Arctic and Alpine Research, Vol. 19, No. 4, 1987, pp. 479-489

ROAD DUST AND ITS ENVIRONMENTAL IMPACT ON ALASKAN TAIGA AND TUNDRA

D. A. WALKER
Institute of Arctic and Alpine Research and Department of Environmental, Population, and Organismic Biology
University of Colorado, Boulder, Colorado 80309, U.S.A.

K. R. EVERETT
Byrd Polar Research Center and Department of Agronomy
The Ohio State University, Columbus, Ohio 43210, U.S.A.

ABSTRACT

The physical and chemical characteristics and ecological consequences of road dust in arctic regions are reviewed with emphasis on recent information gathered along the Dalton Highway and the Prudhoe Bay Spine Road in northern Alaska. The primary observed ecological effects of dust are (1) early snowmelt in roadside areas due to lower albedos, resulting in a snow-free band of vegetation within 30 to 100 m of the road in early spring, which is used by waterfowl and numerous other species of wildlife; (2) a decrease in *Sphagnum* and other acidophilous mosses near the road; (3) an increase in many minerotrophic mosses; (4) a decrease in soil lichens, particularly species of *Cladina, Peltigera,* and *Stereocaulon;* (5) elimination of corticolous lichens near the road in areas of particularly high dust fall; (6) a general opening of the ground cover near the road and a consequent colonization of these barren surfaces by many taxa that are common on mineral-rich soils; (6) few effects on vascular plant abundance except in areas of very high dust, where ericaceous taxa and conifers are affected; (7) increased depth of thaw within 10 m of the road, possibly due to decreased plant cover and earlier initiation of thaw; and (8) contribution to thermokarst in roadside areas. Enhanced dust control measures should be considered, particularly where the road passes through scenic lichen woodlands, acidophilous tundra, annd in calm valleys where dust commonly is a traffic safety hazard.

INTRODUCTION

A thorough understanding of the effects of both natural and road-generated dust in the Arctic is important for proper road design and maintenance, the selection of transportation corridors, and the implementation of various dust control methods. In this paper, we review the recent information specifically related to road dust in the Arctic and summarize the results of our investigations along two high-speed gravel highways in arctic Alaska: the Dalton Highway and the Prudhoe Bay Spine Road (Figure 1).

Gravel roads are still common throughout the world, including much of rural North America, but until recently, the effects of dust generated by travel on gravel roads has received little attention from an environmental perspective (Dyck and Stukel, 1976; Rohl et al., 1977). Within the last two decades, the spread of gravel roads and road networks has reached into the otherwise pristine landscape of arctic North America, including the taiga

A version of this paper was presented at the Seventh Conference of the Comité Arctique International—Restoration and Vegetation Succession in Circumpolar Lands—7-13 September, 1986, Reykjavik, Iceland.

and tundra regions of northern Alaska. Substantial quantities of ground ice lie close beneath a surface dominated, in the taiga, by black spruce, and in the tundra, by sedges, moss, and low-growing herbaceous vegetation. The addition of dust from roads has a localized but profound impact upon vegetation, soils, ground ice, and wildlife. Along the Dalton Highway and the Prudhoe Bay Spine Road, these impacts have received study nearly from their inception and, thus, it is possible to record a history of change (Alexander and Miller, 1978; Walker and Webber, 1980; Werbe, 1980; Spatt and Miller, 1981; Klinger et al., 1983; Walker et al., 1985).

The Spine Road (Figure 1), built in 1969/70, is the major arterial highway through the Prudhoe Bay oilfield and the most heavily traveled road in northern Alaska. The 577-km-long Dalton Highway from the Yukon River to Prudhoe Bay was constructed in 1974 to provide access for building the trans-Alaska pipeline; it now serves as a supply link between Fairbanks and the northern oil fields. Traffic is currently restricted north of the Brooks Range to authorized vehicles, mostly truck traffic, although the road will likely be opened to the public in the future.

This paper summarizes the physical and chemical characteristics of road dust and its impact on arctic vegetation that we have observed at study sites shown in Figure 1. Even in this relatively pristine environment it is often difficult to separate the impact of road dust from other road-related impacts, especially in the first few meters from the road where, for example, transient impoundment, gravel spray, off-road vehicle trails, toxic spills (Johnson, 1984), snowbanks (Klinger et al., 1983), and revegetation efforts (Kubanis, 1982) often make it difficult to isolate the effects of dust. In the absence of controlled experiments there are, however, numerous obvious effects of road dust that have occurred along these roads and which have not been reported in the open literature.

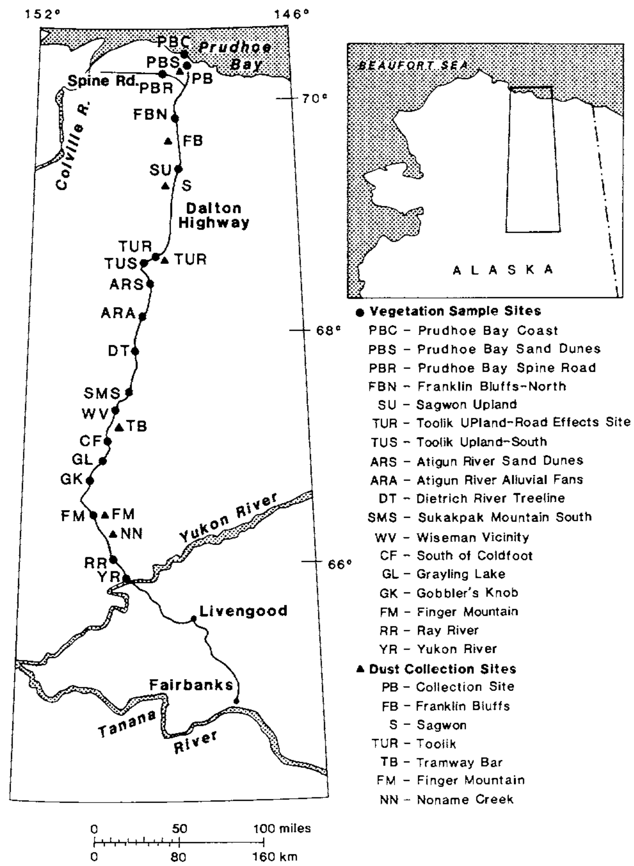

FIGURE 1. Principal road dust study sites in northern Alaska along the Dalton Highway north of the Yukon River.

