THIRD ANNUAL REPORT

VEGETATION IMPACT ASSESSMENT AND MONITORING STUDIES, RED DOG MINE, ALASKA, 2008

PREPARED FOR

TECK COMINCO ALASKA, INC.
ANCHORAGE, ALASKA

PREPARED BY

ABR, INC.–ENVIRONMENTAL RESEARCH & SERVICES
FAIRBANKS, ALASKA

VEGETATION IMPACT ASSESSMENT AND MONITORING STUDIES, RED DOG MINE, ALASKA, 2008

THIRD ANNUAL REPORT

Prepared for

Teck Cominco Alaska, Inc.
3105 Lakeshore Dr.
Building A, Suite 101
Anchorage, Alaska 99517

Prepared by

ABR, Inc.—Environmental Research & Services
P.O. Box 80410
Fairbanks, Alaska 99708

February 2009

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

PROJECT OVERVIEW

Mining and mill operations at the Red Dog Mine have resulted in the deposition of dust derived from many sources, including blasting, load-haul-dump activities, ore stockpiles, crushing activities, the main waste stockpile, the overburden stockpile south of the tailings pond, concentrate handling and transport, and exposed mill tailings. Dust derived from mined ore is likely to be rich in metal sulfides (iron, zinc, and lead), and iron sulfate, and produces sulfuric acid during oxidative decomposition (Cox 1995). In 2006, ABR, Inc.—Environmental Research & Services (ABR), under contract to Teck Cominco Alaska, Inc. (TCAK), initiated a 3-year study to determine the extent to which plant communities have been affected by dust, and identify potential treatment options for mitigating impacts. The objectives of the study were to (1) determine the specific cause(s) of plant mortality in affected areas; (2) identify and evaluate treatments that may be effective in promoting recovery of the disturbed plant communities; and (3) establish a monitoring program to document long-term changes in the structure and composition of plant communities surrounding the mine site.

In the first year of the study, we focused on assessing the extent and causes of plant mortality observed in four areas near the mine where other studies had documented dust-related vegetation impacts and elevated soil concentrations of lead and zinc. These areas are generally downwind of mine facilities and are subject to dust deposition from the various local sources listed above. In each area, we qualitatively assessed the cover of each plant species and assigned a damage index, ranging from 1 (1–5% of plants affected) to 7 (all individuals killed or severely affected). We also collected samples of plant tissue and soil in the affected areas for analysis of key metals. The preliminary results of this impact assessment suggested that the primary causes of the observed vegetation impacts were deposition of acid-forming dust, input of iron sulfate and zinc sulfate from fugitive dust, and reduction of soil aluminum to soluble forms. Accordingly, we set up treatment blocks in three of the four assessment areas (Figure 1) to test the effectiveness of dolomitic lime in promoting vegetation recovery in the affected areas (by reducing soil pH and aluminum availability). The blocks were treated with lime in August 2006.

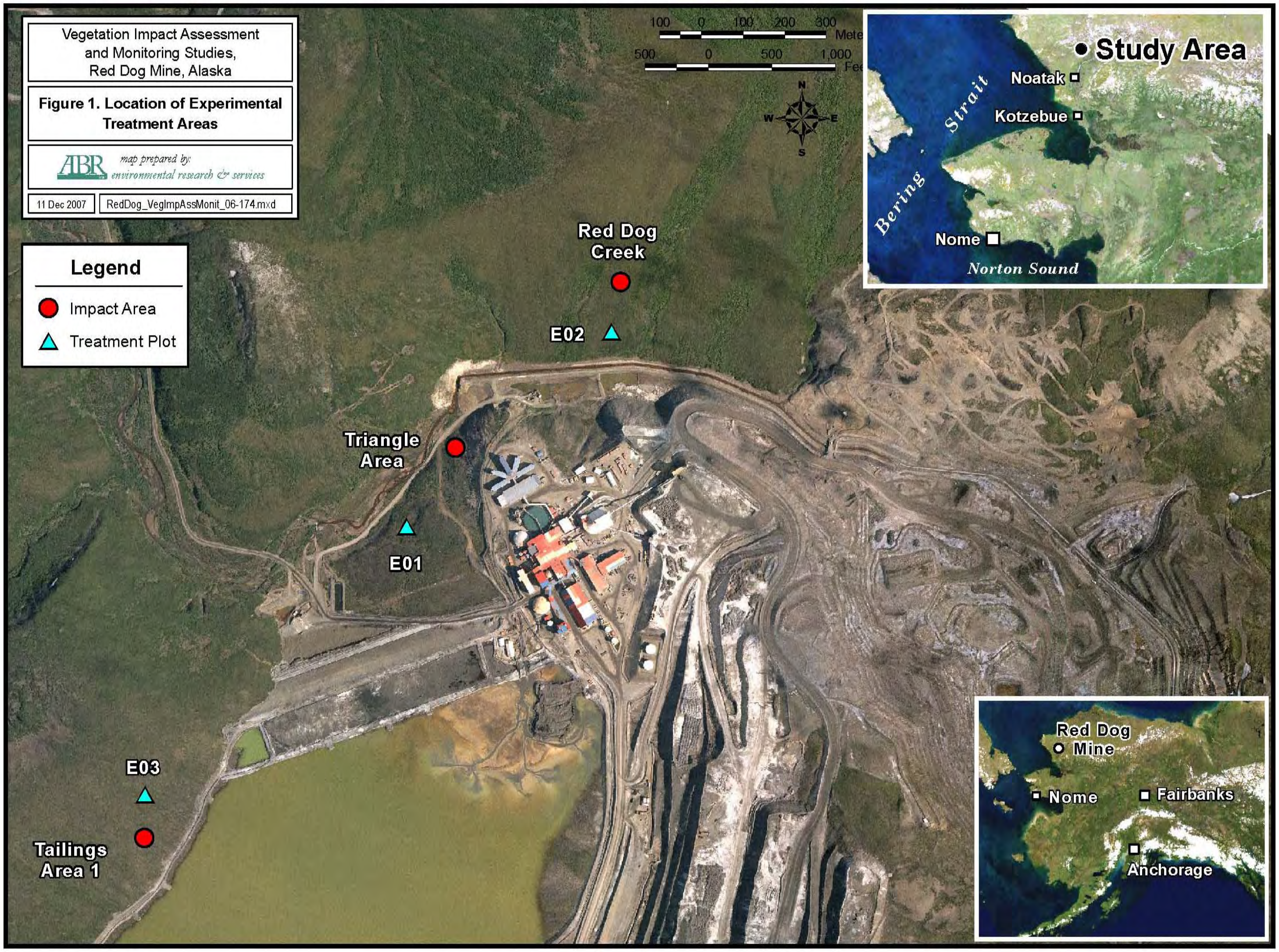


Figure 1. Locations of experimental treatment areas, Red Dog Mine, Alaska, 2008.

We also established a long-term vegetation monitoring program, to track vegetation recovery within affected areas in response to efforts to reduce fugitive dust emissions from mine facilities. Nine 4-km long transects were set up in 2006; each extends across both dust-affected areas and areas outside the mine dust shadow. Vegetation sampling plots (5 × 10 m dimensions) were set up at 0 m, 500 m, 1000 m, 1500 m, 2500 m, and 4000 m from the origin of each transect. Monitoring of these plots is tentatively scheduled for 2009.

In 2007, a third treatment, triple super phosphate, was added to one block within each of the assessment areas. This treatment was intended to reduce soil lead concentrations; elevated lead levels were associated with some of the highest vegetation damage index rankings in the assessment areas. The 2007 monitoring effort also focused on collecting baseline vegetation data in the lime, untreated (reference) and triple super phosphate treatment blocks.

This report summarizes the results for the third, and final year of the study. Monitoring efforts included collecting a second year of vegetation cover data and collecting soil samples for the three treatment blocks set up in August 2006. The results of the study will be used to determine whether the treatments were effective in reducing concentrations of aluminum (Al) (lime treatment) and lead (Pb) (triple phosphate treatment) and increasing pH (lime treatment), thereby increasing the neutralizing potential of the soil.

STUDY AREA

Based on a site assessment of vegetation impact areas in late June 2006 (ABR 2007), three locations were selected for testing two ameliorative treatments (Figure 1). The Triangle Area (E01) is just north of the tailings dam, has a northwest-facing slope and supports an upland low shrub community composed of *Betula nana* (dwarf birch), *Vaccinium uliginosum* (blueberry), and several species of willow (*Salix* sp.). Graminoids were dominated by *Carex bigelowii* (Bigelow sedge) and *Festuca altaica* (Altai fescue). This area is situated in the lee of both the mill and stockpile areas and has probably received fugitive dust from both concentrate loading and hauling operations (prior to upgrades to the concentrate loading facility) and the ore stockpile.

The Red Dog Creek area (E02) is located along the north side of the Red Dog Creek diversion channel. Much of the area is situated on a south-facing slope and consists of a lowland shrub birch-sedge community interspersed with narrow bands of willows that have colonized hillside water tracks. This area is downwind of the mine pit and stockpiles.

The Tailings Area (E03) was referred to as Tailings Area 1 in the original site assessment. This area encompasses a broad southeast-facing slope on the west side of the tailings pond. The majority of the slope consists of lowland shrub birch-sedge vegetation. Wetter inclusions support shrub birch-tussock communities. The area is directly downwind of the tailings pond and the waste rock stockpile and likely has received significant amounts of dust from intermittently exposed tailings beach sediments.

METHODS

EXPERIMENTAL DESIGN

Based on the results from the 2006 vegetation impact assessment (ABR 2007), we suspected that the impacts to vegetation in the immediate mine area were due primarily to deposition of acid-forming dust, input of iron sulfate and zinc sulfate from fugitive dust, and reduction of soil Al to soluble forms. To identify potential treatments for reducing dust effects, we tested the effectiveness of lime and triple super phosphate for ameliorating soil conditions. The lime was intended to raise the pH of the soil surface, thus lowering levels of available Al and to add neutralization capacity to counteract potential acidic inputs from spring runoff. Triple super phosphate was applied to assess its potential for reducing Pb concentrations. Although it was not certain that elevated Pb levels were responsible for vegetation impacts found in the 2006 assessment, elevated Pb levels were associated with some of the highest vegetation damage index rankings.

We established treatment blocks 29–30 August 2006 in the Triangle Area, Red Dog Creek Area, and Tailings Area (Figure 1). Within each treatment block, 3 replicate (5 × 10 m) plots were established and marked with corner stakes for a total of nine plots. At the Red Dog Creek Area and Tailings areas, plots were laid out in 3 rows of 3 with a lime (L) treatment, Triple phosphate (T) treatment, and untreated, reference (R) plot placed randomly in each row

(Figure 2). The Triangle Area plots were established in a single row, as the slope length was not sufficient for the grid configuration used at the other sites. Each plot was photographed in all 3 years of the study. Paired comparisons of plot photos from baseline data (2006) and final data 2008 are presented in Appendix A.

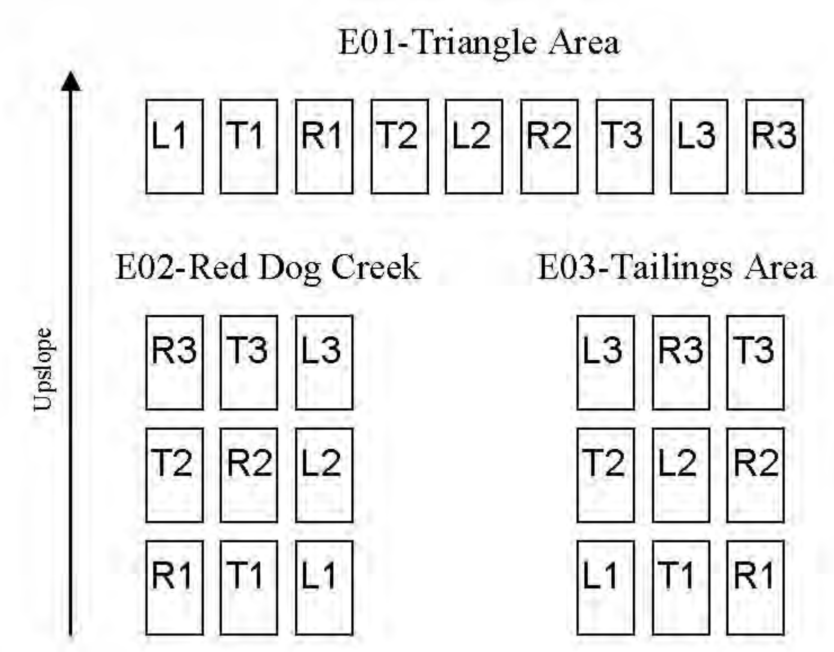


Figure 2. Ameliorative treatment plot layout in each experimental area. The treatments include lime application (L), triple superphosphate application (T), and untreated, reference (R) plots. E01 was set up in a single row because the slope length was insufficient to accommodate placing plots in multiple rows.

