3 Disturbance and Recovery of Arctic Alaskan Vegetation

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3.1 Introduction

The discovery of oil at Prudhoe Bay in 1968 prompted considerable interest and funding for disturbance research in arctic ecosystems. Most of the early studies focused on small-scale disturbances relating to oil spills, off-road vehicle trails, roadside disturbances, and old oil-well sites. During the late 1980s and 1990s, scientific interest turned to the broader-scale issues relating to the basic ecosystem processes involved in disturbance and recovery (Oechel 1989; Chaps. 1 and 2, this Vol.), cumulative impacts of large oil-field developments (Walker et al. 1987a), restoration of affected areas (Wyant and Knapp 1992), effects of contamination of the arctic atmosphere from sources at lower latitudes (Landers et al. 1992), and issues relating to climate change (Chapin et al. 1992).

This chapter discusses most of the common disturbances to northern arctic Alaskan vegetation, their patterns of recovery, and recent techniques used for rehabilitating the disturbed areas. Much of the literature consists of unpublished agency and industry reports from the Prudhoe Bay region, but the findings apply to most of the circumpolar Low Arctic – the area of continuously vegetated tundra between the arctic tree line to the south and the intermittently vegetated High Arctic to the north (Bliss and Matveyeva 1992).

3.2 Disturbance and Recovery

Disturbance is a change in vegetation or underlying substrate caused by some external factor (White and Pickett 1985; Pickett et al. 1989). Disturbance can result in altered thermal, hydrological, or nutrient regimes, as well as in changes in the species composition, vegetation structure, or primary production. Disturbance is a natural part of all ecosystems (Chap. 1, this Vol.). It plays a central role in the evolution of ecosystems and is essential to maintaining characteristic diversity and productivity that we associate with a given vegetation type. Anthropogenic disturbances often differ in scale from their natural analogs, but the processes of recovery are often similar (Table 3.1). The final stage of recovery is a healthy functioning ecosystem that can maintain a steady-state equilibrium over a few decades.

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Table 3.1. Natural analogs of anthropogenic disturbances

Anthropogenic disturbance	Natural analog
Microsite disturbances	
Trash and solid waste	Ice-pushed boulders, driftwood from storm surges, floods
Small barren patches	Frost scars, blow outs
Berms of bladed trails	Ice-pushed turf, debris flows, animal dens
Diesel or gasoline spills	None
Mesosite to macrosite disturbances	
Thermokarst and thermal erosion	Natural thermokarst and thermal erosion
Crude oil spills	Oil seeps
Seawater and brine spills	Salt kill from ocean storm surges
Snow drifts from roads, buildings, snow fences	Natural snow drifts
Impoundments	Thaw lakes
Fire	Fire
Off-road vehicle trails	Caribou trails, natural thermokarst, thermal erosion
Ice roads, pads	River icings
Roads, pads, borrow pits	Gravel bars in river floodplains, talus
Offshore gravel drilling islands, causeways	Barrier islands, spits
Regional disturbances	
Dust from roads	Loess from rivers
Acid rain or increased sulfates, NO_x industrial pollution	Fallout from fires
Cumulative impacts of road networks	None
Climate change	
Temperature	Coastal temperature gradient
Precipitation	Elevation gradient, redistribution of snow caused by topographic effects

Recovery is thus a pragmatic term, useful in terms of human life spans. The original native vegetation is the standard against which recovery is measured (Fig. 3.1). A vegetation type may have no possibility of returning to its original state, because the prevailing climate has changed since the original community formed, or because the set of conditions leading to the original community cannot be repeated or the disturbance has completely changed the substrate character (Komárková and Webber 1978; Webber and Ives 1978). Disturbance often affects the thermal and hydrological properties of the soil surface (Hinzman et al. 1991; Chap. 6, this Vol.). For example, complete recovery to original species composition is unlikely on heavily thermokarsted sites because of altered microtopography, hydrology, and thermal regimes, but an ecosystem with greater productivity often occurs because of enhanced decom-