METHODS

Physical and Chemical Characteristics

Collection and characterization of road dust began in 1977 at four arctic sites along the Dalton Highway: Toolik, Sagwon, Franklin Bluffs, and Prudhoe Bay (Figure 1). In 1978, two sites were added along the same road in the taiga at Finger Mountain and at Tramway Bar (Figure 1). At each site dust was collected from paired 890-cm^2 pans spaced at 8, 30, 125, 312, 500, and 1000 m perpendicular to and on each side of the road. Each collection site was equipped with a Woelfle-type mechanical wind recorder placed at 125 m. The pans were emptied and washed every 30 d. Samples were centrifuged, dried, and weighed; they were then treated with 30% H_2O_2 to remove organic matter and then reweighed.

Soil samples were collected at each dust collection pan site at depths between 0 and 2.5 cm and 2.5 and 5.0 cm. These were dried, ground, sieved, and leached with ammonium acetate prior to analysis for cations with a Varian atomic absorption spectrophotometer.

Dust samples collected from two to four composite snow cores were taken in April from each of the six sample distances at the four tundra sites. These samples are considered as representative of winter period road dust fall. Neutron activation analysis was performed on selected samples of dust from snow and dust collectors.

Vegetation Transects

Seventeen permanent vegetation transects were established along the Dalton Highway and Spine Road during the summers of 1976 to 1978 (Figure 1). The presence of all taxa that could be identified in the field was noted in 100-cm^2 quadrats. The quadrats were spaced at 1-m intervals along 25-m lines placed normal to both sides of the road. The transects were resampled in 1983, but two of the transects were not resurveyed because of major roadside alterations. An additional transect was added at the Prudhoe Bay Spine Road and here roadside areas were compared against relatively undisturbed tundra at 200 m from the road. In 1983 each transect was marked with permanent photo points at 2, 5, 10, 25, and 50 m from the road to monitor changes in future years. Thaw depth was measured at 1-m intervals along each transect. Measurements were made with a 1-m-long graduated metal probe. In addition, detailed notes were taken along each transect to record changes that did not appear in the quadrat data.

Because of the variety of vegetation types encountered, the data did not lend themselves well to a quantitative analysis. Several of the transects showed little change between surveys. The comments on vegetation effects are based mainly on observations from transects in heavy dust areas.

DUST CHARACTERISTICS

There is no universally agreed upon definition of road dust (Techman Engineering Ltd., 1982), but it is generally composed of particles ranging in sizes from >3 to <10 μm (Roberts et al., 1975) derived from road surface aggregate and thrown into suspension by road traffic. Particles >10 μm include sand and gravel suspended largely by saltation and falling back to the road surface or within a few meters of the road edge. The bulk of what is seen as suspended dust is composed of particles <20 μm (Patterson et al., 1976; Techman Engineering Ltd., 1982) which may travel great distances. For example, naturally occurring loess particles (6 to 3 μm) may travel in suspension up to 300 km from their source (Van Heuklon, 1977) and particles <2 μm may become part of the stratospheric dust load (Prospero and Ness, 1977).

The amount of dust derived from a road surface is a function of the composition and moisture state of the surface, number of vehicles passing, and such vehicle-related variables as number of tires and their width, gross weight, and speed (Struss and Mikucki, 1977; Techman Engineering Ltd., 1982).

The exponential plots of dust load versus distance from three stations on the Dalton Highway (Figure 2) are all quite similar even when allowances are made for surfacing material ranging from bank-run gravel (Prudhoe Bay and Franklin Bluffs) to crushed bedrock (Sagwon and Toolik). At the taiga sites, a similar relationship holds but is complicated by dust interception by trees. The tabulated dust loads (Table 1) indicate some considerable temporal and spatial variability. The differences in dust load on opposite sides of the road are due largely to wind pattern (Everett, 1980). More than twice the amount of dust was collected in the downwind collectors as that which fell in upwind collectors at sites where the roads were perpendicular to the strong easterly winds. Regardless of the site, 70 to 75% of the total dust load is dropped in the first 10 m; by 30 m, 93% is deposited; and by 125 m, 97% is deposited. This is consistent with the findings of Hoover (1981) who studied road dust deposition in Iowa and generally so with those of Alexander and Miller (1978).

The progressive change in particle size through the first 125 to 300 m for a site near Franklin Bluffs is shown in Figure 3. Beyond 8 m the bulk of the dust is in the silt range. The shift to fine silt probably continues to 1000 m and beyond, with clay-sized particles constituting a small but constant proportion.

Three dust-load zones can be defined adjacent to the gravel road: (1) road edge to 10 m heavy deposition (up to 24 kg ha^{-1} d^{-1}), 70% sand-sized material, and relatively unreactive chemically; (2) 10 to 30 m, deposition of 24 to 0.6 kg ha^{-1} d^{-1}, 70% silt- and clay-sized material with

TABLE 1

Summer season 1977 to 1978 dust load (g m^{-2}) vs distance (m) from Dalton Highway

	8 m		30 m		125 m		312 m		500 m		1000 m	
	E	W	E	W	E	W	E	W	E	W	E	W
Prudhoe												
1978	531		111		28		11		5.8		7.6	
1977	463		151		27		14		*[b]		5.2	
Franklin												
1978	*	717	54	129	13	37	5.7	12.8	2.5	5.1	3.1	2.3
1977	81	*	19	—	4	31	2.5	12.9	1.4	6.3	1.4	3.5
Sagwon												
1978	708	520	174	145	32	25	11.4	6	4.4	3.5	3.3	1.7
1977	199	138	45	80	—	—	2.6	3	2.4	2.1	—	0.8
Toolik												
1978	214	221	56	57	11	13	3	4.5	2.3	2.8	1.6	1.7
1977	244	133	30	53	1.3	8	1.7	4.4	1.0	2.2	0.8	1.2

[a]Data from Everett (1980).

[b]*Collector destroyed or vandalized.

electrostatic properties and large reaction surfaces; (3) 30 to >1000 m, deposition of 0.6 to 0.02 kg ha^{-1} d^{-1}, 85 to 90% silt- and clay-sized material with 40 to 50% fine silt and clay with very large reaction surfaces and electrostatic properties.