Pelletized dolomitic lime was applied to the lime treatment plots at 220 kg/ha (200 lbs/acre) on 29–30 August 2006. Pelletized triple superphosphate (calcium phosphate) fertilizer was applied on 30 June 2007, also at 220 kg/ha (200 lbs/acre). The phosphate application was delayed because analytical results identifying lead as a potential stressor were not yet available when the lime treatment was applied in 2006. Both lime and phosphate were applied evenly throughout each plot using hand spreaders.

SOIL MONITORING

SAMPLING AND LABORATORY ANALYSIS

To establish baseline values prior to application of treatments, three soil samples were collected from each treatment plot within each block (n = 27) for analysis of selected chemical parameters and metals. At each plot a grab sample (approximately 2–5 cm below the moss layer) was taken at a randomly selected location, avoiding the plot margins and plant sampling grid transects. The samples were collected 30 August 2006 and analyzed for total available aluminum (Al), iron (Fe), manganese (Mn), lead (Pb), zinc (Zn), and cadmium (Cd). Total nitrate (NO_3), phosphorous (P), potassium (K), and pH and electrical conductivity (EC) also were measured in each sample. The samples were analyzed by Colorado Analytical Laboratories, Inc., Brighton, Colorado, using standard methods (Table 1) (Klute 1986). Samples were collected again from the reference and lime treatment plots on 23 August 2007 and from all plots between 25–27 July 2008. The triple phosphate treatment block only was sampled in 2006 (baseline) and 2008 because this treatment was not applied until late June 2007, as we did not expect to see any measurable change in soil properties after only a 2-month lapse following treatment application.

Table 1. Soil analytical methods for samples from treatment and reference (untreated) areas, Red Dog Mine, Alaska, 2008.

Analyte	Method No.[a]	Description
Conductivity	10-3.3	Saturated paste conductivity cell
pH	12-2.6.5	Saturated paste standard probe
Sulfate	10-3.7	
Selected Metals (available)		
Al	16-3.2.2	1N KCl extract
Cd	19-3.2.2	DTPA Extract
Fe	17-4.3	DTPA Extract
Pb	21-5	DTPA Extract
Mn	18-3.4	DTPA Extract
Zn	19-3.2.2	DTPA Extract
Available Nutrients		
N (NO_3)	33-8-3	Colorimetric
P	24-5.4.2	P soluble in Sodium Bicarbonate (Olsen extractable P)
K	9-3.1.2, 1	1N NH_4Oac extract

[a] Methods numbers as listed in “Methods of Soil Analysis, Parts 1 and 2”, Second Edition, American Society of Agronomy and Soil Science Society of America. Madison, WI 1982.

STATISTICAL ANALYSIS

We analyzed the soils data using a 2 factor analysis of variance (ANOVA) in which we compared the treatment blocks with the untreated reference (control) blocks.

In order to compare effects of the lime treatment over time we ran a multivariate repeated measures analysis of 2007 and 2008 data with plots repeated by year, treatment (Reference or Lime) and location as factors, and the 12 soil analytical measures as response variables. The 2006 data were excluded due to concerns over consistency in soil collection methods between 2006 and subsequent years. Because the interaction between treatment and location was not significant for any of the response variables (all $P > 0.05$), the interaction term was dropped. The natural logarithm transformation was applied to the response variables Al, pH, Cd, Pb, Mn, NO_4, P, and K, to meet assumptions of normality.

Since we did not have a complete set of data for all three years, we also ran a multivariate general linear model of 2008 data, with treatment (Lime, Reference, and Triple phosphate) and location as factors and the 12 soil measures as response variables. The interaction term between location and treatment was not significant for any soil measures, so it was not included in the analysis. To meet assumptions of normality, the natural logarithm transformation was used for the same response variables listed above. All statistical analyses were performed using SPSS (2007).

VEGETATION SURVEY

FIELD SAMPLING

Vegetation cover in all treatment blocks was measured for the first time during 28–30 June 2007. Seasonal senescence prevented accurate determination of baseline cover following treatment set-up in late August 2006. Final vegetation cover measurements were made 25–27 July 2008. Vegetation was sampled in each 5 × 10 m plot using the point intercept method: 100 points were sampled on a 2 × 0.025 m grid by stretching a 5 m tape measure across the plot at the 1, 3, 5, 7, and 9-m intervals (Figure 3), and measuring plant cover at 25-cm intervals along the

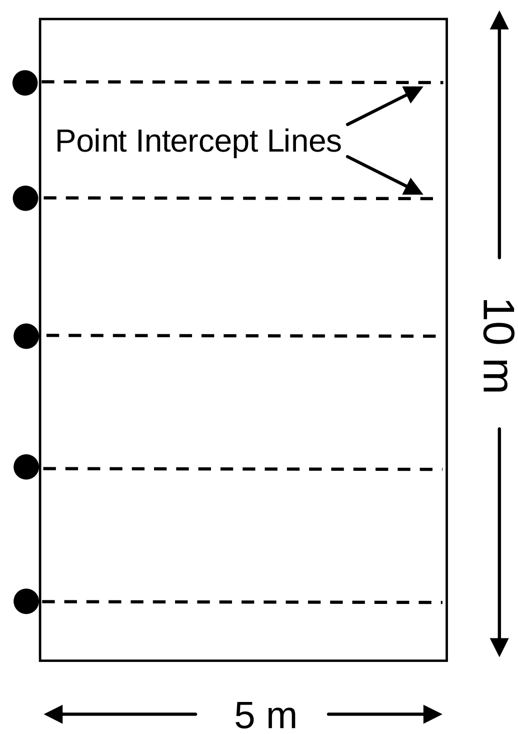


Figure 3. Diagram of vegetation sampling grid overlaying each treatment plot.

tape within the plot. A small laser pointer mounted on an aluminum rod was used to identify a discrete sample point at each grid location. All plant species were recorded at each point, including multiple layers (canopies). This method gives a repetitive cover estimate that can exceed 100%, but generally is well correlated with biomass (Jonasson 1988). Litter and bare soil were recorded only if there was no live plant cover. Mean cover by class (water, soil, litter, lichen, moss, graminoid, evergreen shrub, deciduous shrub, forb, and total live cover) was calculated for each treatment (n = 3) in each experimental block (total of 27 plots). Trace cover (those species not sampled along the transects) also was compiled for each plot. Taxonomic nomenclature follows *Flora of Alaska* (Hultén 1968). The vegetation cover data are summarized in Appendix D.

STATISTICAL ANALYSIS

We ran a multivariate repeated measures analysis of 2007 and 2008 total live vascular cover data, to assess the preliminary vegetation response to the lime and phosphate treatments. Plots were repeated by year (2007, 2008), treatment (reference, lime, phosphate) and location (Triangle Area, Red Dog Creek, Tailings Area) as factors, with total live cover (TLC) as the response variable. The interaction between treatment and location was not significant and was dropped for the final analysis. We dropped the analysis of total nonvascular cover (TNVC) because a high number of plots have no or minimal nonvascular cover.

RESULTS

SOIL CHARACTERISTICS

The multivariate repeated measures analysis of soils data showed no significant differences among the three treatments, although there were significant differences among the three locations (Tables 2 and 3). This is not surprising, as the three study sites have notably different site characteristics, both in terms of soil parameters (Figures 4–6; Appendix Figures B1 and B2) and vegetation cover and composition (Figure 7; Appendix Tables D1–D3). Soil properties also varied among years, but these differences were not related to treatment. When comparing 2006 soil data with 2007 and 2008, concentrations of some metals were an order of magnitude higher in 2006 (Appendix Figures B1 and B3). Possible explanations include variation in rates of dust

Table 2. Results of multivariate repeated measures analysis of 12 soil parameters for the lime and reference (untreated) treatments, 2007 and 2008, Red Dog Mine, Alaska.

Variable	F	df	P-value
Intercept	**15344.5**	**12,3**	**<0.001**
Treatment	3.971	12,3	0.141
Location	**14.939**	**24,6**	**0.001**
Year	**32.016**	**12,3**	**0.008**
Year*Treatment	4.938	12,3	0.107
Year*Location	**12.882**	**24,6**	**0.002**

Table 3. Results of multivariate general linear model analysis of 12 soil parameters for the triple superphosphate and reference (untreated) treatments, 2008, Red Dog Mine, Alaska.

Variable	Wilk’s Lambda Test Statistic	F	df	P-value
Intercept	**0.001**	**1077.9**	**12,24**	**<0.001**
Location	**0.003**	**14.606**	**24, 24**	**<0.001**
Treatment	0.175	1.277	24, 22	0.284

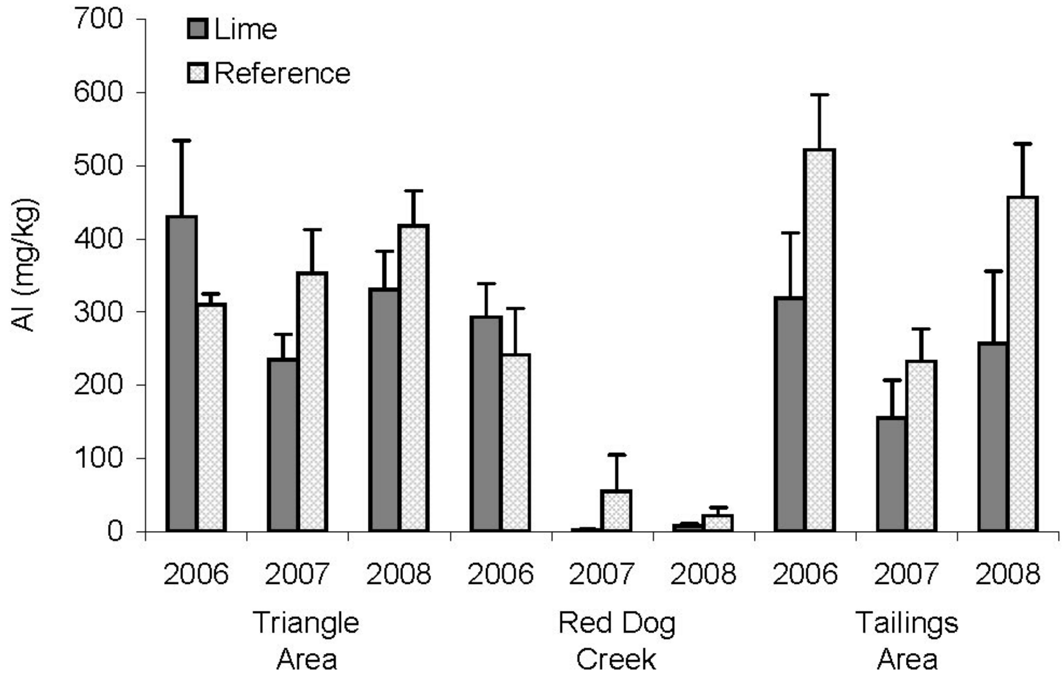


Figure 4. Comparisons of concentrations of Al in lime-treated and reference (untreated) experimental test plots, 2006–2008, Red Dog Mine, Alaska.

