Cumulative impacts on Alaskan arctic tundra of a quarter century of road dust\textsuperscript{1}

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Abstract: Tundra ecosystems are sensitive to disturbance and slow to recover. To account for environmental costs of development in the North, cumulative impacts of roads and dust deposition must be quantified. After a previous study, we re-examined tundra adjacent to the 577-km-long Dalton Highway in northern Alaska to assess 13 y of additional calcareous road dust deposition. Dust loading continues to alter substrate properties and community composition. Moist, acidic, tussock-sedge tundra typically has a soil pH of 4. At the road margin the pH of the fibric horizon had increased to pH 5.5 by 1989 and to pH 6.0 by 2002. Plots adjacent to the road have significantly higher graminoid and Rubus chamaemorus biomass and less moss, evergreen shrub, lichen, and forb biomass. Graminoid cover ranges from 30\% in undisturbed tundra to over 80\% within 5 m of the road. We observed an 80 g·m\textsuperscript{-2} increase in graminoid biomass and a 130 g·m\textsuperscript{-2} decline in moss biomass across the study site between 1989 and 2002. Ordinations indicate a broadened zone of dust disturbance in 2002. This evidence of cumulative impacts of dust will improve our evaluation of the ecological costs of future road development in the North.

Keywords: cumulative impacts, oil development, pH, press disturbance, road dust, tundra vegetation.

Résumé : Les écosystèmes toundriques sont sensibles aux perturbations et se regénèrent lentement. Pour évaluer les coûts environnementaux du développement dans le Nord, les impacts cumulatifs des routes et de la déposition de poussiére doivent être évalués. Suite à une étude précédente, nous avons réexaminé la toundra adjacente à l’autoroute Dalton, longue de 577 km dans le nord de l’Alaska, afin d’évaluer 13 années additionnelles de dépôt de poussière calcaire de la route. La charge de poussière continue d’altérer les propriétés du substrat et la composition des communautés. Le sol humide et acide de la toundra recouvert de touffes de carex a normalement un pH de 4. En 1989, le pH de l’horizon fibrique des bords de route avait augmenté à 5.5 et en 2002 à 6.0. Les parcelles adjacentes à la route ont significativement plus de biomasse de graminées et de Rubus chamaemorus et moins de biomasse de mousses, de lichens, d’arbustes à feuilles persistantes et d’autres herbacées. La couverture de graminées varie de 30 \% dans la toundra non perturbée à plus de 80 \% à moins de 5 m de la route. Nous avons observé une augmentation de 80 g·m\textsuperscript{-2} de la biomasse de graminées et un déclin de 130 g·m\textsuperscript{-2} de la biomasse de mousses entre 1989 et 2002 pour l’ensemble du site d’étude. De plus, la zone perturbée par la poussière s’était élargie en 2002. Ces évidences d’impacts cumulatifs de la poussière contribueront à préciser notre évaluation des coûts écologiques du développement futur dans le Nord.

Mots-clés : exploitation pétrolière, impacts cumulatifs, perturbation chronique, pH, poussière de la route, végétation de la toundra.


Introduction

Oil development in the Arctic has wide-reaching effects on ecosystem health, including both direct habitat destruction and indirect cumulative impacts on the adjacent landscape (Walker & Walker, 1991; NRC, 2003). Vehicle transport is one of the most widespread forms of arctic disturbance (Forbes, Ebersole & Strandberg, 2001). The direct ecological impacts of gravel roads and off-road vehicle traffic in the Arctic, such as vegetation disturbance, soil erosion, and pollution, are extensive and have estimated recovery times of centuries to millennia (Chapin & Shaver, 1985; Forbes, Ebersole & Strandberg, 2001). Indirect effects of vehicle traffic from dust deposition continue to alter the adjacent tundra ecosystem years after road construction.

The greatest sensitivity of a natural community to road dust has been documented in the High Arctic (Farmer, 1993). Road dust acts on many of the physico-chemical characteristics of the soil to which tundra community composition is most sensitive, including microclimate and pH (Walker & Everett, 1987; Walker & Walker, 1991). Dust can directly affect vegetation by coating leaves or, in the case of calcareous dust, by elevating soil pH to a level toxic to tundra acidophiles. It can also act indirectly by modifying microenvironment and ecosystem processes, altering canopy structure, soil chemistry, microbial decom-

In 2003, the American National Research Council produced a synthesis of research on the impacts of oil and gas development on Alaska’s North Slope to assess cumulative environmental effects. The report highlighted the need for long-term studies of the ecological impacts of roads. A complete analysis of cumulative impacts requires the synthesis of multiple individual assessments of ecosystem response to disturbance over time (National Research Council, 2003).