Summer dust loads exceeded 500 g m^{-2} at 8 m from the road at Prudhoe Bay, Franklin Bluffs, and Sagwon in 1978 (96 collection days). Near Deadhorse dust loads measured 1000 m from the road were several times those at similar distances from the road at other sites. This was thought to be an effect of the dense road network at Prudhoe Bay with road dust coming from many sources. Dust loads during the rest of the year contributed an additional 100 to 150 g m^{-2} at 8-m distances from Dalton Highway sites.

Along the heavily traveled Prudhoe Bay roads, the 9-mon winter dust volumes were about the same as the 3-mon summer volumes near the road; but at the 1000-m collection stations, winter dust fall was nearly 10 times greater than in the summer. The winter collection data showed more scatter from the usual logarithmic distribution downwind from the road presumably due to repeated drifting and erosion of the snow pack (Everett, 1980).

The winter dust fall has major ecological effects, which are apparent in the early phase of melt-off. Benson et al. (1975) noted the presence of road dust recorded on winter Landsat images of the Prudhoe Bay region. The principal effect of the dust is to decrease albedo and cause melting and surface exposure up to 10 to 14 d before general melt-off (initiation of stream flow). The early snowmelt occurs mainly within a zone out to 100 m. Several things happen in this zone: soil thaw begins early, and some plants (for example, *Eriophorum vaginatum*) commonly flower well before those farther from the road; mosses and other shallow rooted species begin to photosynthesize. Perhaps the most profound effect of this early melt corridor is the concentration of waterfowl, ptarmigan, and their predators (Figure 4). The wave of tundra

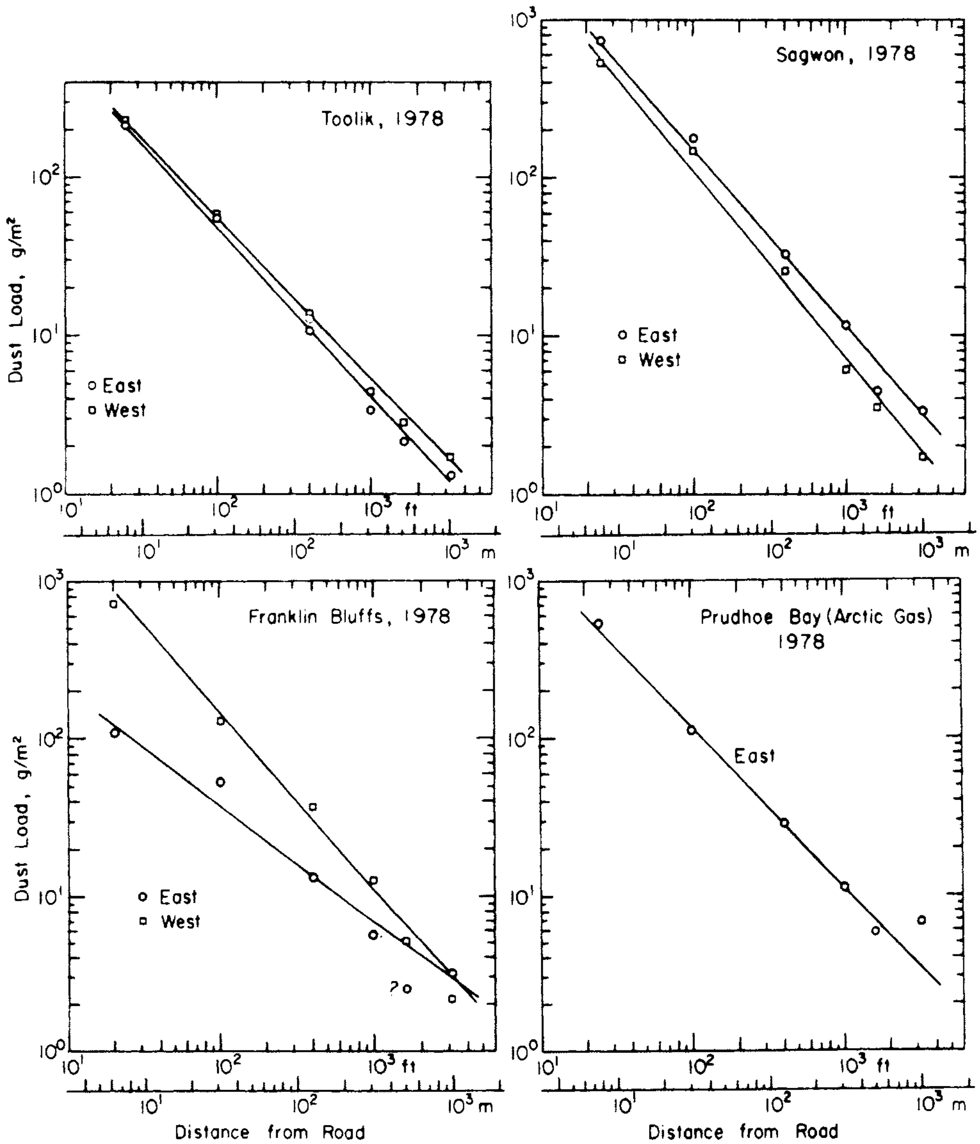

FIGURE 2. Summer dust loads from the four sites for 1978; period of collection was 96 d. The effect of the predominant east wind is clear at Franklin Bluffs. From Everett (1980)

nesters moves slowly north as the corridor opens. This phenomenon appears to have increased over the years since the road has been in place (13 yr). In 1986, concentrations of ptarmigan numbering in the thousands occurred, with large flocks commonly sitting on the road and subject to being hit by fast-moving traffic. Caribou take advantage of the early snow-free areas for grazing, and grizzly bears, raptors, and other predators use these areas to hunt ground squirrels and voles.