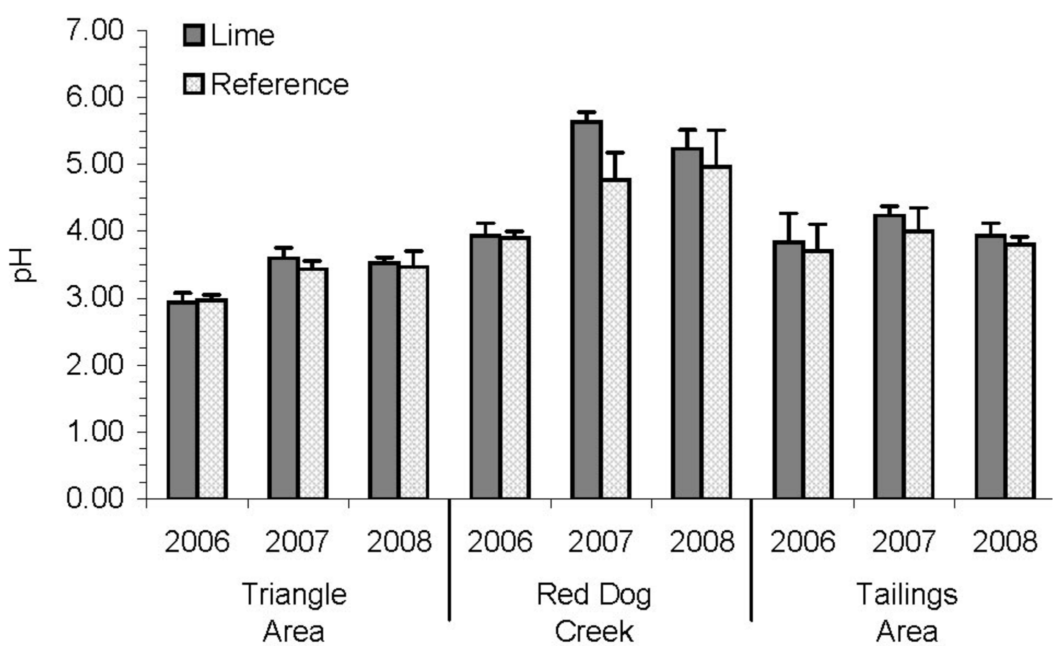


Figure 5. Comparisons of pH in lime-treated and reference (untreated) experimental test plots, 2006–2008, Red Dog Mine, Alaska.

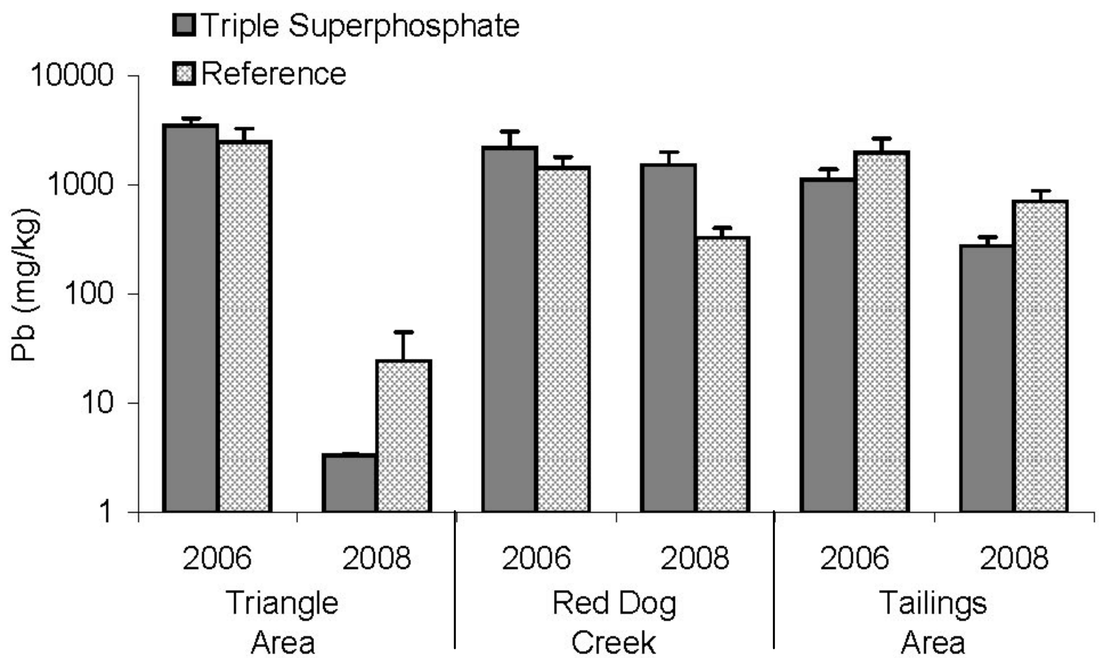


Figure 6. Comparisons of concentrations of Pb in triple super phosphate-treated and reference (untreated) experimental test plots, 2006 and 2008, Red Dog Mine, Alaska. Note that the triple superphosphate was not applied until 2007; thus, the 2006 data represent baseline conditions in both treatment blocks.

deposition among years or differences in sampling methods. We believe that soil samples were collected in all years according to the protocol established for the study, which stated that samples would be collected just beneath the moss mat to a depth of 5 cm. Nevertheless, because the soil sampling was conducted by different personnel, it is possible that the 2007 and 2008 soil samples included soil from greater depths than in 2006, which could have resulted in lower metal concentrations. A previous study of metal concentrations in soils in the vicinity of the Red Dog mine found that Pb and Zn concentrations dropped off steeply at depths > 5 cm below the surface (TCAK, unpublished data).

In both 2007 and 2008, Al concentrations were significantly lower in the lime treatment plots compared to the untreated reference plots (Figure 4, Appendix Table C1), although values in both treatments were higher in 2008 than in 2007. Soil pH was significantly higher in the lime treatment plots compared to the untreated reference plots in both years.

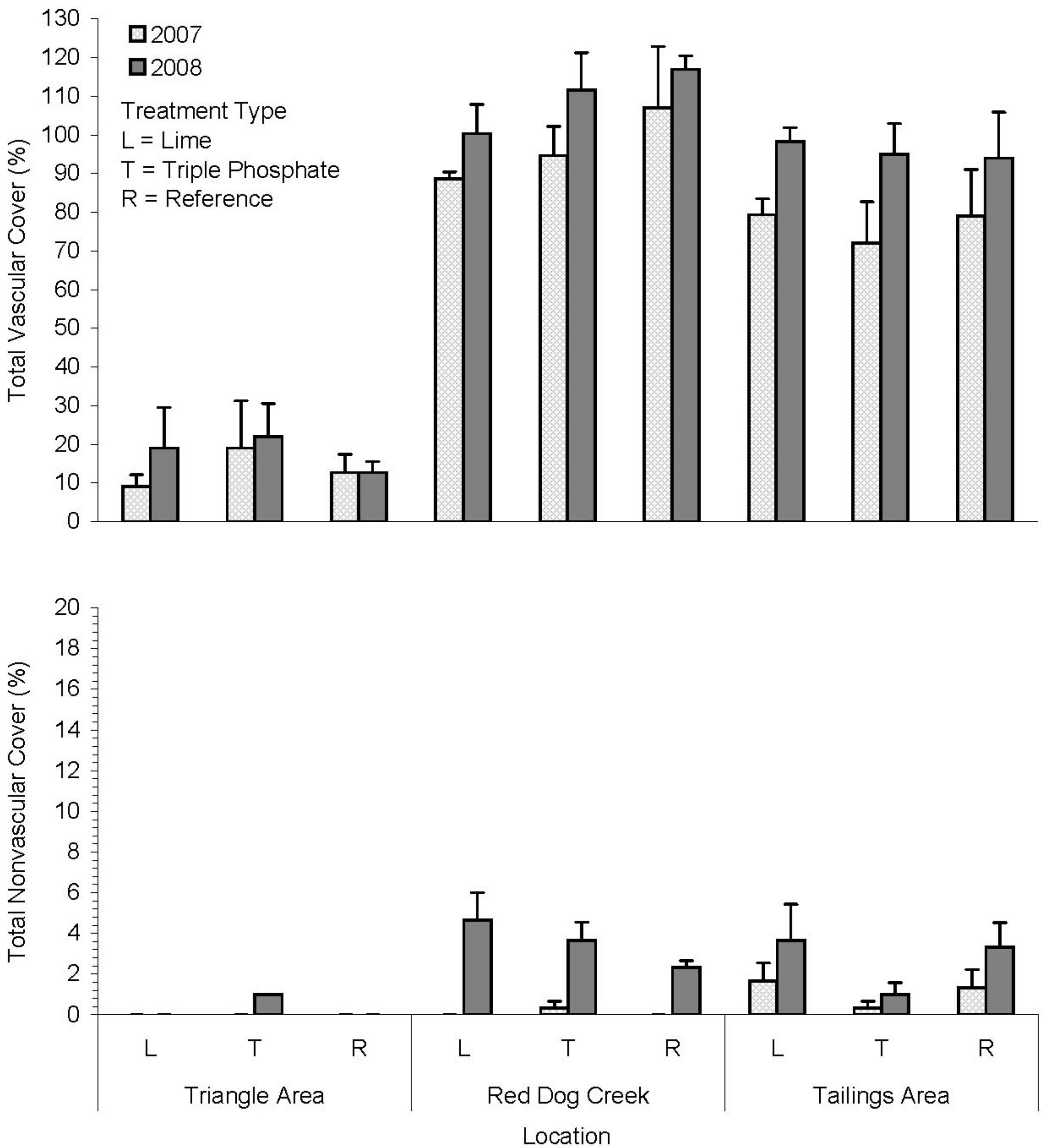


Figure 7. Comparisons of total vascular and nonvascular cover among the three treatments and study areas, 2007 and 2008, Red Dog Mine, Alaska.

The statistical analysis showed that P concentration was significantly higher in the triple super phosphate treatment compared to the reference and lime treatment plots (Appendix Figures B2 and B4, Appendix Table C2). Pb concentrations were lower in the triple super phosphate plots compared to the reference (untreated) plots in the Triangle Area and Tailings Areas (Figure 6), but the differences were not significant (Appendix Table C2).

VEGETATION COVER

Similar to the statistical results for soil parameters, total vascular cover (TVC) differed significantly among locations and years, but not treatments (Tables 4 and 5). TVC was generally higher in 2008 than in 2007, but the increases occurred in both the treated and untreated (reference) plots (Figure 7). The higher cover values in 2008 may in part reflect the drier than normal conditions in 2007, which likely resulted in reduced plant growth.

Despite the lack of a significant difference in TVC among the treatments, we observed some changes that suggest the treatments applied may promote recovery in the longer term. In the Triangle Area (Figure 7), where we observed the greatest vegetation impacts, we recorded small increases in TVC in 2008 for both treatments (3–10%), whereas cover remained essentially unchanged in the reference plots (-0.3%) (Figure 7). Shrubs (3.3–6%) and grasses (4.7%) (lime treatment only) accounted for the greatest increases (Appendix Table D1). Three forb species

Table 4. Results of repeated measures analysis of total vascular cover by treatment and location, 2007 and 2008, Red Dog Mine, Alaska.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Year	**1956.019**	**1**	**1956.019**	**20.727**	**.000**
Intercept	252833.796	1	252833.796	812.104	.000
Location	**77598.370**	**2**	**38799.185**	**124.623**	**.000**
Treatment	204.037	2	102.019	.328	.724
Error	6849.296	22	311.332		

Table 5. Results of univariate analysis of variance of total vascular cover by treatment and location, 2007 and 2008, Red Dog Mine, Alaska.

Vascular Cover	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	38901.204[a]	4	9725.301	62.476	.000
Intercept	126416.898	1	126416.898	812.104	.000
Location	**38799.185**	**2**	**19399.593**	**124.623**	**.000**
Treatment	102.019	2	51.009	.328	.724
Error	3424.648	22	155.666		
Total	168742.750	27			
Corrected Total	42325.852	26			

[a] R Squared = .919 (Adjusted R Squared = .904).

were recorded in 2008 in the triple phosphate treatment, where they were absent previously. Additionally, a small amount of moss and lichen cover (1%) was present in the triple super phosphate treatment block in 2008, whereas not even a trace of these lifeforms was evident in 2007.

At Red Dog Creek, TVC increased in 2008 in all treatments (Figure 7). Similar to the Triangle Area, increases in TNVC were greater for the lime (7%) and triple phosphate treatments (4.7%) compared to the reference (untreated) (3.6%) plots, although these differences are within the range of sampling error. We also found a modest increase in the cover of grasses and sedges in the lime treatment in 2008 (Appendix Table D2).

In the Tailings Area, increases in TVC and TNVC between 2007 and 2008 were similar for all treatments (Figure 7, Appendix Table C3). The only notable exception was the sedge *Carex bigelowii*, which showed slightly greater increases in cover in the lime and triple phosphate treatments (5.4–6.0%) than in the reference plots (2%).

DISCUSSION AND CONCLUSIONS

The assessment of the effectiveness of the two treatments in improving soil conditions and promoting vegetation recovery of dust-affected areas was largely inconclusive. We found some increases in pH and reductions in Al concentrations in the plots treated with lime, although the differences were not significantly different from those measured in the untreated, reference plots.