The Dalton Highway, a 577-km-long gravel road that connects the Prudhoe Bay Oilfield in arctic Alaska with southern supply points, was completed in 1975 (Brown & Berg, 1980). Heavy trucks traveling along this road disturb dust that settles on adjacent plant communities. An initial study of road-dust effects adjacent to the Dalton Highway was conducted in 1989. This study documented increased soil pH and altered vegetation composition resulting from calcareous road dust deposition (Auerbach, Walker & Walker, 1997). Species richness decreased by 50%, with a virtual elimination of Sphagnum mosses, forbs, and lichens near the road. In our study we returned to the site of previous research to assess the cumulative impacts of three decades of calcareous road dust deposition on tundra.

**Methods**

**Study site**

This study was conducted adjacent to the Dalton Highway on a plateau of the Arctic foothills near Toolik Field Station, Alaska (68° 41' N, 149° 10' W; 808 m elevation). The study site vegetation is characteristic of moist, acidic tussock-sedge tundra (Walker et al., 1994). Eriophorum vaginatum and Sphagnum spp. are the dominant species in the undisturbed tundra. The soil is loamy and acidic with a peaty surface layer that is poorly drained and a shallow active layer (Auerbach, Walker & Walker, 1997).

Dust load decreases logarithmically with distance from the road (Everett, 1980; Santelmann & Gorham, 1988). In the late 1970s, average dust deposition rates were 30 to 250 g·m⁻²·d⁻¹ within 100 m from the road and 0.8 to 13 g·m⁻²·d⁻¹ from 100 to 1000 m from the road (Walker & Everett, 1987). The distance that road dust travels depends on traffic, gravel properties, size and amount of dust particles, moisture content of the road soil, use of dust retardants, and the direction of prevailing winds (Everett, 1980). At this study site, winds are primarily northwesterly (Everett, 1980), leading to greater dust deposition and more pronounced vegetation effects on the eastern side of the road (Auerbach, Walker & Walker, 1997). The dust is highly alkaline because road materials were quarried from limestone bedrock and calcareous alluvial deposits (Walker & Everett, 1987). Gravel spray and snowplow-deposited gravel is present in areas directly adjacent to the road (Everett, 1980). Apart from road traffic, there is no other major human disturbance in this remote region.

In August 2002, we returned to the site first sampled in 1989 by Auerbach, Walker, and Walker (1997). Five 800-m-long transects 20 m apart and perpendicular to and downwind (E) of the road were marked with iron stakes at sampling locations 2, 5, 10, 25, 50, 100, 400, and 800 m. Sample distances were chosen based on the observation that the zone of maximum dust fall is within 300 m of the Dalton Highway (Everett, 1980). To avoid overlap with areas clipped by Auerbach, Walker, and Walker (1997) we re-sampled sites 2 m north of the staked locations from 1989.

**Soil properties**

Soil characteristics were determined by measuring pH and active-layer depth following the methodology of Auerbach, Walker, and Walker (1997). We collected forty 10- × 10-cm soil samples at each sample location from moss mats between tussocks. Soils were sampled from the base of the green moss to the base of the fibric (O₂) horizon (least decomposed horizon of the organic soil); therefore, sample volumes varied. We dried the soil samples at 60 °C. We measured soil pH using the paste method (Auerbach, Walker & Walker, 1997). We formed a slurry of homogenized soil and deionized water, using a ratio of approximately 1 g of soil to 5 mL of water, and measured pH using a pH meter (Orion Water Analysis Instruments, Beverly, Massachusetts, USA). Maximum seasonal active-layer thickness (depth from the moss surface to frozen ground) was measured at 10 arbitrary points at least 10 cm apart within a metre of each sampling location, using a 120-cm fiberglass frost probe. Thaw depth was measured from the base of Eriophorum vaginatum tussocks.