The early snowmelt also contributes to early initiation

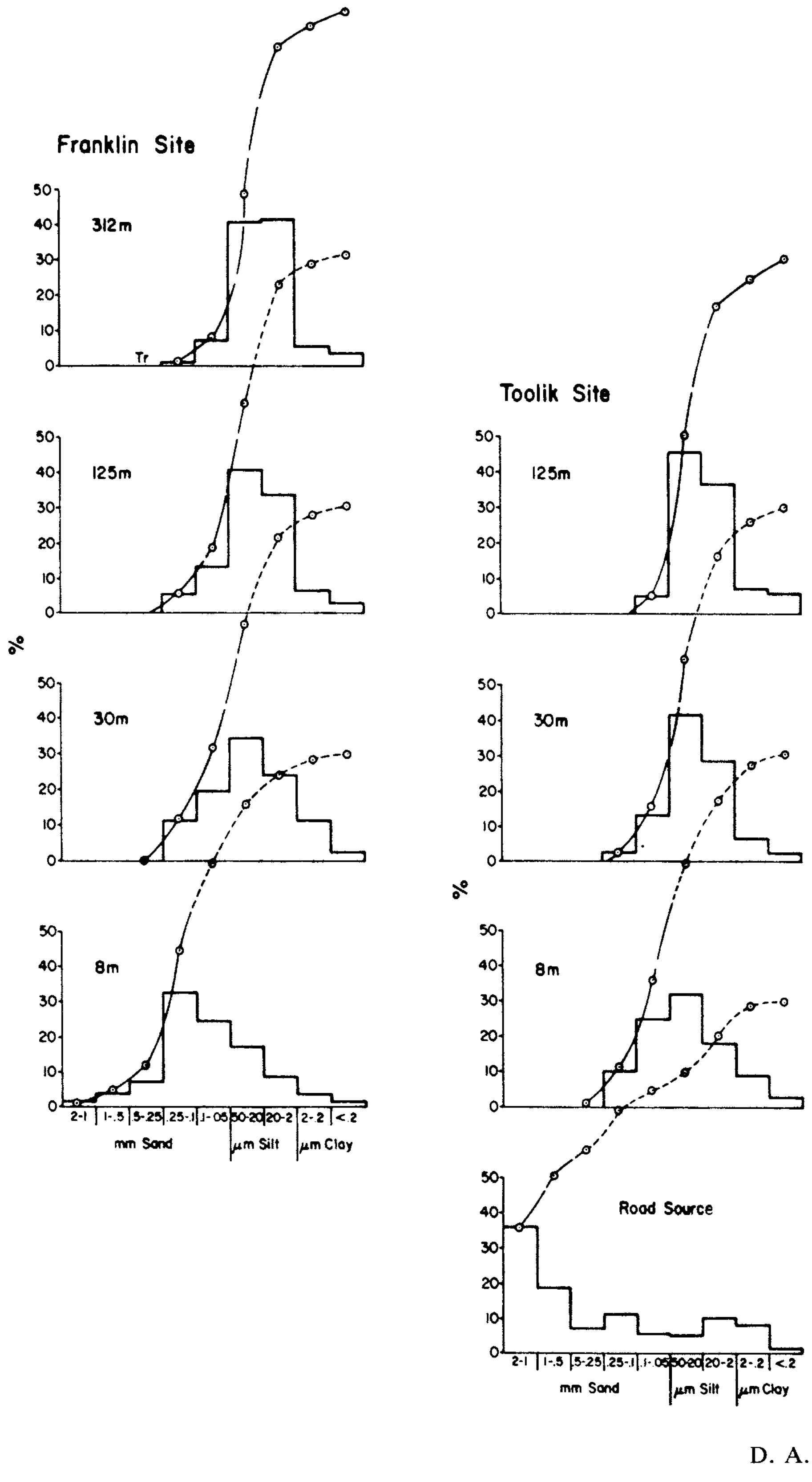

FIGURE 3. Particle size distribution of road material and road dust collected at 8, 30, and 125 m from the west side of the Dalton Highway (1978). Median particle diameters read from a cumulative curve.

of soil thaw. A model of the long-term albedo changes from coal dust for the Prudhoe Bay area resulted in a 20% increase in thaw with especially higher thaw rates occurring during the early summer (Makihara, 1983). This figure is less than differences measured along the Spine Road, where depth of thaw in ice-wedge-polygon basins within 10 m of the road was 49 ± 6 cm, and in similar microsites >50 m from the road the thaw was 37 ± 5 cm (Walker et al., 1985). However, many factors other than dust alone contribute to increased thaw along the Spine Road. Increased seasonal active-layer thickness develops adjacent to heavily used roads and is found to a distance of 10 m or more.

Considerable spatial variation is observed in the chemical composition of road dust north of the Brooks Range (Figure 5), which is to a high degree related to source of road materials. Most road surface materials south of the coastal plain are composed of crushed bedrock, largely quartzose sandstone and conglomerate, but on the coastal plain, surface materials are largely bank-run gravels with carbonate-rich fines.

At distances beyond 30 m and certainly beyond 100 m,

FIGURE 4. Concentrations of migrating waterfowl adjacent to the Dalton Highway near Happy Valley at the beginning of general melt in this area. The horizon in this photograph is about 100 m distant. Beyond, the area is completely snow-covered. Such flocks are composed mostly of white fronted geese and may number several thousand per kilometer. White birds are snow geese. Raptor populations have been observed to be 1 or more per kilometer in some areas.