Applying triple superphosphate did not significantly reduce Pb levels in treated plots. High variability in metal concentrations among samples within the same area may have been a factor preventing the detection of significant treatment effects. Although every effort was made to maintain consistency during the collection of soil samples (including having the same personnel conduct the sampling in 2007 and 2008), values for many parameters had wide ranges. It also is possible that the soil amendment application rates were not sufficient for reducing the concentrations of the selected metals. The application rate we used (220 kg/ha) is considerably lower than rates (2–30 ×1000 kg/ha) that have been applied elsewhere (e.g., Mays and Bengston 1978, Redente and Richards 1997). It may be worthwhile to double or triple the rate in any future applications.

Despite the lack of measurable improvements in soil characteristics, the preliminary vegetation response we observed in the treatments is encouraging, although the measured increases in cover were modest. In particular, the colonization of mosses and lichens suggests that soil surface conditions may have become more favorable for vegetation establishment over time. It is not unusual for there to be a lag in vegetation response as a result of improved soil conditions. Since mosses and lichens are among the most sensitive lifeforms to dust impacts, we suspect a more measurable response will be detected in these groups in the future. Additional monitoring of the treatment plots (and possibly repeated treatment applications) in another 3–5 years may provide the time frame needed to detect significant changes in soil characteristics and vegetation cover.

REFERENCES

ABR, Inc.—Environmental Research & Services (ABR). 2007. Vegetation impact assessment and monitoring studies, Red Dog Mine, Alaska. Report for Tech Cominco Alaska Inc. by ABR, Inc.—Environmental Research & Services.

Cox, M. 1995. Oxidation in Red Dog mine ore. Unpublished report for TeckCominco, 25 October 1995.

Hultén, E. 1968. Flora of Alaska and Neighboring Territories. Stanford University Press. Stanford, CA. 1,008 pp.

Jonasson, S. 1988. Evaluation of the point intercept method for the estimation of plant biomass. Oikos 52:101–106.

Klute, A. (ed.) 1986. Methods of Soils Analysis. Part 1-Physical and Mineralogical Methods. Soils Science Society of America Inc. Madison, WI. 1,188 pp.

Mays, D. A., and G. W. Bengston. 1978. Lime and fertilizer use in land reclamation in humid regions. Pages 307–327 in Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

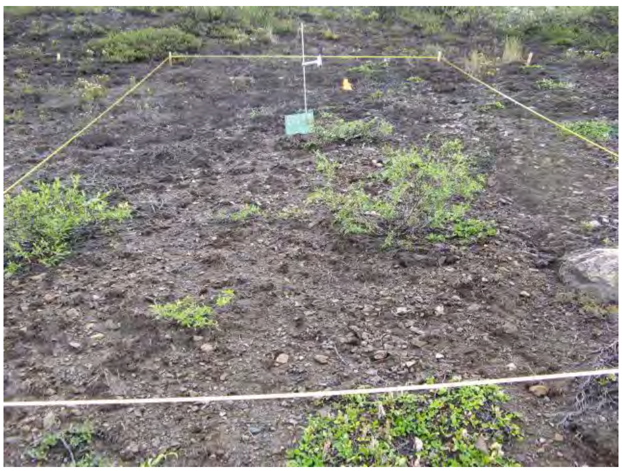
Redente, E. F., and J. L. Richards. 1997. Effects of lime and fertilizer amendments on plant growth in smelter impacted soils in Montana. Arid soil research and rehabilitation. 11: 353–366.

SPSS. 2007. SPSS 16.0 for Windows, SPSS, Inc., Chicago Illinois.

APPENDIX A. PHOTOGRAPHIC LOG OF TREATMENT BLOCKS, 2007 AND 2008, RED DOG MINE, ALASKA

Lime (L) treatment plot (rep 1), Triangle Area (E01), 28 June 2007.

Lime (L) treatment plot (rep 1), Triangle Area (E01), 25 July 2008.



Phosphorus (T) treatment plot (rep 1), Triangle Area (E01), 28 June 2007.

Phosphorus (T) treatment plot (rep 1), Triangle Area (E01), 25 July 2008.

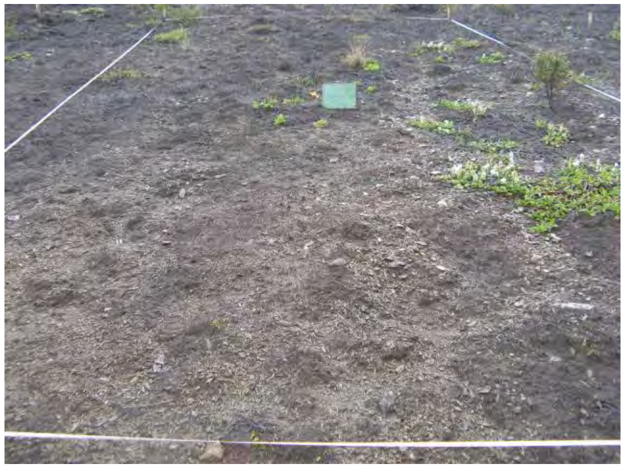
Untreated reference (R) plot (rep 1), Triangle Area (E01), 28 June 2007.

Untreated reference (R) plot (rep 1), Triangle Area (E01), 25 July 2008.

Phosphorus (T) treatment plot (rep 2), Triangle Area (E01), 28 June 2007.

Phosphorus (T) treatment plot (rep 2), Triangle Area (E01), 25 July 2008.

Lime (L) treatment plot (rep 2), Triangle Area (E01), 28 June 2007.



Lime (L) treatment plot (rep 2), Triangle Area (E01), 25 July 2008.

Untreated reference (R) plot (rep 2), Triangle Area (E01), 28 June 2007.

Untreated reference (R) plot (rep 2), Triangle Area (E01), 25 July 2008.

Phosphorus (T) treatment plot (rep 3), Triangle Area (E01), 28 June 2007.

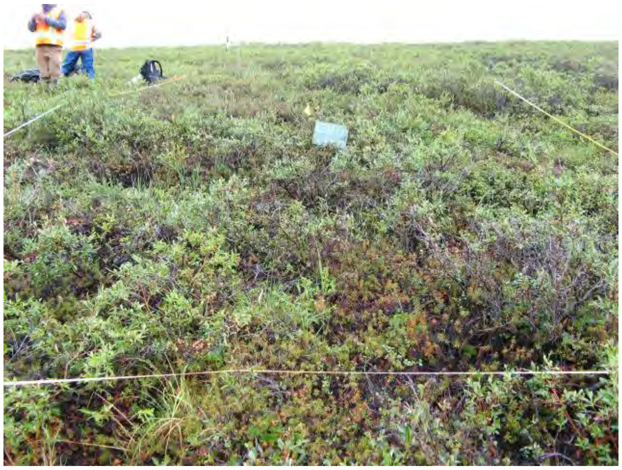
Phosphorus (T) treatment plot (rep 3), Triangle Area (E01), 25 July 2008.

Lime (L) treatment plot (rep 3), Triangle Area (E01), 28 June 2007.

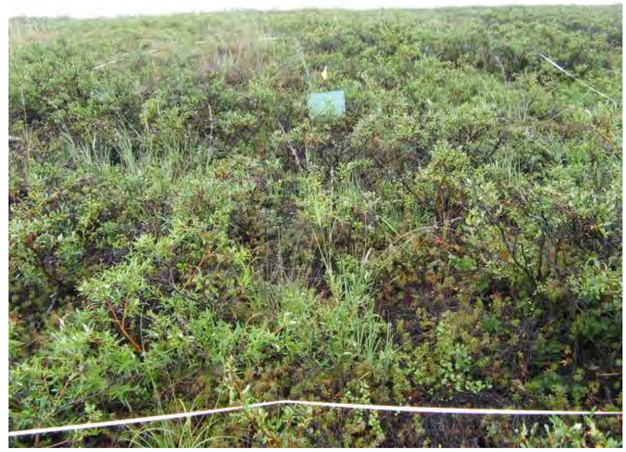
Lime (L) treatment plot (rep 3), Triangle Area (E01), 25 July 2008.

Untreated reference (R) plot (rep 3), Triangle Area (E01), 28 June 2007.

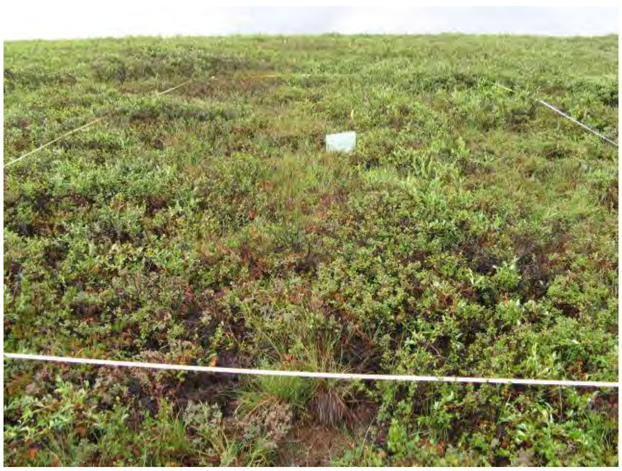
Untreated reference (R) plot (rep 3), Triangle Area (E01), 25 July 2008.



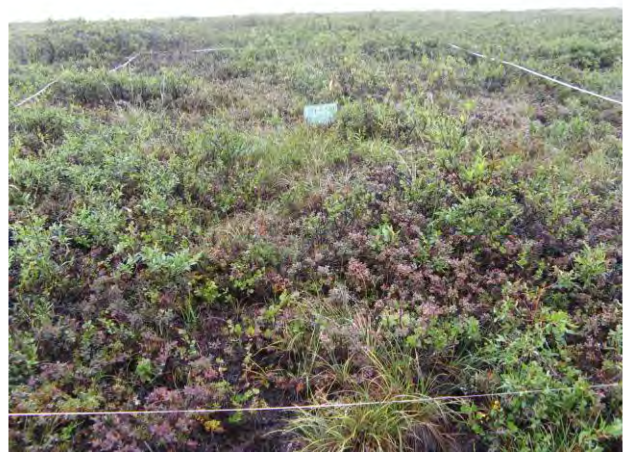
Lime (L) treatment plot (rep 1), Red Dog Creek (E02), 28 June 2007.



Lime (L) treatment plot (rep 1), Red Dog Creek (E02), 25 July 2008.



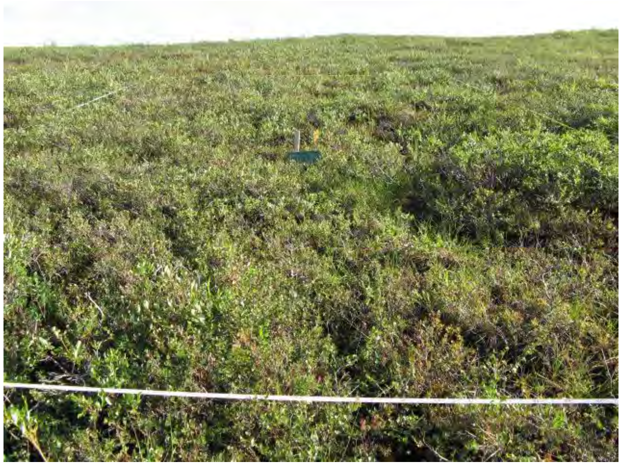
Phosphorus (T) treatment plot (rep 1), Red Dog Creek (E02), 28 June 2007.



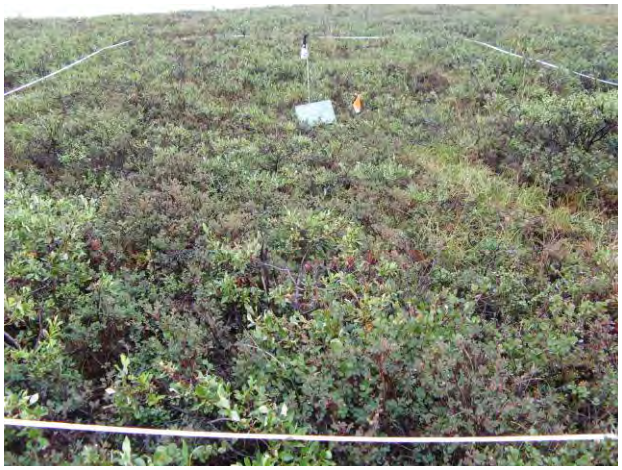
Phosphorus (T) treatment plot (rep 1), Red Dog Creek (E02), 25 July 2008.

Untreated reference (R) plot (rep 1), Red Dog Creek (E02), 28 June 2007.