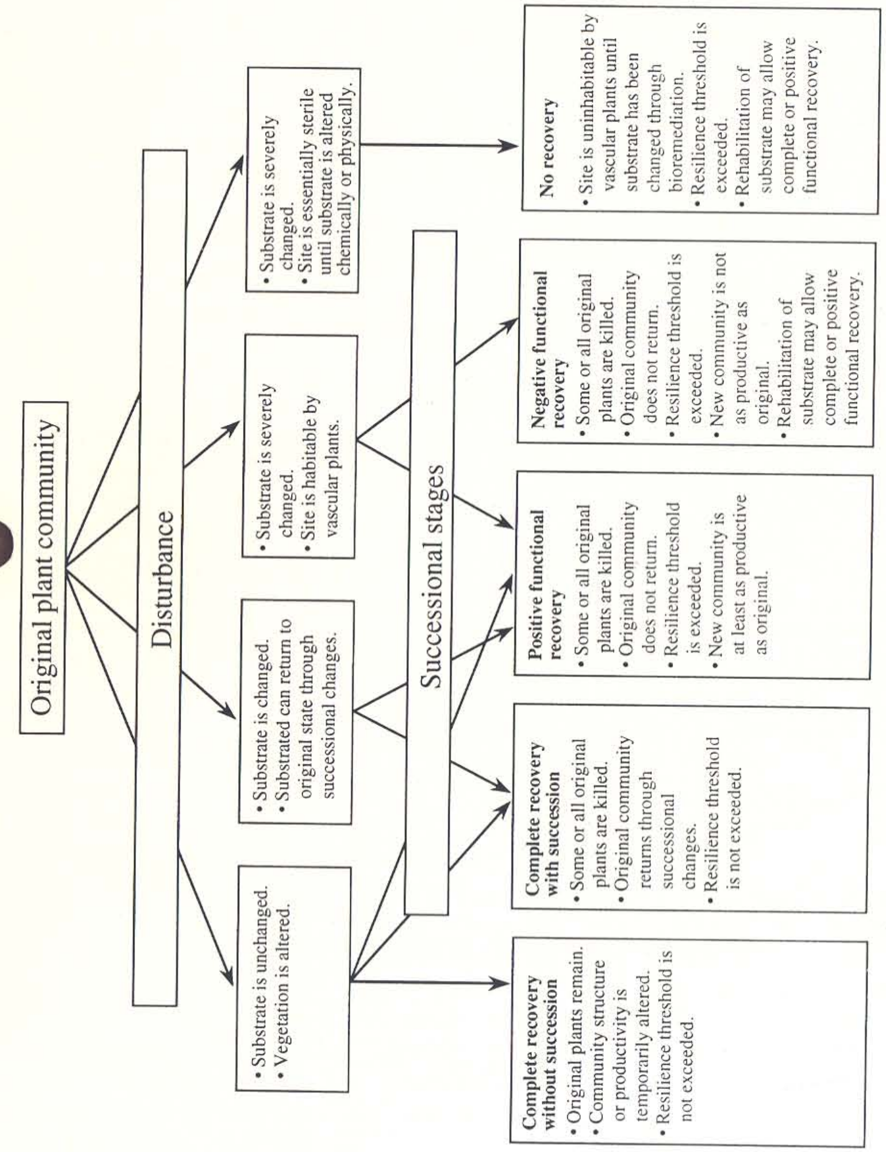

Fig. 3.1. Pathways of recovery following disturbance, without rehabilitation of the site. Substrate rehabilitation on severely disturbed sites can lead to complete or positive functional recovery. (Modified from Walker et al. 1987a)