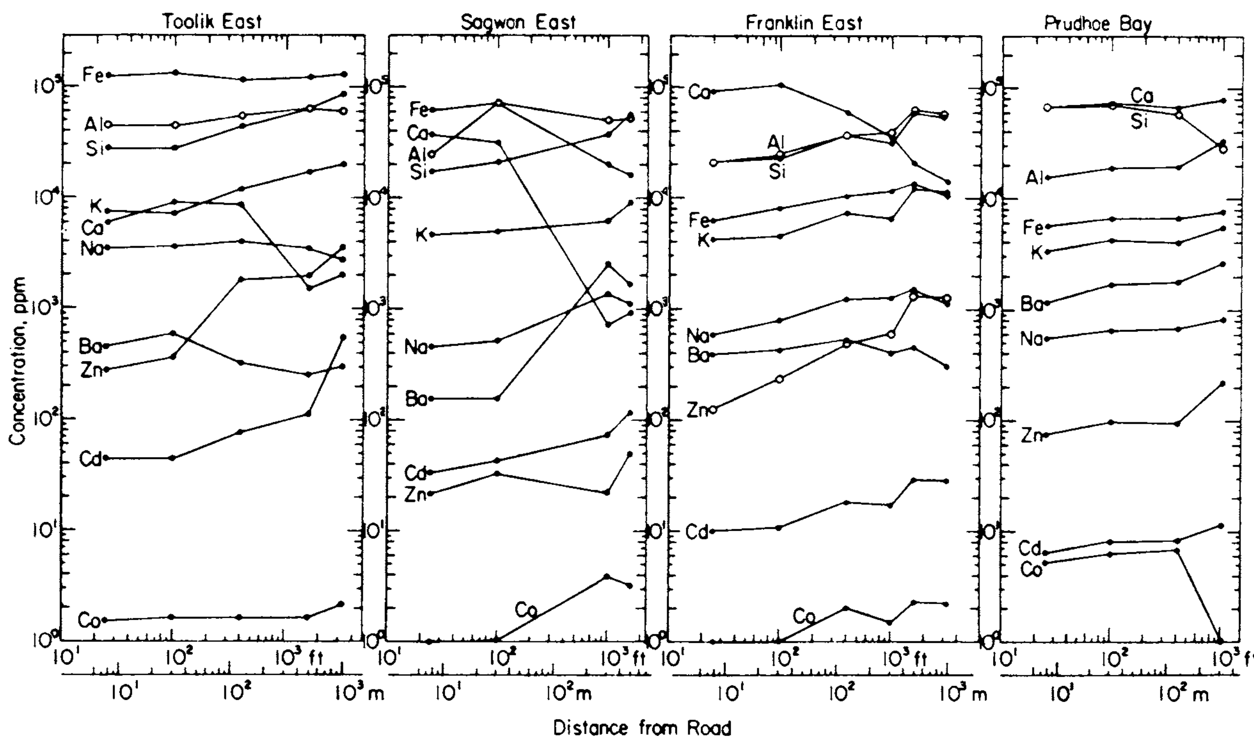

FIGURE 5. Concentrations of selected elements in the summer dust as determined by neutron activation analyses. Differences in the order of abundance are mainly a function of the source of road materials (see text). From Everett (1980)

the physical effects of road dust and, to a large degree the chemical effects, are difficult to document. In acid-tundra regions traversed by the Dalton Highway (the taiga sites and the tundra sites of Toolik and Sagwon), the very high buffering capacity provided by the dominance of hydrogen on the soil organic exchange complex (>40 meq $100 g^{-1}$) required nearly 7 yr to be neutralized in the zone of maximum dust loading. Cumulative dust loading will likely cause neutralization of some areas beyond 30 m in future years, particularly in areas of exceptionally high dust loads or in areas with overlapping dust sources such as at Prudhoe Bay.

EFFECTS ON VEGETATION

On heavily traveled roads, the 10-m-wide area adjacent to the road is primarily one of physical impact in the form of burial of mosses and very low-satured vegetation (Figure 6). Dust blankets up to 10-cm thick have been measured adjacent to the Spine Road. Several morphological factors contribute to plant susceptibility to heavy dust loads, including mat or prostrate growth form, lack of a protective stem cortex or leaf cuticle, evergreen leaves, and intricate branching or closely spaced leaves that tend to trap dust.

Cryptogams are particularly affected by road dust. A reduction and, in extreme cases (Figure 6), elimination of mosses occurs in the 0- to 10-m zone adjacent to the road. The effects are most severe for acidophilous taxa such as *Sphagnum* (Spatt, 1978; Werbe, 1980; Walker et al., 1985). Spatt (1978) observed that total conductivity, pH, and calcium of water extracted from *Sphagnum* were the greatest in the heavily dusted area immediately adjacent to the Dalton Highway as compared to samples at points 125 and 250 m distant. Chlorophyll and photosynthetic rates for *Sphagnum* were lowest in the heavily dusted areas. Clymo's (1973) observations regarding the toxic effects of calcium on *Sphagnum* support these observations. Spatt and Miller (pers. comm., 1979) recorded calcium ion concentrations of 4 to 27 ppm for water contained in *Sphagnum* polsters growing within 25 m of the road; beyond 200 m, *Sphagnum* water contained <1 ppm Ca^{2+}. As particle size decreases beyond 30 m, the reactive surface of the particles increases and affords the potential for rapid release of ions due to weathering. Spatt (1978) concluded that a long-term loss in the vitality of *Sphagnum* near the road could be expected. Observations in 1983 (Walker et al., 1985) showed that at the Toolik Lake transect, an area of tundra, *Sphagnum* had indeed been eliminated within 20 m of the road but was at least partially replaced by other mosses such as *Ceratodon purpureus, Bryum* spp., and *Polytrichum juniperinum.*

The loss of the moss carpet along the Prudhoe Bay Spine Road also appears to have played a role in the development of roadside thermokarst (Figure 6). Transects across the road (Figure 7) show a significant increase in thaw within 10 m of the road. The increased thaw roughly corresponds to the area where mosses and other vegetation have been eliminated. But thaw is also affected by other synergistic causes including early snowmelt and

FIGURE 6. Roadside area along the Prudhoe Bay Spine Road. Within 10 m of the road vegetation has been buried by road dust. Impoundments are thermokarst features that form along eroded ice wedges.

poor roadside drainage. Over time, especially along the Prudhoe Bay Spine Road, ice wedges associated with low-centered polygons have melted out producing a topographic reversal of the features, i.e., converting them to high-centered forms (Figure 6), a process which also occurs, for example, when thaw lakes drain (Everett, 1979; Walker et al., 1980). Along the Dalton Highway, thaw depths within a few meters of the road are generally deeper than equivalent sites away from the road but this zone is narrower than at Prudhoe Bay and the thaw depths generally not as deep.

In less heavily impacted areas, total moss diversity often increases. Common pioneering taxa include *Bryum* spp., *Ceratodon purpureus,* and *Polytrichum juniperinum.* Several other common minerotrophic species appear to be increasing due to nutrient enrichment from the road. Examples include *Aulacomnium turgidum, Cinclidium* spp., *Drepanocladus* spp., and *Tomenthypnum nitens.* Most mosses, however, are affected by desiccation and smothering effects of dust, and in areas of the highest dust concentrations, such as near Coldfoot and at Prudhoe Bay, virtually all bryophytes are eliminated within a few meters of the road (Walker et al., 1985).

Lichens are the most affected growth form in roadside environments and are eliminated in high dust areas. The soil lichens *Cladina* spp. and *Peltigera* spp. are among the most easily affected. This is most pronounced in lichen woodlands south of the Brooks Range. For example, near Coldfoot (Milepost 182) within 10 m of the road, there is a heavy kill of *Cladina* spp. and other ground lichens, and most mosses are also dead. At 25 m from the road, lichens are infrequent and are mainly *Cetraria cucullata, C. islandica, C. nivalis, Cladina pyxidata,* and *C. squamosa;* these occur among dead *Cladina* and other ground lichens. *Stereocaulon* sp. begins to occur at about 25 m. *Cladina arbuscula* occurs at 35 m but is not common. At this site, the ground cover does not regain its normal character until beyond 70 m from the road.