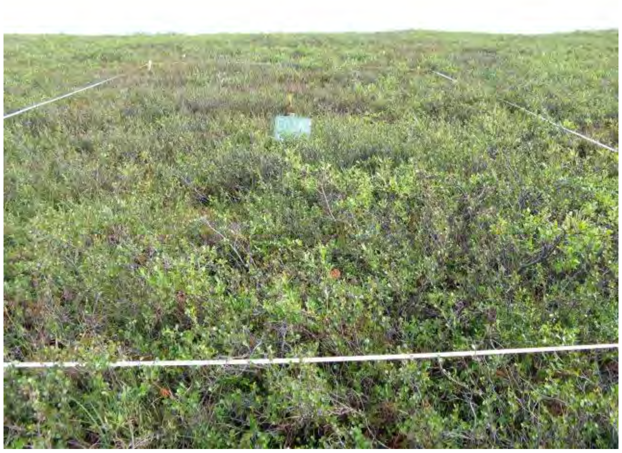
Untreated reference (R) plot (rep 1), Red Dog Creek (E02), 25 July 2008



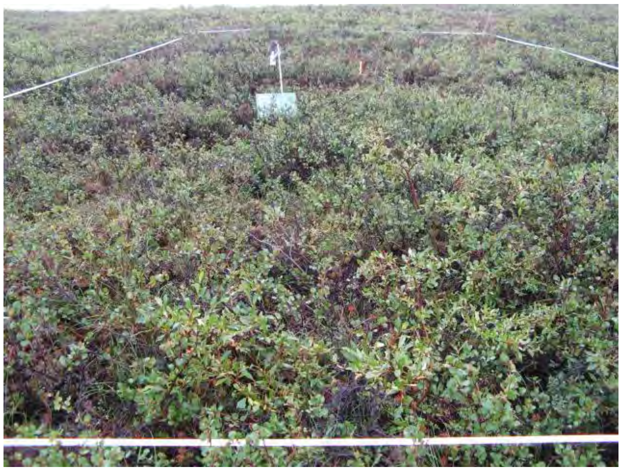
Lime (L) treatment plot (rep 2), Red Dog Creek (E02), 29 June 2007.



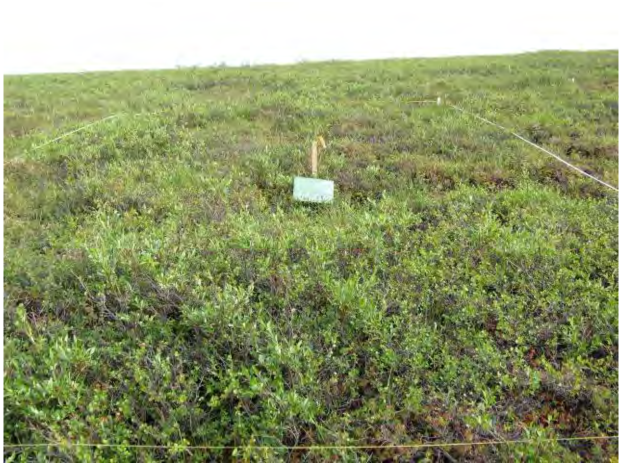
Lime (L) treatment plot (rep 2), Red Dog Creek (E02), 26 July 2008.



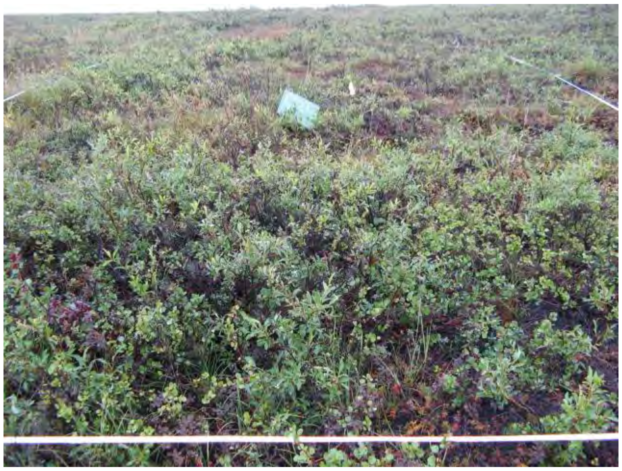
Untreated reference (R) plot (rep 2), Red Dog Creek (E02), 29 June 2007.



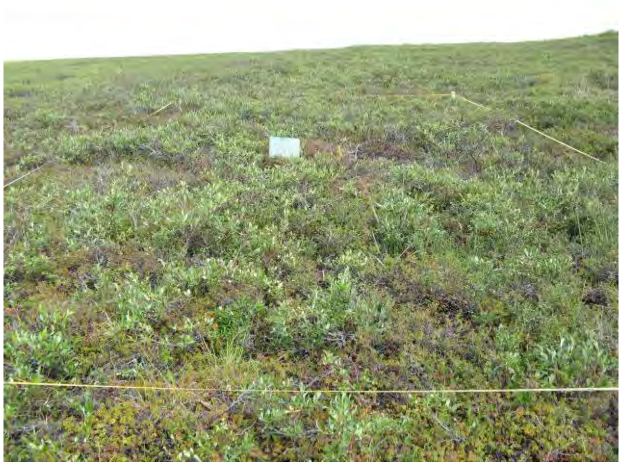
Untreated reference (R) plot (rep 2), Red Dog Creek (E02), 26 July 2008.



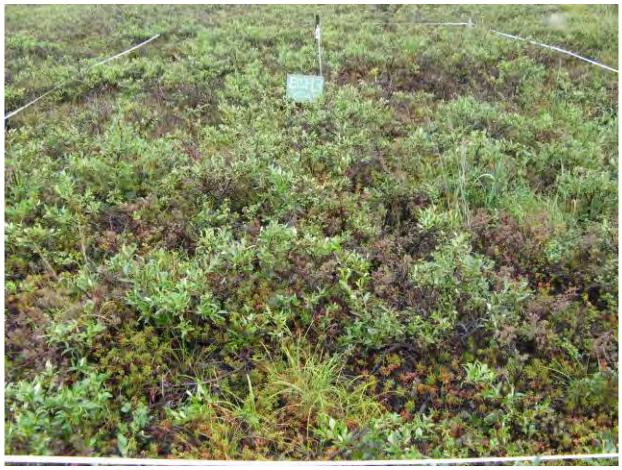
Phosphorus (T) treatment plot (rep 2), Red Dog Creek (E02), 29 June 2007.



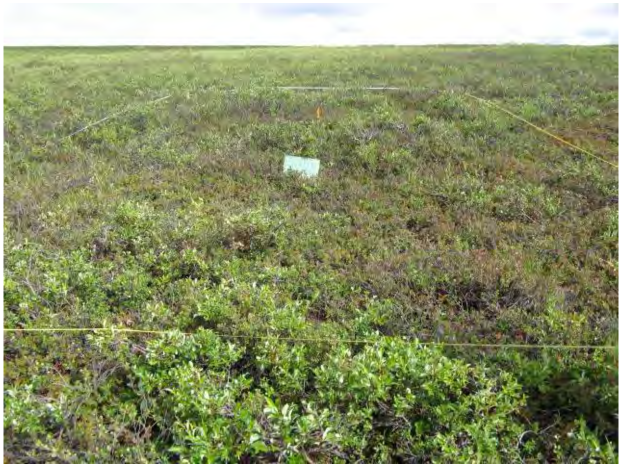
Phosphorus (T) treatment plot (rep 2), Red Dog Creek (E02), 26 July 2008.



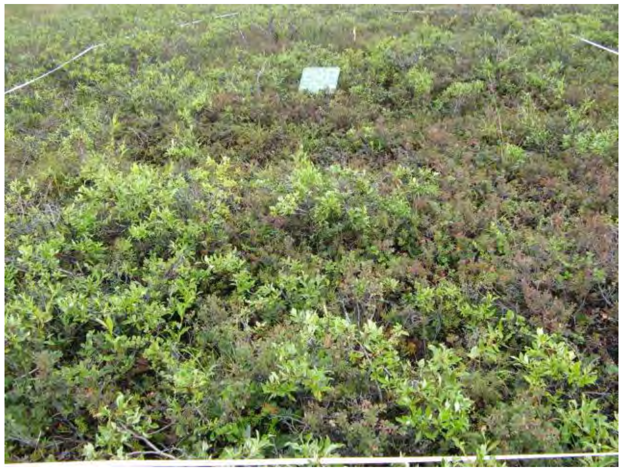
Lime (L) treatment plot (rep 3), Red Dog Creek (E02), 29 June 2007.



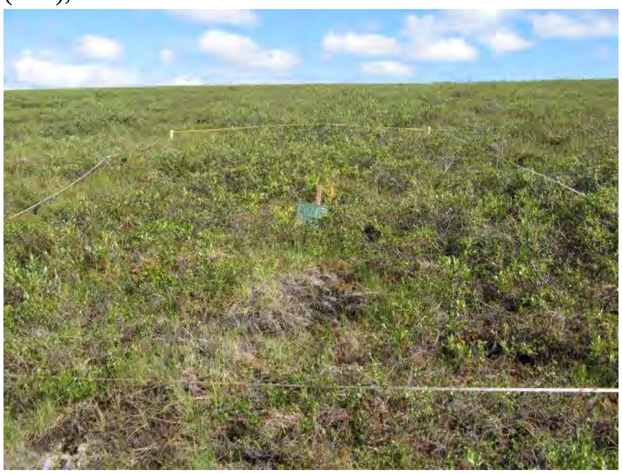
Lime (L) treatment plot (rep 3), Red Dog Creek (E02), 26 July 2008.



Phosphorus (T) treatment plot (rep 3), Red Dog Creek (E02), 29 June 2007.

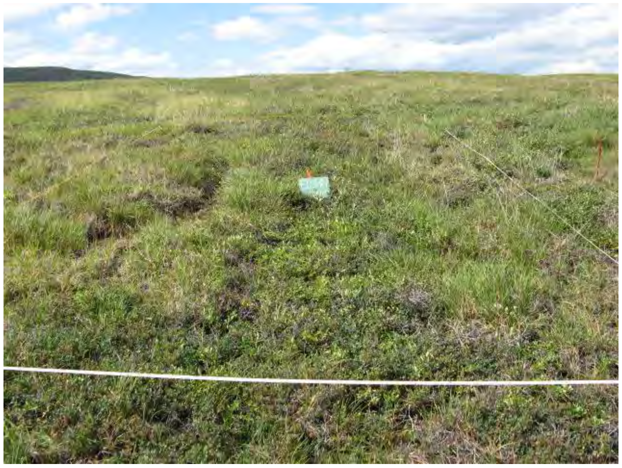


Phosphorus (T) treatment plot (rep 3), Red Dog Creek (E02), 26 July 2008.

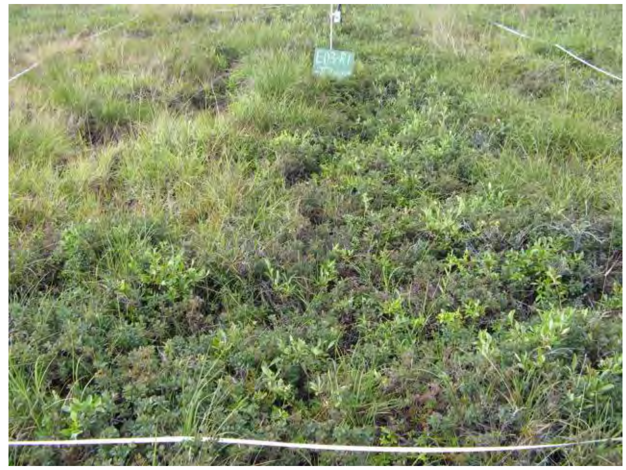


Untreated reference (R) plot (rep 3), Red Dog Creek (E02), 29 June 2007.

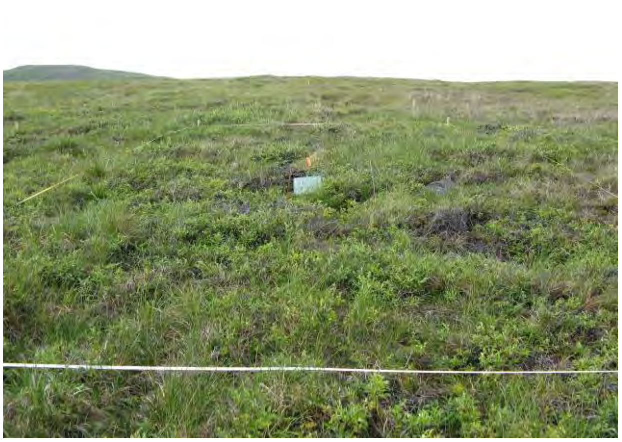
Untreated reference (R) plot (rep 3), Red Dog Creek (E02), 26 July 2008.