**Vegetation characteristics**

We described vegetation characteristics using % cover and biomass as in the previous study (Auerbach, Walker & Walker, 1997). Plant cover was estimated visually using a 1-m² quadrat at sampling sites less than 50 m from the road and a 50- × 50-cm quadrat at greater than 50 m along the transect. The smaller quadrat size was used at the farther distances because of time constraints of estimating plant cover in these more diverse plots. Plant biomass was estimated by clipping all live vegetation to the base of the green moss within a 20- × 50-cm quadrat (Auerbach, Walker & Walker, 1997). We sorted vegetation into live fractions of graminoids, evergreen shrubs, deciduous shrubs, mosses, lichens, forbs, and the single species Rubus chamaemorus (Rubus chamaemorus was sorted separately from other deciduous shrubs or forb species). Sub-sampling was used to speed the separation process when samples contained large quantities of graminoid, moss, or lichen biomass. Vegetation fractions were oven dried at 60 °C for 24 h and weighed. Sub-samples of 0.3 g of the live graminoid E. vaginatum were ground and analyzed for carbon and nitrogen contents using a Costech CN elemental analyzer (Valencia, California, USA). We chose to analyze E. vaginatum as it was the only species present at all sampling locations.

**Statistical analysis**

Analyses of variance were conducted with JMP IN 5.1.2 (SAS Institute, Cary, North Carolina, USA). We used ANOVA to compare soil properties and vegetation characteristics between 1989 and 2002 and with distance from the road. We used general linear models, removing factors and their interactions to produce the minimally significant models. Where appropriate, quadratic functions were included in the models. Data were transformed to best meet the assumptions of normality and homoscedasticity (Ln[x + 1]):
pH and thaw depth, $x^{1/3}$: % leaf N, graminoid biomass, total biomass, graminoid % cover, moss % cover, evergreen % cover, $x^{1/2.5}$: moss biomass, $x^{1/2.5}$: evergreen biomass, none: soil organic matter, PCA 1 and PCA 2).

We analyzed pH, thaw depth, organic matter depth, leaf nitrogen, biomass, and % cover of vegetation using multivariate methods in Primer (Plymouth Marine Laboratories, Plymouth, England). Analysis of similarities (ANOSIM) with 10,000 iterations ($\alpha = 0.05$) was used to test for differences in soil properties, biomass, and cover of vegetation between years. This procedure is analogous to an ANOVA in univariate statistics. It analyzes whether dissimilarities within pre-defined groupings (i.e., distance from road or year) are higher than those expected by chance (Clarke & Warwick, 1994).

Since the biomass data set was subject to less measurement error between years than the % cover data, we conducted further multivariate analyses on these data. Multi-dimensional scaling (MDS) ordination was used to graphically represent the similarities between sites at each distance from the road in different years for the biomass data. We used Principal Components Analysis to determine which vegetation types were most sensitive to disturbance. Scores for PCA axis 1 and 2 for each year were plotted against distance from the road. Percentage similarity in both biomass and cover, at each distance from the road and for each year, were calculated and the important discriminating vegetation types identified using the procedure SIMPER in Primer (Clarke & Warwick, 1994).

**Results**

### Soil Properties

Significant logarithmic relationships were observed for soil pH, active-layer thaw depth, and organic layer depth with distance from the road (Table I). Fibric horizon pH values decreased with distance from the road (Figure 1), as observed in 1989, from 6.0 at 2 m to 4.0 at greater than 100 m. The thaw depth was 8 cm deeper at 2 m than at 100 m from the road (Figure 1). Soil organic matter was 9 cm more shallow at 2 m than at distances beyond 100 m from the road (Figure 1).

We observed significant differences between 1989 and 2002 for both pH and active-layer thaw depth with distance from the road. In 2002, pH in the 100 m adjacent to the road (5.3 ± 0.12, mean ± SE) was on average 0.6 units higher than that recorded in 1989 (4.7 ± 0.14, Figure 1). Thaw depth was observed to be 8.6 cm shallower in 2002 next to the road (Figure 1). ANOSIM found significant differences in these soil characteristics between years (Global $r = 0.370$, $P = 0.001$) and with distance from the road (Global $r = 0.473$, $P = 0.001$).