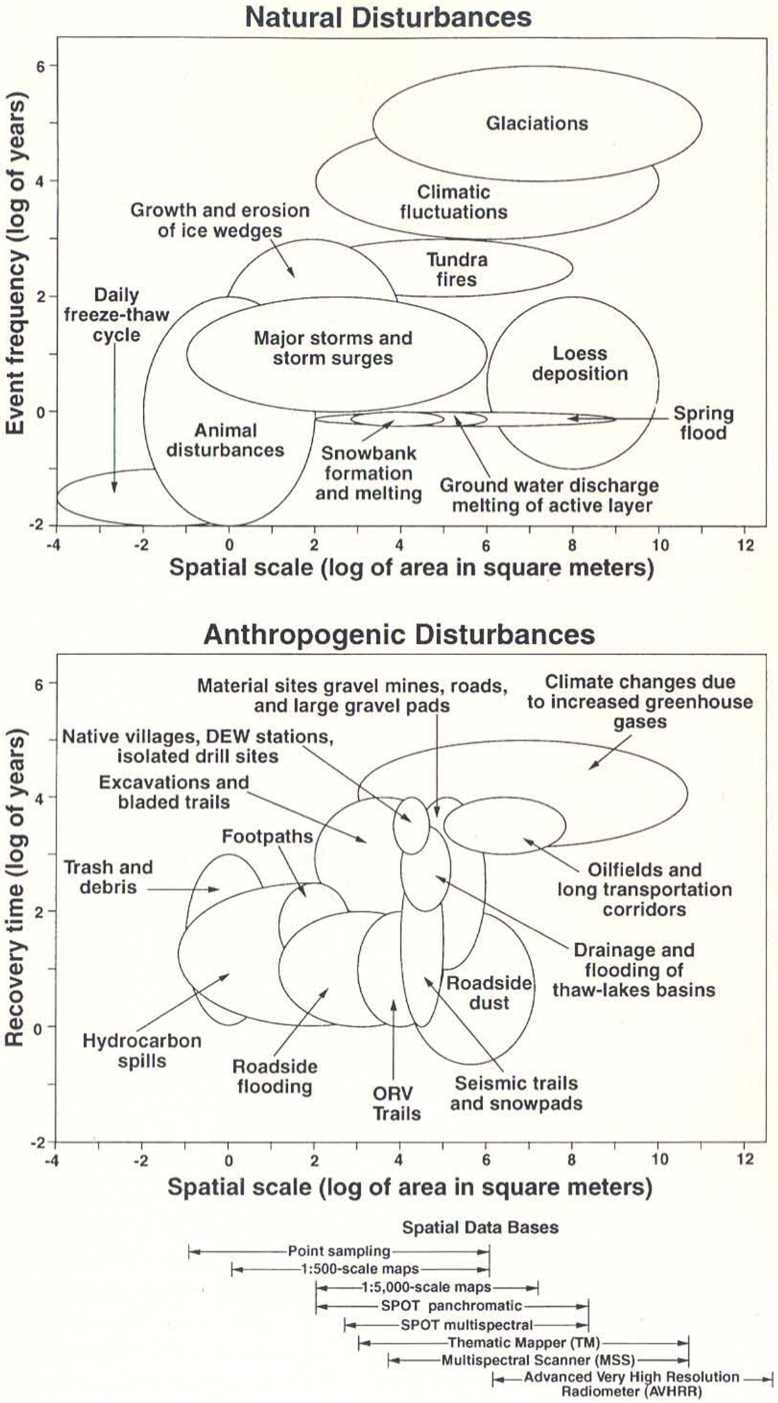

Fig. 3.2. Spatial and temporal domains of natural and anthropogenic disturbances in the arctic and the scales of spatial databases appropriate for monitoring change. *ORV*, off-road vehicle. (Modified from Walker and Walker 1991)

position and higher soil temperatures (positive functional recovery; Ebersole and Webber 1983).