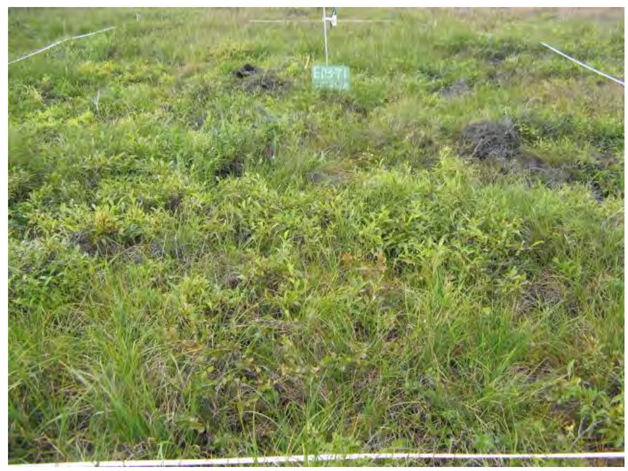
Untreated reference (R) plot (rep 1), Tailings Area (E03), 29 June 2007.



Untreated reference (R) plot (rep 1), Tailings Area (E03), 26 July 2008.

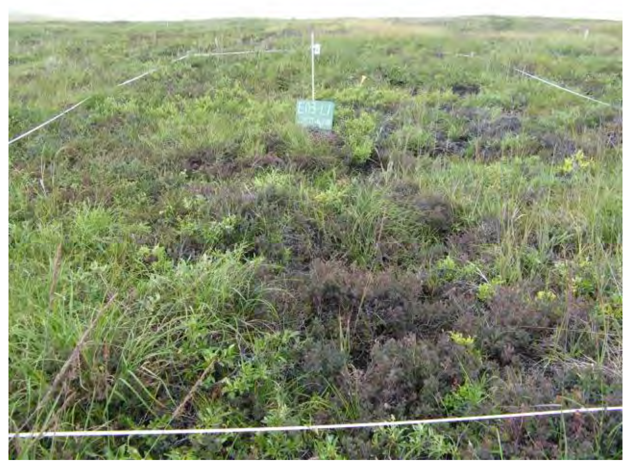


Phosphorus (T) treatment plot (rep 1), Tailings Area (E03), 29 June 2007.

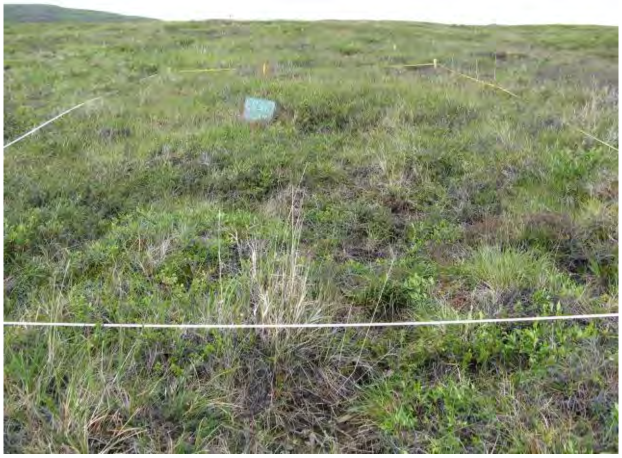


Phosphorus (T) treatment plot (rep 1), Tailings Area (E03), 26 July 2008.

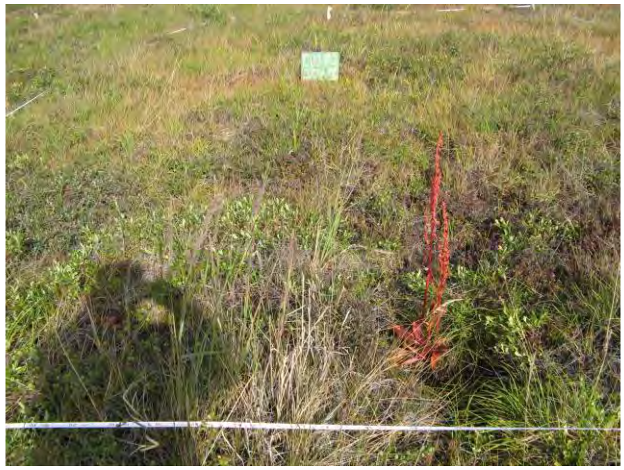
Lime (L) treatment plot (rep 1), Tailings Area (E03), 29 June 2007.



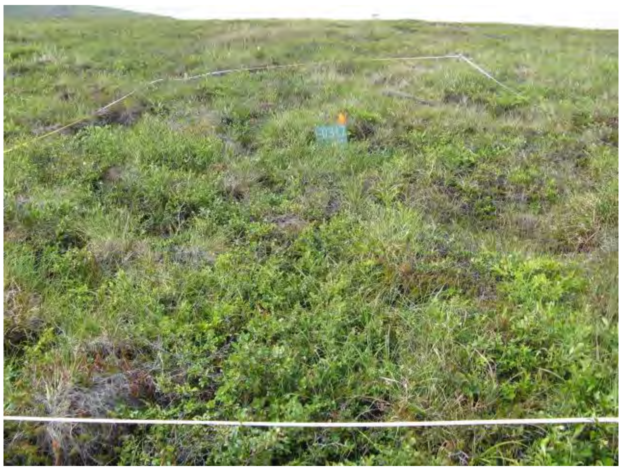
Lime (L) treatment plot (rep 1), Tailings Area (E03), 26 July 2008.



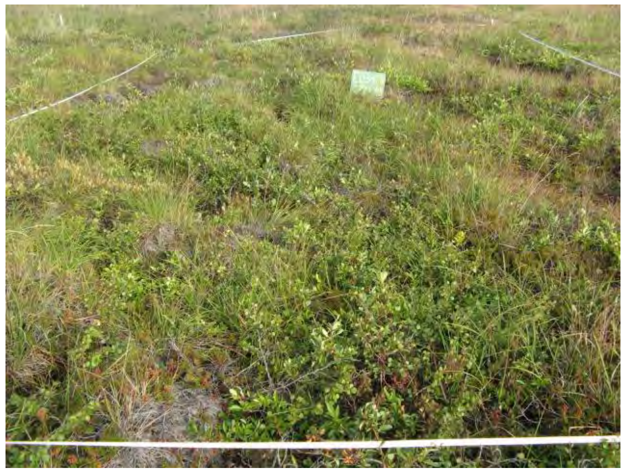
Untreated reference (R) plot (rep 2), Tailings Area (E03), 29 June 2007.



Untreated reference (R) plot (rep 2), Tailings Area (E03), 27 July 2008.



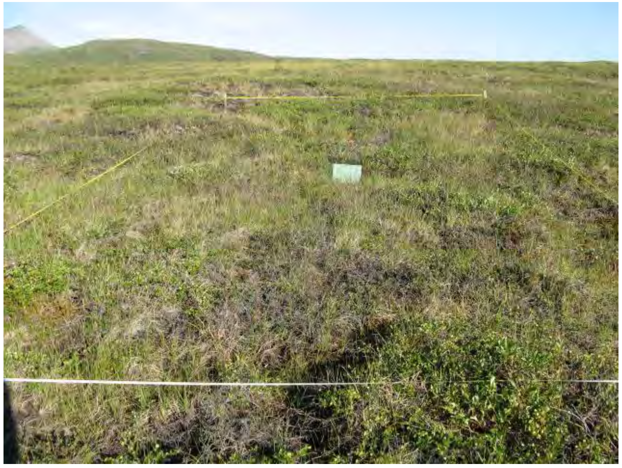
Lime (L) treatment plot (rep 2), Tailings Area (E03), 29 June 2007.



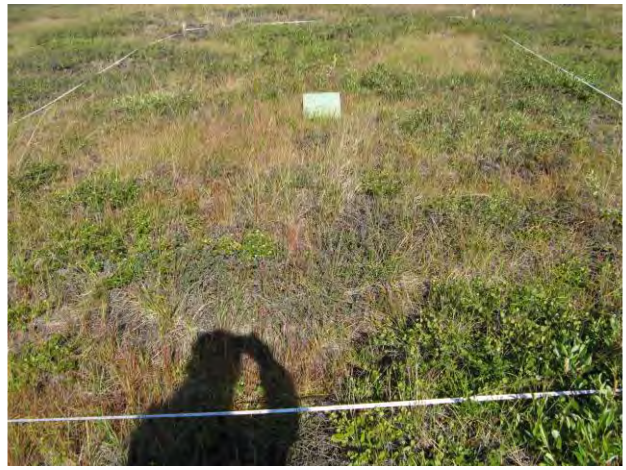
Lime (L) treatment plot (rep 2), Tailings Area (E03), 27 July 2008.

Phosphorus (T) treatment plot (rep 2), Tailings Area (E03), 29 June 2007.

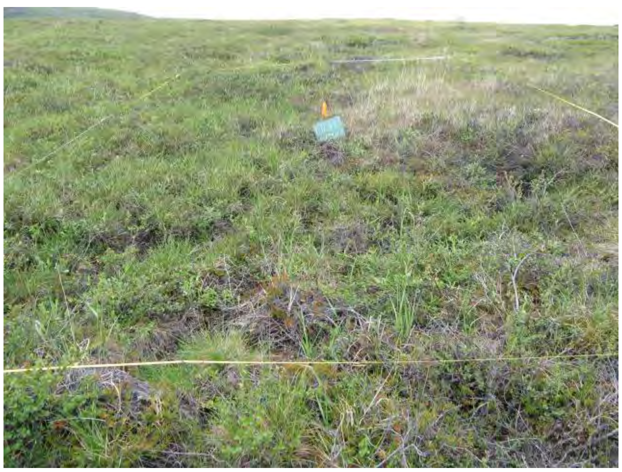
Phosphorus (T) treatment plot (rep 2), Tailings Area (E03), 27 July 2008.



Phosphorus (T) treatment plot (rep 3), Tailings Area (E03), 30 June 2007.

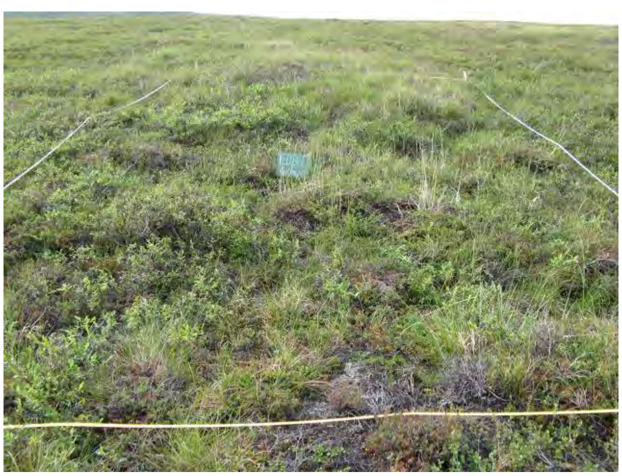


Phosphorus (T) treatment plot (rep 3), Tailings Area (E03), 27 July 2008.

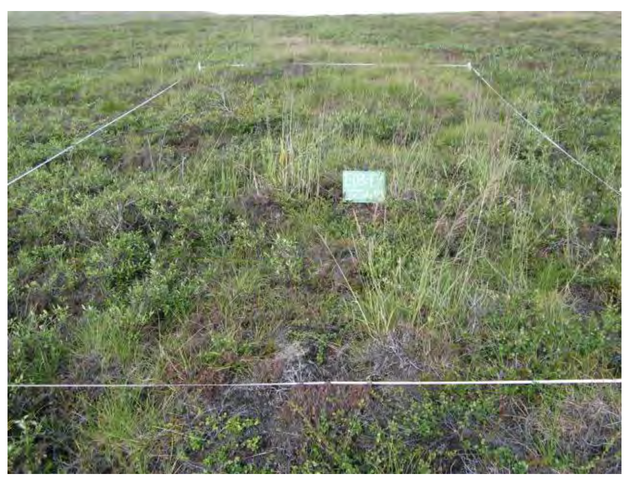


Untreated reference (R) plot (rep 3), Tailings Area (E03), 29 June 2007.

Untreated reference (R) plot (rep 3), Tailings Area (E03), 27 July 2008.



Lime (L) treatment plot (rep 3), Tailings Area (E03), 29 June 2007.