### Vegetation Characteristics

The most pronounced vegetation changes observed were an increase in biomass and cover of graminoids (Figure 2 and 3) near the road and a decrease in mosses (Figure 2). We observed on average 84% cover of *E. vaginatum* (cotton grass) and less than 10% cover of other plant types in this highly disturbed area (Figure 2). The natural-state tundra observed in 2002 was only 35% *E. vaginatum* and over 50% mosses, with larger proportions of evergreen shrubs and lichens (Figure 3). The highest biomasses of evergreen species occurred between 10 and 50 m from the road (Figure 3). Graminoid biomass and % cover increased, whereas moss and evergreen biomass and % cover decreased significantly between 1989 and 2002 (Table I).

Multivariate analysis of biomass and cover data showed clear shifts in the vegetative communities between years (Figure 4). ANOSIM showed a significant difference in community composition between 1989 and 2002 for both % cover (Global $r = 0.924$, $P < 0.001$) and biomass (Global $r = 0.510$, $P < 0.001$). Analysis of percentage similarities revealed that the differences in communities were largely a result of changes in graminoid and moss biomass, contributing 43% and 37% to global percentage similarities, respectively.

Principal Components Analysis identified two clear axes associated with changes in cover of graminoids and deciduous species (Table II). PC 1 was also associated with lower cover of *Rubus* spp. and increased cover of mosses, including *Sphagnum* spp. While sites closest to the road scored low on PC 1 in both 1989 and 2002, sites at 50 m and greater distances from the road had consistently higher PC 1 scores in 1989 than in 2002, indicative of a reduction in mosses, lichens, and forbs and an increase in graminoids and deciduous species between sample years (Figure 3). Patterns against PC 2 were less clear (Figure 3), but scores in 2002 appeared to be lower. The MDS ordination (Figure 4) indicate that the change in overall community composition between 1989 and 2002 is mainly driven by plots far from the road. Samples close to the road in both 1989 and 2002 formed distinct clusters. In 2002, the spread of the ordination scores at sites 25 m and greater from the road was more dispersed than in 1989. PC 1 is highly correlated with soil pH ($R^2 = 0.46$, Table II). Increased spread of 2002 scores along axis 1 of Figure 4 indicate a broadened zone of dust impact.

### Nitrogen

No significant change in *E. vaginatum* leaf nitrogen was observed across the transect in 1989 or 2002 (Figure 1, Table I). However, % nitrogen was significantly lower in 2002, with an average of 1.78 ± 0.04 in 1989 and 1.65 ± 0.03 in 2002.

### Discussion

**Soil Properties**

The major effects of dust deposition on soil are an increase in pH and a deeper active-layer thaw depth close to the road. The pH has increased 0.6 pH units between 1989 and 2002. We attribute the pH increase over time to the additional 13 y of calcareous road dust deposition. Changes in the other soil properties are likely caused by interactions between dust deposition, microclimate alteration, and ecosystem response.

Deeper active-layer thaw depth near the road was observed in 1977 (Walker & Everett, 1987) and in 1989 (Auerbach, Walker & Walker, 1997). Auerbach, Walker, and Walker (1997) attributed the change to reduced cover of insulative mosses close to the road. We believe the change in thaw depth between 1977 and 1989 could also indicate a long-term effect of dust on snow pack depth and albedo.
Shallower thaw depths observed across the transect in 2002 (Figure 1), however, are very likely the result of weather differences between the two sample years. The mean May–August air temperature was 7.3 °C in 1989 and 5.5 °C in 2002 (Shaver, 2005). In addition, the thicker root mat and increased canopy of *E. vaginatum* tussocks close to the road in 2002 could be shading and insulating the frozen soil.

**Vegetation characteristics**

The major response of the vegetation composition to road dust is an increase in graminoids and a decrease in *Sphagnum* spp. and lichens. This pattern of vegetation change was observed by Auerbach, Walker, and Walker (1997) at this study site and also by Forbes (1995) in northwestern Russia. Changes to plant nutrient chemistry (Santelmann & Gorham, 1988) and lichen species composition (Farmer, 1993) may precede the larger plant community restructuring; however, they were not monitored in this study.

*Sphagnum* spp. have been considered “keystone” species for controlling tundra ecosystem functions because of their strong effects in acidifying and insulating soils (Auerbach, Walker & Walker, 1997). We observed a sharp decline in *Sphagnum* mosses in the most disturbed region of the transect. *Sphagnum* spp. are likely declining in response to the increase in soil pH, as this moss is largely restricted to acidic habitats. Lichens, another common indicator of atmospheric deposition, were nearly absent close to the road. We attribute the disappearance of lichens to their high sensitivity to pollutants such as sulfur dioxide and heavy metals (Walker & Everett, 1987; Conti & Cecchetti, 2001) and shading from increased graminoids (Cornelissen et al., 2001) rather than a direct response to dust loading or increase in pH.