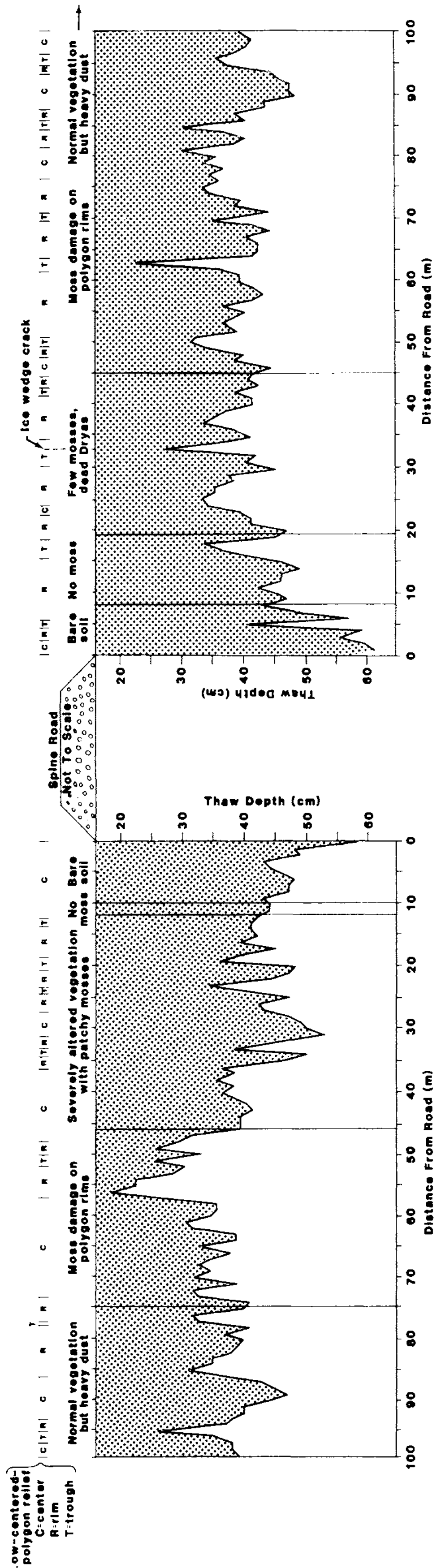

FIGURE 7. Depth of thaw at the Prudhoe Bay Spine Road transect, 3 August 1983. Thaw depths were significantly ($p<0.01$) deeper within 25 m of the road than they were at distances greater than 50 m. This roughly corresponded to the region where the moss cover was either gone or severely altered.

Epiphytic lichens in trees are particularly affected by dust. At the Coldfoot site, nearly all lichens have been eliminated from trees within 35 m of the road, including *Alectoria* spp., *Usnea* spp., *Ramalina* sp., *Physcia* sp., *Cetraria pinastri,* and *Parmelia* spp. Studies in England (Gilbert, 1976) have shown epiphytic lichens to be particularly susceptible to alkaline dust because the pH of their substrate on tree bark can be readily and radically altered by air-borne dust.

Effects on vascular taxa are more subtle and have been difficult to document along the Dalton Highway because of insufficient long-term monitoring in the 0- to 10-m high-impact zone (e.g., Werbe, 1980). *Cassiope tetragona* appears to be particularly susceptible to dust and is killed in most high dust areas (Walker and Werbe, 1980). Other dead and dying ericaceous plants, including *Ledum palustre* ssp. *decumbens* and *Vaccinium uliginosum,* have been observed in lichen woodlands of high dust areas near Coldfoot (Walker et al., 1985). The thick dust also coats the needles of spruces and in some areas of particularly high dust appears to contribute to spruce mortality. Brandt and Rhoades (1972) noted that near cement kilns in southwestern Virginia conifer seedlings are not present in heavily dusted mixed forests and that the forest is gradually shifting dominance to primarily basophilous species. Manning (1971) has shown greatly reduced terminal bud growth in dusted hemlocks (*Tsuga canadensis*) and chlorosis in second-year needles.

The deleterious chemical effects of dust on heath vegetation have been thoroughly documented elsewhere. Tamm and Troedsson (1955) first called attention to the important ecological implications of nutrient additions from road dust to mires in Sweden. They found increased concentrations of calcium, sodium, potassium, and phosphorus in roadside areas and speculated that such increases could account for the vegetational changes reported along roads traversing bogs. Etherington (1976, 1978) demonstrated surface enrichment from limestone-quarrying dust in the limestone heaths near Ewenny, South Wales. This had approximately doubled the calcium content in Lulsgate soils, increased the pH of these soils from a range of 6.0 to 6.6 to about 7.2, and appears to be responsible for extensive chlorosis and observed declines in the ericaceous populations. Etherington (1975) also compared the addition of lime from dust to that which is naturally leached by the average British rainfall; he concluded that the shallow limestone heath soils were being rapidly eutrophicated and that the entire profile could become alkaline within a few decades.

Studies of cement-kiln dust in the United States (Darley, 1966) have indicated that calcium content is not the only factor in dust that is injurious to plants. Chemical composition, particle size, and deposition rate are all important influences that need to be investigated in combination. For example, Eller (1977) has shown that road dust more than doubled absorbed incident radiation for wave lengths over 700 nm and is a major factor affecting increased leaf temperatures of roadside vegetation. And Ricks and Williams (1974) showed that dust particles occluded stomata in *Quercus petraea* resulting in decreased nightly diffusion resistance and an SO_2 uptake five times that of nondusted leaves.

The effects of dust on alkaline tundra, such as at Prudhoe Bay or in areas with limestone substrates, are reduced because the basiphilous vegetation is naturally adapted to high calcium loads (Walker, 1985). Here the plants are less sensitive to additional calcium or magnesium and respond more to the physical impact of dust. If the high volumes of road dust that have occurred in the Prudhoe Bay area were to occur for similar periods of time in ombrotrophic bogs, more noticeable changes to the vegetation would be likely, with elimination of *Sphagnum,* many species of *Cladina,* and other acidophilous species. The rate of change, the composition of the new communities, and whether or not the change would affect the ground ice and natural microtopography would depend mostly on the dust volume.