Lime (L) treatment plot (rep 3), Tailings Area (E03), 27 July 2008.

APPENDIX B. SUMMARY OF SELECTED SOIL CHARACTERISTICS IN TREATMENT BLOCKS, 2006 AND 2008, RED DOG MINE, ALASKA

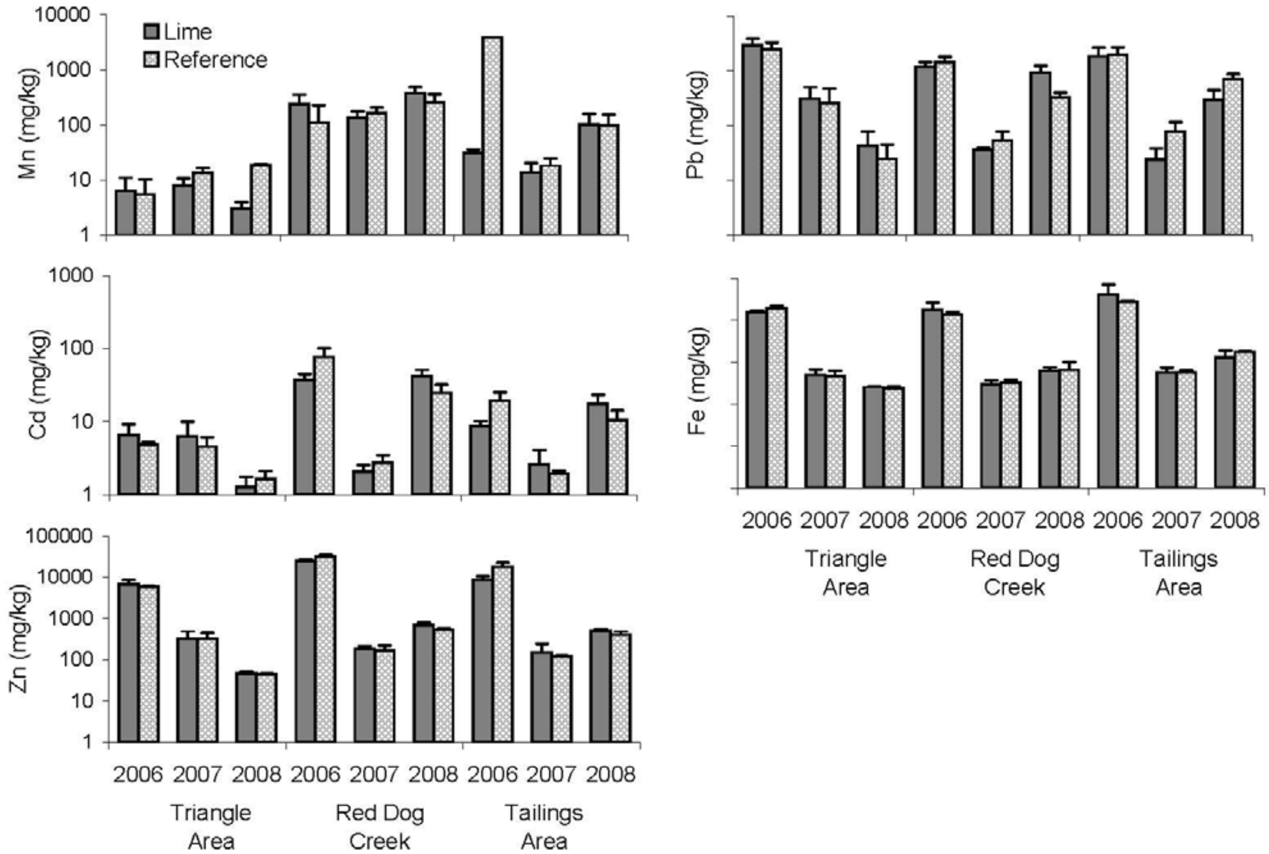


Figure B1. Comparisons of selected metals in lime-treated and reference (untreated) experimental test plots, Red Dog Mine, 2006–2008.

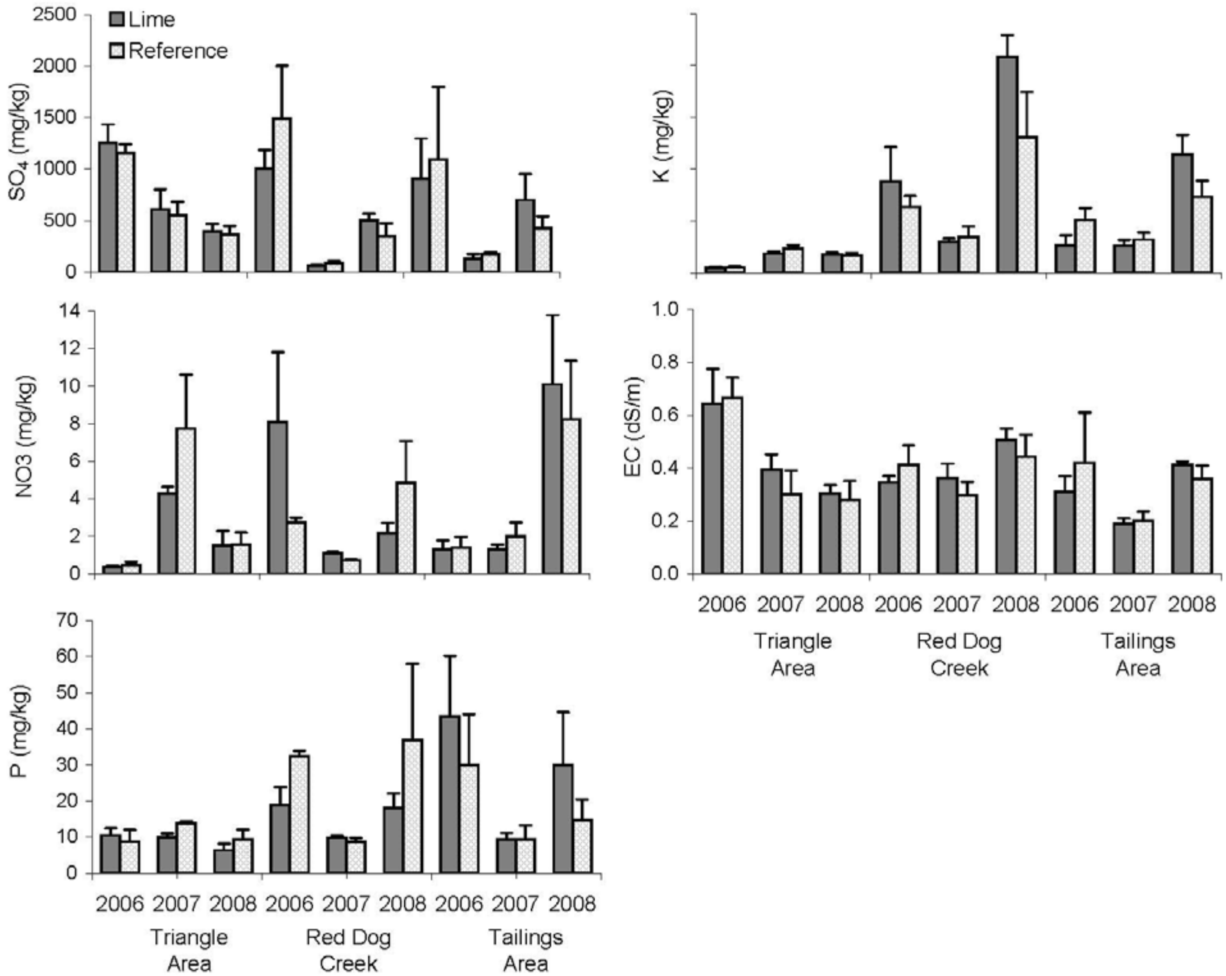


Figure B2. Comparisons of electrical conductivity (EC), selected nutrients, sulfate (SO_4), and potassium (K) in lime-treated and reference (untreated) experimental test plots, Red Dog Mine, 2006–2008.

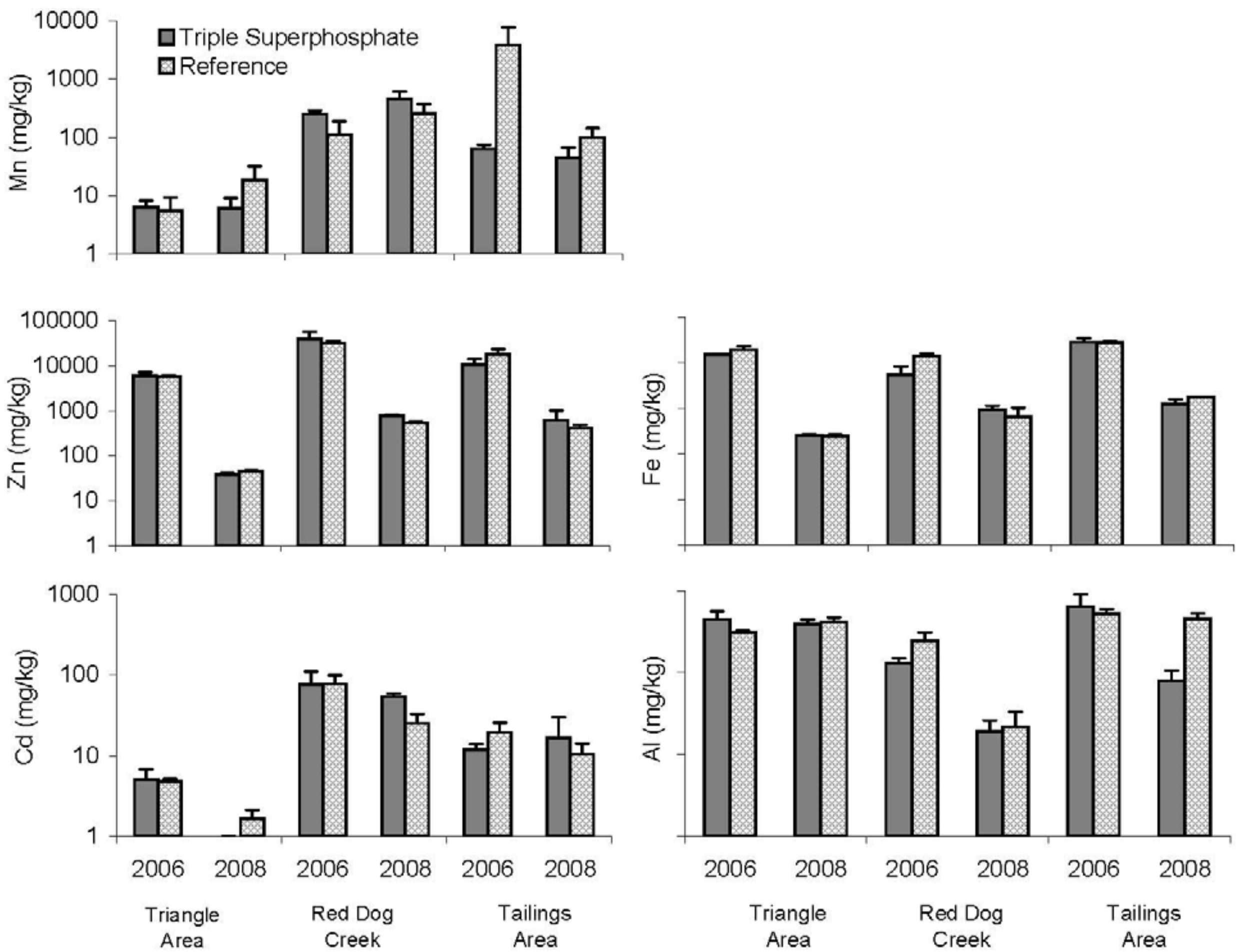


Figure B3. Comparisons of selected metals in triple superphosphate-treated and reference (untreated) experimental test plots, Red Dog Mine, 2006–2008.