**Table I. Summary of ANOVA for soil and vegetation data comparing between 1989 and 2002 and across the transect.**

<table>
<thead>
<tr>
<th>Data set</th>
<th>Year</th>
<th>Distance</th>
<th>Interaction</th>
<th>F₁</th>
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<th>F₁</th>
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<td>pH</td>
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<td>27.13 &gt; 0.001</td>
<td>9.23 0.003</td>
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<td>Thaw depth</td>
<td>**</td>
<td>-</td>
<td>no</td>
<td>10.72 0.002</td>
<td>101.52 &gt; 0.001</td>
<td>4.90 0.030</td>
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<td>Organic layer depth</td>
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<td>yes</td>
<td>0.01 0.909</td>
<td>0.89 0.349</td>
<td>17.36 &gt; 0.001</td>
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<td>% leaf N (E. vaginatum)</td>
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<td>no</td>
<td>10.32 0.002</td>
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<td>% Graminoid cover</td>
<td>*</td>
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<td>yes</td>
<td>10.21 0.002</td>
<td>27.30 &gt; 0.001</td>
<td>4.90 0.030</td>
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<td>% Moss cover</td>
<td>*</td>
<td>+</td>
<td>yes</td>
<td>11.91 0.001</td>
<td>45.61 &gt; 0.001</td>
<td>6.60 0.012</td>
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<td>% Deciduous cover</td>
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<td>% Evergreen cover</td>
<td>*</td>
<td>+/-</td>
<td>yes</td>
<td>1.86 0.177</td>
<td>55.04 &gt; 0.001</td>
<td>7.64 0.007</td>
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<td>% Rubus spp. cover</td>
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<td>% Sphagnum spp. cover</td>
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<td>Graminoid biomass</td>
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<td>0.03 0.869</td>
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<td>4.67 0.034</td>
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<td>10.95 0.001</td>
<td>13.13 &gt; 0.001</td>
<td>12.97 0.001</td>
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<td>Evergreen biomass</td>
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<td>12.58 0.001</td>
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<td>Rubus spp. biomass</td>
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<tr>
<td>Total biomass</td>
<td>***</td>
<td>+/- (1989), (2002) yes</td>
<td>5.30 0.024</td>
<td>3.08 0.083</td>
<td>24.78 &gt; 0.001</td>
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<td>PCA 2</td>
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<td>8.45 0.005</td>
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*P < 0.05, **P < 0.01, ***P < 0.001, ns: non significant; + positive relationship, - negative relationship.

1 Degree of freedom are in parentheses.
The most conspicuous change in community composition is the dominance of *E. vaginatum* close to the road. Nitrophilous, pioneering vegetation such as *E. vaginatum* likely began to flourish after the nutrient release from the decaying *Sphagnum* spp. and soil organic matter. The increased dominance of *E. vaginatum*, with a taller canopy and high nutrient demands, has reduced community diversity over time.

Certain functional groups, such as evergreen species, were observed to thrive in intermediate areas of disturbance, where *E. vaginatum* has yet to establish dominance. Gradual blockage of leaf stomata and shading of photosynthetic tissue in the long-lived leaves of evergreen shrubs may contribute to their decline close to the road (Farmer, 1993; Auerbach, Walker & Walker, 1997). At intermediate distances, however, evergreen shrubs may benefit from...
competitive release caused by the decline in lichens and Sphagnum spp. that are more sensitive to changes in pH or other components of dust deposition.

Increases in graminoid biomass and decreases in moss, evergreen, lichen, and forb biomass between sample years suggest cumulative impacts of dust. This ecosystem is highly sensitive to the initial disturbance of road development and cumulative impacts of dust loading can be observed in the changes in community composition over time.

Dust effects

Dust appreciably impacts environmental variables up to 25 m from the road and vegetation composition beyond 100 m. Modeling of dust effects (calibrated for the nearby Imnaviat Creek watershed) projects that dust should alter the biomass of vascular plants, lichens, and mosses up to 600 m from the Dalton Highway (Leadley et al., 1996). Santelmann and Gorham (1988) observed dust effects on vegetation up to 200 m from a road through a peat bog in New Brunswick, Canada. We did not measure Sphagnum spp. nutrient chemistry or change in moss and lichen species composition. In addition, the logarithmic sampling regime established by Auerbach, Walker, and Walker (1997) contained few sample points at distances further from the road. For these reasons we were not able to detect the maximum distance of dust effects.