DUST CONTROL

Several methods of dust abatement are used in northern Alaska. At Prudhoe Bay, waste oil, water, and reserve pit fluids are used. Calcium chloride, a hygroscopic chemical, has been used with good success along some stretches of the Dalton Highway. The use of oil and reserve pit fluids have been of concern because of heavy-metal contamination in highly valued wetlands. Waste oil contains numerous heavy metals (especially lead), polynucleated aromatics (PNAs), and polychlorinated biphenyls (PCBs) (British Columbia, 1981). Drilling mud also contains numerous toxic chemicals including sodium hydroxide, diesel fuel, salt gel (hydrous magnesium aluminum silicates), sodium bicarbonate, and numerous heavy metals and organic polymers (Sohio Petroleum Co., unpublished data).

Recent studies of reserve pit water and its effect on tundra indicate that the primary limiting factor for the vegetation is salt concentration. Myers and Barker (1984) found that the breakpoint between stress and no stress to the most salt sensitive tundra vegetation was between 2000 and 4000 mg L^{-1} total dissolved solids (TDS). This level of water quality was obtained in reserve pits that had been allowed to sit for long periods of time (up to 7.5 yr) without addition of well fluids. The combined effect of pit dewatering and snowmelt dilution apparently reduces TDS to acceptable levels. French (1985) found that heavy metal concentrations did not increase significantly downstream of reserve-pit fluid dispersal points at a High Arctic site on Ellef Ringnes Island and that potassium and chloride concentrations were the major toxicity threats. Thus, reserve-pit water, especially from old pits, is likely to have minimal effects on roadside vegetation.

Beyond the question of toxicity, however, is the general effectiveness of reserve-pit fluids for dust abatement. Water and reserve-pit fluids must be applied almost continuously to be effective. Numerous studies of dust control methods have shown that the most effective methods are use of hygroscopic chemicals such as calcium chloride and lignin sulfonate (e.g., Harmon, 1957; Hoover, 1981; Techman Engineering Ltd., 1982). These chemicals are especially effective when mixed with a surface layer of road-bed aggregate. Since they need to be applied only infrequently, the effect of these on roadside vegetation is likely minimal although this still needs to be examined in detail. Chemical dust abatement techniques should be considered wherever there are high volumes of traffic. From an environmental viewpoint, they should be used on high-traffic roads passing through lichen woodlands or acidophilous tundra.

CONCLUSION

Road dust in arctic regions is a traffic safety hazard, a health hazard for those working near roads, and an ecological concern because of the pristine nature of these regions and the public desire to keep roadside areas in their natural state wherever possible. There are also unique ecological consequences related to permafrost and the melting of ground ice and other consequences related to wildlife that are still not fully explored. A program that would identify areas of high susceptibility to dust impacts (e.g., lichen woodlands, ombrotrophic peat bogs) prior to road construction would help minimize many of the negative consequences of dust. Use of hygroscopic chemicals in areas of high dust sensitivity would help further reduce the negative consequences. More quantitative information of vegetation effects will require long-term studies where permanent plots are established before or immediately after road construction. In this study, the transects were established two years after initial road construction and some vegetation changes had already occurred. Future studies should concentrate on highly dust-susceptible vegetation types, particularly ones with large amounts of *Sphagnum* and lichens.

ACKNOWLEDGMENTS

This work was sponsored primarily by several grants from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) who obtained monies for research along the Dalton Highway from the U.S. Federal Highway Administration (FHWA) and the Department of Energy (DOE). Publication of this report was supported by DOE's Office of Health and Environmental Research/Ecological Research Division as part of the Research in Response, Resilience and Recovery from Disturbance in Arctic Ecosystems program in arctic tussock tundra. Numerous individuals have helped us at various points with this research, including Dr. Jerry Brown, Dr. Patrick Webber, Margaret Ahlbrandt, Ken Bowman, Nancy Lederer, Peter Spatt, Marilyn Walker, Eleanor Werbe, Jane Westlye, and Mandy Wilson. Their help is much appreciated.

REFERENCES CITED

Alexander, V. and Miller, M. C., 1978: Effects of the pipeline haul road on nearby ponds and lakes across Alaska's North Slope. Unpublished annual Progress Report, U.S. Energy Research and Development Administration Report No. RLO-2229-T9-2. 51 pp.

Benson, C., Holmgren, B., Timmer, R., Weller, G., and Parrish, S., 1975: Observations on the seasonal snow cover and radiation climate at Prudhoe Bay, Alaska during 1972. *In* Brown, J. (ed.), *Ecological Investigations of the Tundra Biome in the Prudhoe Bay region, Alaska.* Biological papers of the University of Alaska, Special Report No. 2, pp. 12–50.

Brandt, C. J. and Rhoades, R., 1972: Effects of limestone dust accumulation on composition of a forest community. *Environmental Pollution,* 3: 217–225.

British Columbia, Ministry of Environment, 1981: Road dust abatement in British Columbia: Alternative to used lubricating oil; summary of available information. B.C. Ministry of Environment, Waste Management Branch, Report No. 81-3. 24 pp.

Clymo, R. S., 1973: The growth of *Sphagnum:* Some effects of environment. *Journal of Ecology,* 61: 849–869.

Darley, E. F., 1966: Studies on the effect of cement-kiln dust on vegetation. *Journal of the Air Pollution Control Association,* 16: 145–150.

Dyck, R. I. J. and Stukel, J., 1976: Fugitive dust emissions from trucks on unpaved roads. *Environmental Science and Technology,* 10: 1046–1048.

Eller, B. M., 1977: Road dust induced increase of leaf temperature. *Environmental Pollution,* 13: 99–107.

Etherington, J. R., 1975: *Environment and Plant Ecology.* London: Wiley. 347 pp.

———, 1976: The effect of limestone quarrying dust on a limestone heath in South Wales. *Nature in Wales,* 15: 218–223.

———, 1978: Eutrophication of limestone heath soil by limestone quarrying dust and its implications for conservation. *Biological Conservation,* 13: 309–319.

Everett, K. R., 1979: Evolution of the soil landscape in the sand region of the Arctic Coastal Plain as exemplified at Atkasook, Alaska. *Arctic,* 32: 207–223.

———, 1980: Distribution and properties of road dust along the northern portion of the Haul Road. *In* Brown, J. and Berg, R. (eds.), Environmental engineering and ecological baseline investigations along the Yukon River–Prudhoe Bay Haul Road. *U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report,* 80-19: 101–128.