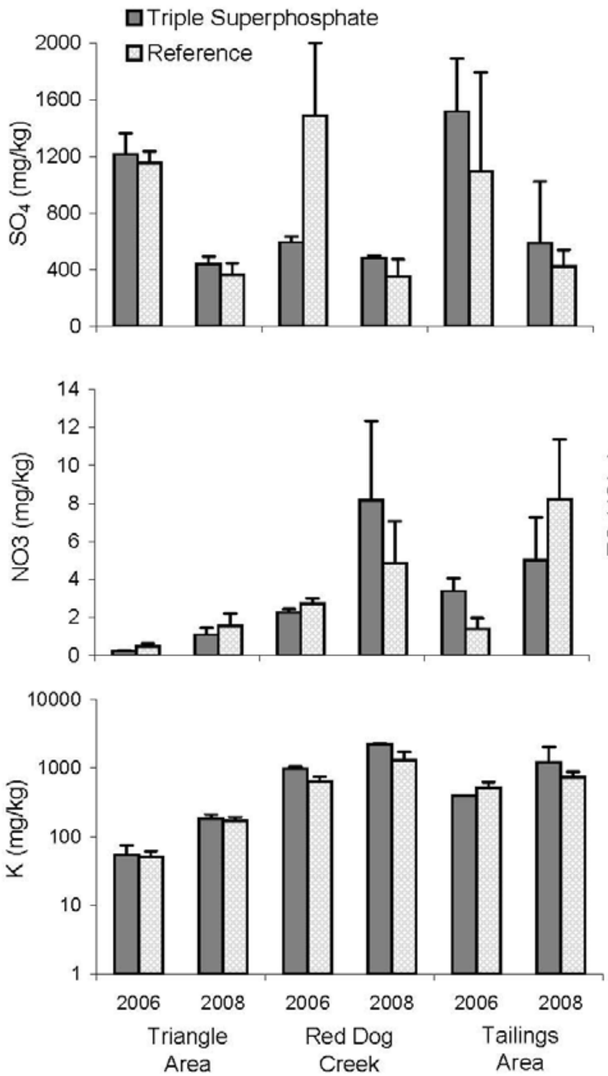


Figure B4. Comparisons of electrical conductivity (EC), selected nutrients, sulfate (SO_4), and potassium (K) in triple superphosphate-treated and reference (untreated) experimental test plots, Red Dog Mine, 2006–2008.

APPENDIX C. SUMMARY OF STATISTICAL ANALYSIS OF SOIL PARAMETERS IN TREATMENT BLOCKS, 2007 AND 2008, RED DOG MINE, ALASKA

Table C1. Results of univariate tests of between-subject effects 2007 and 2008.

Variable	Response	F	df	P-value
Treatment	Conductivity	1.526	1, 14	0.237
	pH	**4.842**	1, 14	**0.045**
	Sulfate	1.088	1, 14	0.315
	Aluminum	**22.296**	1, 14	**< 0.001**
	Cadmium	.252	1, 14	0.623
	Iron	.424	1, 14	0.526
	Lead	.010	1, 14	0.923
	Manganese	.398	1, 14	0.538
	Nitrate	.185	1, 14	0.674
	Phosphorus	.037	1, 14	0.850
	Potassium	.451	1, 14	0.513
	Zinc	1.061	1, 14	0.320
Location	Conductivity	2.936	2, 14	0.086
	pH	**50.140**	2, 14	**<0.001**
	Sulfate	3.433	2, 14	0.061
	Aluminum	**230.304**	2, 14	**<0.001**
	Cadmium	**9.580**	2, 14	**0.002**
	Iron	**14.375**	2, 14	**<0.001**
	Lead	1.565	2, 14	0.244
	Manganese	**35.910**	2, 14	**<0.001**
	Nitrate	2.949	2, 14	0.085
	Phosphorus	1.628	2, 14	0.231
	Potassium	**24.223**	2, 14	**<0.001**
	Zinc	**6.510**	2, 14	**0.010**

Table C2. Results of univariate tests of within-subject effects 2007 and 2008.

Variable	Response	F	df	P-value
Year	**Conductivity**	30.711	1, 14	<0.001
	pH	0.574	1, 14	0.461
	Sulfate	10.245	1, 14	0.006
	Aluminum	0.964	1, 14	0.343
	Cadmium	33.470	1, 14	<0.001
	Iron	8.302	1, 14	0.012
	Lead	11.367	1, 14	0.017
	Manganese	9.677	1, 14	0.008
	Nitrate	6.009	1, 14	0.028
	Phosphorus	4.302	1, 14	0.057
	Potassium	155.547	1, 14	<0.001
	Zinc	16.679	1, 14	0.001

Table C2. Continued.

Variable	Response	F	df	P-value
Year*Treatment	Conductivity	0.010	1, 14	0.923
	pH	0.536	1, 14	0.476
	Sulfate	1.747	1, 14	0.207
	Aluminum	0.423	1, 14	0.526
	Cadmium	0.649	1, 14	0.434
	Iron	0.399	1, 14	0.538
	Lead	0.171	1, 14	0.686
	Manganese	0.069	1, 14	0.797
	Nitrate	0.036	1, 14	0.853
	Phosphorus	0.001	1, 14	0.976
	Potassium	**16.019**	**1, 14**	**0.001**
	Zinc	0.800	1, 14	0.386
Year*Location	**Conductivity**	**19.940**	**2, 14**	**<0.001**
	pH	0.238	2, 14	0.791
	Sulfate	**11.379**	**2, 14**	**0.001**
	Aluminum	0.041	2, 14	0.960
	Cadmium	**39.025**	**2, 14**	**<0.001**
	Iron	**8.062**	**2, 14**	**0.005**
	Lead	**18.104**	**2, 14**	**<0.001**
	Manganese	**5.309**	**2, 14**	**0.019**
	Nitrate	**28.599**	**2, 14**	**<0.001**
	Phosphorus	**6.043**	**2, 14**	**0.013**
	Potassium	**59.858**	**2, 14**	**<0.001**
	Zinc	**32.285**	**2, 14**	**<0.001**

APPENDIX D. SUMMARY OF VEGETATION COVER IN TREATMENT BLOCKS, 2007 AND 2008, RED DOG MINE, ALASKA

Table D1. Mean (n = 3) percent cover of vegetation in Triangle Area, 2007 and 2008.

Cover Type/Species	Lime		Triple Phosphate		Reference (untreated)	
	2007	2008	2007	2008	2007	2008
Total Live Cover	9.0	19.0	19.0	23.0	12.7	12.7
Live Vascular Cover	9.0	19.0	19.0	22.0	12.7	12.7
Deciduous Shrubs	7.7	13.7	15.7	19.0	12.0	11.7
Betula nana[a]	2.0	6.0	1.0	2.7	3.3	3.3
Salix chamissonis	0.7	1.7	4.3	4.0	0.7	1.0
S. phlebophylla				0.3		0.3
S. pulchra	1.3	0.7	2.7	3.7	4.3	3.7
S. reticulata	0.7			0.3		
S. rotundifolia		1.0		0.3		0.3
Spiraea beauverdiana	0.3	2.0		0.7	0.7	0.7
Vaccinium uliginosum	2.7	2.3	7.7	7.0	3.0	2.3
Forbs				1.0		0.3
Artemisia arctica				0.3		
Minuartia arctica				0.3		0.3
Parrya nudicaulis				0.3		
Grasses	0.3	5.0	3.3	1.7	0.7	0.3
Calamagrostis canadensis	0.3	2.7		1.0		0.3
Festuca altaica		2.3	3.3	0.7	0.7	
Sedges	1.0	0.3		0.3		0.3
Carex atrofusca				0.3		0.3
C. bigelowii	1.0	0.3				
Non-Vascular Cover				1.0		
Unknown moss				0.7		
Lichens				0.3		
Cetraria islandica				0.3		
Bare Cover	93.7	85.0	88.7	82.3	92.3	91.3
Soil	57.0	55.0	54.0	54.7	49.3	57.7
Litter	36.7	30.0	34.7	27.7	43.0	33.7

[a] Previously identified as *Betula glandulosa*, and may represent a hybrid of the two species.

Table D2. Mean (n = 3) percent cover of vegetation at Red Dog Creek, 2007 and 2008.

	Lime		Triple Phosphate		Reference (untreated)	
	2007	2008	2007	2008	2007	2008
Total Live Cover	88.7	105.0	95.3	115.3	107.0	119.3
Live Vascular Cover	88.7	100.3	95.0	111.7	107.0	117.0
Deciduous Shrubs	43.7	43.3	48.0	51.0	59.0	54.0
Betula nana	12.0	11.0	10.3	9.3	21.0	19.3
Salix pulchra	15.7	14.3	14.0	18.0	21.0	25.3
Vaccinium uliginosum	16.0	18.0	23.7	23.7	17.0	9.3
Evergreen Shrubs	41.3	40.7	36.3	41.7	39.7	42.3
Empetrum nigrum	1.3	0.7	0.3	1.0	0.3	0.7
Ledum decumbens	20.7	17.7	19.3	24.7	23.7	27.0
Vaccinium vitis-idaea	19.3	22.3	16.7	16.0	15.7	14.7
Forbs	1.3	2.7	1.7	4.3	1.7	4.3
Petasites frigidus						0.3
Rubus chamaemorus	1.3	2.7	1.7	4.3	1.7	4.0
Grasses	1.3	4.7	1.3	2.0	1.0	3.3
Arctagrostis latifolia	1.3	2.0	1.3	0.7	1.0	3.0
Calamagrostis canadensis		2.0		1.0		
Poa arctica				0.3		
P. glauca		0.7				0.3
Sedges	1.0	9.0	7.7	12.7	5.7	13.0
Carex bigelowii	1.0	8.3	7.7	12.3	5.7	12.7
Eriophorum vaginatum		0.7		0.3		0.3
Non-Vascular Cover		4.7	0.3	3.7		2.3
Unknown moss		2.3		2.7		1.0
Lichens		2.3	0.3	1.0		1.3
Cladina sp.		0.3				
Cladonia sp.		0.3				0.3
Thamnolia subuliformis		0.3				
Unknown lichen		1.3	0.3	1.0		1.0
Total Bare Cover	43.0	34.3	37.3	32.7	33.7	32.0
Water	0.3	0.3	0.7	1.0		
Litter	42.7	34.0	36.7	31.7	33.7	32.0

Table D3. Mean (n = 3) percent of vegetation in the Tailings Area, 2007 and 2008.

	Lime		Triple Phosphate		Reference (untreated)	
	2007	2008	2007	2008	2007	2008
Total Live Cover	81.0	102.0	72.3	96.0	80.3	97.3
Live Vascular Cover	79.3	98.3	72.0	95.0	79.0	94.0
Deciduous Shrubs	39.7	43.3	36.7	40.7	40.0	50.7
Betula nana[a]	12.0	9.7	15.0	13.7	15.3	17.7
Salix pulchra	15.7	16.3	14.3	19.0	5.0	10.3
Vaccinium uliginosum	12.0	17.3	7.3	8.0	19.7	22.7
Evergreen Shrubs	16.3	20.0	9.0	12.7	21.0	15.3
Empetrum nigrum	1.0	2.3	1.0	2.7	1.3	2.0
Ledum decumbens	9.7	13.7	3.0	4.3	10.3	8.3
Vaccinium vitis-idaea	5.7	4.0	5.0	5.7	9.3	5.0
Forbs	0.7	2.7		0.7		1.0
Petasites frigidus	0.3	0.3				
Polygonum bistorta		0.7		0.3		0.3
Rubus chamaemorus	0.3	1.3		0.3		0.3
R. arcticus						0.3
Stellaria laeta		0.3				
Grasses	3.3	6.0	8.0	16.0	1.3	9.0
Arctagrostis latifolia	1.0	1.3	0.3	1.0	0.7	1.3
Calamagrostis canadensis	2.0	2.3	7.3	13.0	0.3	4.3
Hierochlöe alpina		0.3		0.7		1.7
Poa arctica	0.3	1.0	0.3	0.3	0.3	0.7
P. glauca		1.0		1.0		1.0
Sedges	19.3	26.3	18.3	25.0	16.7	18.0
Carex atrofusca					1.3	
C. bigelowii	18.0	24.7	18.3	23.7	15.0	17.0
C. podocarpa				0.3		0.3
Eriophorum vaginatum	1.3	1.3		1.0	0.3	0.3
Luzula multiflora		0.3				0.3
Non-Vascular Cover	1.7	3.7	0.3	1.0	1.3	3.3
Unknown moss	1.7	3.3	0.3	1.0	1.3	3.3
Lichens		0.3				
Thamnolia subuliformis		0.3				
Total Bare Cover	42.7	43.3	47.7	42.0	44.7	39.7
Bare Ground	1.7	2.3	0.3	3.0	1.0	2.3
Bare Soil	1.7	1.7	0.3	3.0	1.0	2.3
Water		0.7				
Litter	41.0	41.0	47.3	39.0	43.7	37.3

[a] Previously identified as *Betula glandulosa*, and may represent a hybrid of the two species.