Leaf and soil nitrogen

Despite strong gradients in pH, thaw depth, floristic composition, and biomass, the percentage of nitrogen in leaves of Eriophorum vaginatum, the dominant sedge, did not vary with distance in either 1989 or 2002 (Figure 1, 2, and 3). Nutrient turnover is enhanced close to the road, judging from the greater biomass of high-turnover species such as deciduous shrubs and graminoids and the thinner organic horizon (Figure 1 and 2). However, Auerbach, Walker, and Walker (1997) found lower concentrations of plant available N, P, and K in soils near the road. We speculate that tight cycling of nutrients and the dilution of tissue nutrients by increased growth resulted in a similar concentration of leaf nitrogen across the gradient, despite different soil nutrient pools.

Dust acts as a press disturbance (Bender, Case & Gilpin, 1984), causing a sustained alteration of community composition by modifying soil characteristics and ecosystem processes. Our study provides strong evidence for cumulative impacts of calcareous dust deposition along the Dalton Highway. Soil pH and graminoid biomass and cover continued to increase between 1989 and 2002. Close to the road, cover of lichens and mosses (especially Sphagnum spp.) are greatly reduced. These species are sensitive to pollutants (Walker & Everett, 1987) and have been found to decline in response to experimental addition of nutrients.

Figure 3. Graminoid, moss, evergreen, deciduous, lichen, forb, Rubus spp., total biomass, and PCA scores 1 and 2 versus distance from the road (log scale) for measurements taken in August 1989 (black circles and lines) and 2002 (grey circles and dashed lines). Lines are plotted for statistically significant relationships determined using ANOVA (Table I).
Together these vegetation trends suggest continued change to a new state characterized by rapidly growing species with high nutrient requirements. Heavy dust deposition favours a community dominated by graminoid species that outcompete other natural vegetation. Sphagnum spp. decline generates a positive feedback to higher soil pH and graminoid species dominance (Figure 5).

In contrast, at 400–800 m from the road, disturbance effects are minimal, suggesting substantial resistance to low levels of dust input, or longer ecosystem reaction time to subtle disturbance. Our results indicate a loss of resistance at intermediate distances. For example, at 100 m from the highway, all parameters were similar to those for more distant plots in 1989. By 2002, however, pH increased and cover of lichens and Sphagnum mosses decreased relative to distant plots. The cumulative increase in soil pH is changing the community composition. Impacts over time (Table III) indicate that the press disturbance of dust deposition will continue to alter the adjacent tundra ecosystem unless abatement procedures are employed.

**Conclusion**

Road effects are major ecological disturbances acting on one-fifth of the land area of North America (Forman & Alexander, 1998). Developers often downplay the ecological impacts of arctic oil expansion because of the small areal extent of roads and infrastructure; however, impacts of road
dust have been observed along the Dalton Highway and in the dense road networks of Prudhoe Bay in Alaska (Walker & Everett, 1987) and in Northern Russia (Forbes, 1995). If we extrapolate our results to the entire Dalton Highway, significant disturbance may have occurred in a 200-m-wide corridor adjacent to the roadway. This implies a potential disturbed area of 115 km² of interior and arctic Alaska, a total area roughly the size of the District of Columbia. Dust abatement measures, such as spraying calcium chloride solutions (a hygroscopic chemical), may reduce dust levels (Walker & Everett, 1987; Sanders & Addo, 1997); however, this might increase salt accumulation in soils adjacent to the road. An alternative measure is chip-sealing, covering the loose gravel road surface with a layer of asphalt. If the Dalton Highway is chip-sealed adjacent to our study site this will provide an opportunity to assess the persistence of the altered state and the recovery of the natural ecosystem. Given the cumulative impacts of dust observed to date, the Precautionary Principle (Foster, Vecchia & Repacholi, 2000) suggests that this disturbance should be seriously considered when assessing long-term consequences of new development in the Arctic. Of particular concern are proposals for further oil development in Northern Alaska, which could expand the area of road-disturbed tundra.

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Literature cited