French, H. M., 1985: Surface disposal of waste drilling fluids, Ellef Ringnes Island, N.W.T.: Short-term observations. *Arctic,* 38: 292–302.

Gilbert, O. L., 1976: An alkaline dust effect on epiphytic lichens. *Lichenologist,* 8: 173–178.

Harmon, J. P., 1957: Use of lignin sulfonate for dust control on haulage roads in arid regions. U.S. Department of Interior, Bureau of Mines Information Circular 7806. 11 pp.

Hoover, J., 1981: Emission oriented dust control and surface improvement processes for unpaved roads. Engineering Research Institute, Iowa State University Project 1308, Ames, Iowa.

Johnson, L., 1984: Revegetation along pipeline rights-of-way in Alaska. *In: Proceedings of the Third International Symposium on Environmental Concerns in Rights-of-Way Management, 15-18 February 1982, San Diego, CA.* Published by Mississippi State University, 254–264.

Klinger, L. G., Walker, D. A., and Webber, P. J., 1983: The effects of gravel roads on Alaskan Arctic Coastal Plain tundra. *In: Permafrost: Fourth International Conference Proceedings.* Washington, D.C.: National Academy Press, 628–633.

Komárková, V., 1985: Vegetation changes on road disturbances along the Dalton Highway, 1977–1983. *In* Webber, P. J., Walker, D. A., Komárková, V., and Ebersole, J. J., Baseline monitoring methods and sensitivity analysis of Alaskan arctic tundra. Final report to U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH 03755. Contract no. DACA89-81-K-006, Attachment A. 19 pp. plus appendices.

Kubanis, S., 1982: Recolonization by native plant species and persistence of introduced species along the Yukon River–Prudhoe Bay Haul Road, 1977–1981 (Abstract). *In: Proceedings, 33rd Alaska Science Conference, Fairbanks, Alaska,* 46.

Makihara, J. S., 1983: The effects of coal dust on surface albedo and thaw depth in northern Alaska (Abstract). *In: Final Proceedings, Permafrost: Fourth International Permafrost Conference.* Washington, D.C.: National Academy Press, 324.

Manning, W. J., 1971: Effects of limestone dust on leaf condition, foliar disease incidence and leaf surface microflora of mature plants. *Environmental Pollution,* 2: 69–76.

Myers, K. C. and Barker, M. H., 1984: Examination of a drilling reserve pit fluids and effects of tundra disposal at Prudhoe Bay, Alaska, 1982–1983. Report prepared for ARCO Alaska, Inc. 109 pp.

Patterson, E. M., Gillette, D. A., and Grams, G. W., 1976: The relation between visibility and the size-number distribution of airborne soil particles. *Journal of Applied Meteorology,* 15: 470–478.

Prospero, J. M. and Ness, R. T., 1977: Dust concentration in the atmosphere of the equatorial north Atlantic and possible relationship to the Sahelian drought. *Science,* 196: 1196–1198.

Ricks, G. R. and Williams, R. J. H., 1974: Effects of atmospheric pollution on deciduous woodland. 2. Effects of particulate matter upon stomatal diffusion resistance in leaves of *Quercus petraea. Environmental Pollution,* 6: 87–109.

Roberts, J. W., Walters, H. A., Mangold, C. A., and Rossano, A. T., 1975: Cost benefits of road dust control in Seattle's industrial valley. *Journal of the Air Pollution Control Association,* 25: 948–952.

Rohl, A. N., Lauger, A. M., and Selikoff, I. J., 1977: Environmental asbestos pollution related to use of quarried Serpentine rock. *Science,* 196: 1319–1322.

Spatt, P. D., 1978: Seasonal variation of growth conditions on a natural and dust impacted *Sphagnum* (Sphagnaceae) community in Northern Alaska. M.S. thesis, University of Cincinnati. 103 pp.

Spatt, P. D. and Miller, M. C., 1979: Personal communication. Effects of road dust on growth conditions and productivity of *Sphagnum* in the Alaskan arctic (unpublished manuscript). Department of Biological Sciences, University of Cincinnati, Cincinnati, Ohio. 29 pp.

———, 1981: Growth conditions and vitality of *Sphagnum* in a tundra community along the Alaska Pipeline Haul Road. *Arctic,* 34: 48–54.

Struss, S. E. and Mikucki, W. J., 1977: Fugitive dust emissions from construction haul roads. Construction Engineering Research Laboratory Special Report N-17, National Technical Information Service, Springfield, Va. 22151. 53 pp.

Tamm, C. O. and Troedsson, T., 1955: An example of the amounts of plant nutrients supplied to the ground in road dust. *Oikos,* 6: 61–70.

Techman Engineering Ltd., 1982: Road dust suppression in northern and western Canada. Vol. 1: Review of alternatives and existing practices; Vol. 2: Manual of recommended procedures. Prepared for Environment Canada; Alberta Environment; Ministry of Environment, British Columbia; Manitoba Environment; Northwest Territories Environmental Services.

Van Heuklon, T. K., 1977: Distant source of 1976 dustfall in Illinois and Pleistocene weather models. *Geology,* 5: 693–695.

Walker, D. A. and Werbe, N., 1980: Dust impacts on vegetation. *In* Brown, J. and Berg, R. L. (eds.), Environmental engineering and ecological baseline investigations along the Yukon River–Prudhoe Bay Haul Road. *U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report,* 80-19: 126–127.

Walker, D. A. and Webber, P. J., 1980: Vegetation mapping. *In* Brown, J. and Berg, R. L. (eds.), Environmental engineering and ecological baseline investigations along the Yukon River–Prudhoe Bay Haul Road. *U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report,* 80-19: 45–58.

Walker, D. A., Lederer, N. D., and Walker, M. D., 1985: Vegetation changes at permanent transects along the Dalton Highway and the Prudhoe Bay Spine Road. *In* Webber, P. J., Walker, D. A., Komárková, V., and Ebersole, J. J., Baseline monitoring methods and sensitivity analysis of Alaskan arctic tundra. Final report to U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH 03755. Contract no. DACA 89-81-K-006, Attachment F. 28 pp.

Webber, P. J., Komárková, V., Walker, D. A., and Werbe, N., 1979: Geobotanical studies along a latitudinal gradient between the Yukon River and Prudhoe Bay, Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Internal Report 585. 366 pp.

Werbe, E., 1980: Disturbance effects of a gravel highway upon Alaskan tundra vegetation. M.A. thesis, University of Colorado, Boulder. 153 pp.