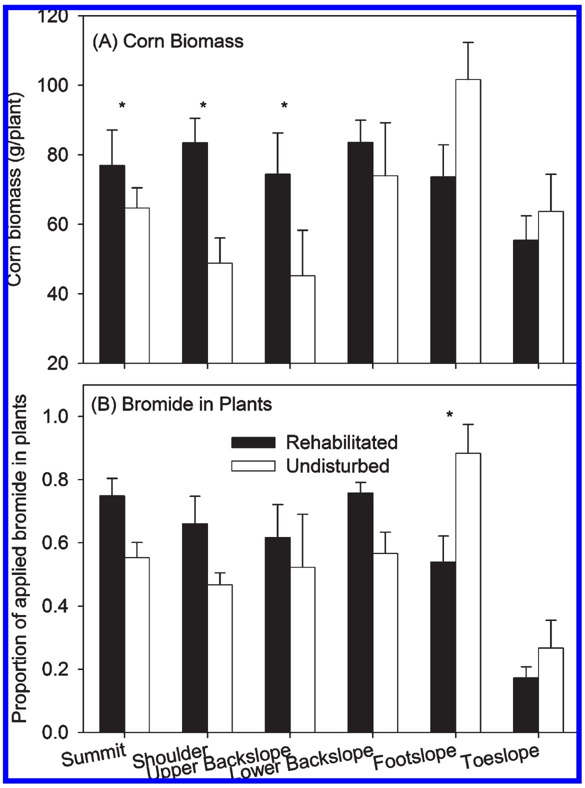

Figure 7. Landscape position effects on (**A**) corn biomass and (**B**) spring-applied bromide measured in plants on June 26, 2007, 40 days after spring bromide application. Asterisks indicate significant differences between undisturbed and rehabilitated plots ($\alpha = 0.05$).

Plant bromide concentrations were measured 40 days after spring application. Plant uptake of spring-applied bromide was affected by landscape position. Corn biomass (**Figure 7A**) was affected by landscape position and by soil-landscape rehabilitation: plants were larger in areas of soil addition (summit, shoulder, and upper backslope of rehabilitated plots) compared to the undisturbed plots. Plants in areas of soil removal (footslope and toeslope of rehabilitated plots) were smaller than in the same landscape positions of undisturbed plots. The same trends were observed for spring bromide uptake (**Figure 7B**). The proportion of spring-applied bromide that was detected in plant biomass in the toeslope was much lower than in all other landscape positions (**Figure 7B**). Plant biomass in the toeslope was not significantly different from that in any other landscape position (**Figure 7A**), so the low bromide uptake is not likely due to decreased biomass.

Several factors may have contributed to the low bromide uptake from the root zone of the toeslope, including differences in soil moisture, soil EC, and bromide distribution. Soil moistures were consistently higher in the toeslope compared to other landscape positions (**Figure 4**), so it is likely that the crop took up a lower proportion of the soil water in the toeslope compared to other landscape positions. The toeslope had significantly higher soil EC than all other landscape positions (**Table 1**). It is possible that the higher ionic strength of the soil solution resulted in a lower proportion of the applied bromide being taken up by plants. Chloride has been found to interfere with bromide uptake (*11*), but carbonates and sulfates are expected to dominate the anion composition of North American prairie soils. For some plants, there is some evidence that the rate of bromide uptake is lower for shallow roots (< 10 cm) than for deeper roots (*11*). In the toeslope, bromide was primarily concentrated in the surface soil (0−10 cm), which may have inhibited bromide uptake in the toeslope relative to other landscape positions. Other factors, such as the corn root distribution, differing rates of bromide transport from corn roots to aboveground biomass, and differing pore size distributions, may have also affected bromide uptake as a function of landscape position.

We obtained excellent mass balance in these systems. Approximately 36% of the fall-applied bromide was detected in the top 1 m of soil on May 1. On June 26, we detected 24% of the applied bromide in the soil and 9% of the applied bromide in plants, accounting for 92% of the bromide that was detected in the root zone on May 1. Similarly, we detected an average of 33% of the spring-applied bromide in soil and 56% in plants, accounting for 89% of the spring-applied bromide. During the 45 days after planting, plants took up ~22 kg ha^{-1} of spring-applied bromide. This bromide uptake by corn was similar to that in previous studies, in which corn uptake of bromide was ~7 kg of Br ha^{-1} 45 days after planting and ~19 kg of Br ha^{-1} 59 days after planting, with a maximum bromide uptake of ~38 kg of Br ha^{-1}, 40% of that applied (*12*).

Our results suggest that bromide was likely removed from the root zone during the winter and early spring by leaching and runoff, but little bromide was leached out of the root zone in the spring. Plant uptake was a major route of bromide dissipation during the growing season. Although landscape position and bulk soil movement within the landform had a large impact on soil properties, we observed no significant differences in bromide dissipation between eroded and rehabilitated landforms. Except for the toeslope, which had a shallower bromide center of mass and less plant uptake of bromide, landscape position had no influence on bromide dissipation in these experiments. In a companion paper (*16*), these results for a nonreactive tracer are compared to the dissipation of a reactive solute, the herbicide *S*-metolachlor, as a function of landscape position and soil-landscape rehabilitation.

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Supporting Information Available: Mass/surface area and depth distribution of bromide remaining in the top 1 m of soil following (a) fall application to undisturbed plots, (b) fall application to rehabilitated plots, (c) spring application to undisturbed plots, and (d) spring application to rehabilitated plots; soil water contents at each sampling time. This material is available free of charge via the Internet at http://pubs.acs.org.

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