Anthropogenic disturbances to arctic tundra span a wide range of spatial scales (Fig. 3.2). Aggregated disturbances caused by activities both inside and outside the Arctic have impacts on arctic vegetation that are quite different from effects studied at the plot level (Walker and Walker 1991). A hierarchic framework is useful for thinking about disturbances at widely divergent scales and their natural analogs, and for choosing appropriate remote-sensing tools to monitor changes (Fig. 3.2; Chap. 7, this Vol.). This chapter reviews the common disturbances along a spatial gradient from bits of trash ($10^{-1}\,m^{-2}$) to landscapes affected by large oil fields ($10^{8}\,m^{2}$).

3.3 Typical Disturbance and Recovery Patterns

3.3.1 Small Disturbed Patches

The most detailed studies of fine-scale arctic disturbances come from Fish Creek and East Oumalik, Alaska. At both sites, short-term recovery was studied on small, newly bared surfaces where debris and solid-waste were removed 30 years after the 1944–1953 exploration of Naval Petroleum Reserve Number 4 (renamed the National Petroleum Reserve in Alaska [NPR-A] in 1976; Komárková 1985; Ebersole 1987). The waste was composed of steel drums, pilings, boardwalks, and remains of camp buildings and equipment. Cleanup operations sponsored by the United States Navy and Department of the Interior removed these materials in 1979 (Gryc 1985). A few similar drill sites outside of NPR-A were not cleared of these materials and remain as monuments to the early days of oil exploration (Fig. 3.3a).

At Oumalik short-term recovery was studied on 73 newly bared sites ranging in size from about 0.1–1.5 m^2 (Komárková 1985; Ebersole 1987). After 4 years most of the plant cover was due to vegetative colonization by rhizomatous species. Forty taxa, representing adjacent communities, were present (e.g., *Equisetum arvense, Vaccinium vitis-idaea, Ledum palustre, Lupinus arcticus, Arctagrostis latifolia*, and *Eriophorum angustifolium* in moist plots, and *Carex aquatilis* and *Eriophorum angustifolium* in wet plots). On larger plots, seedling establishment was responsible for most of the cover. Seeds in the seed bank apparently did not survive 30 years of burial by the debris; nevertheless, seedlings were abundant (except on dry sites, aquatic sites, and intact organic mats), apparently dispersed from the surrounding vegetation. The vegetation type of the surrounding community was the most important single factor affecting colonization. A few forbs that dominated in the early phases (e.g., *Senecio congestus, Epilobium palustre*, and *Saxifraga cernua*) were uncommon on the surrounding 30-year-old disturbed sites, indicating that these species were eliminated during later phases of succession.

a

b

c

Fig. 3.3a–c.

d

e

f

Fig. 3.3d–f. (*continued.*)

g

h

Fig. 3.3a–h. Common anthropogenic disturbances in northern Alaska. **a** Debris from 1960s drilling operation about 60 km south of Prudhoe Bay near the Kuparuk River. Note the wooden derrick in the background, thermokarst, and lush vegetation caused by altered hydrology. **b** Erosion channel along a bulldozed trail to Prudhoe Bay constructed in the 1960s, near Sagwon, approximately 110 km south of Prudhoe Bay. Massive ice in the uplands melted, eroding more than 3 m of soil. The resulting gully is now protected from winter winds and has enhanced snow cover, permitting willows up to 2 m tall. Willow growth is enhanced by the warmer soils, deeper thaw, high decomposition rates and richer nutrient regimes. **c** Peat road, now 15 years old, near the Putuligayuk River in the Prudhoe Bay Oil Field. The road was formed by scraping material from both sides to form a raised surface. Impoundments have developed in the scraped areas, eroding the road surface and making it impassable. These peat surfaces are very slow to revegetate. **d** Winter seismic trail created in 1984 near the Hulahula River in the Arctic National Wildlife Refuge. Multiple tracks created trails wider than 10 m. Trains of vehicles included tracked vehicles mounted with vibrators or drills, small personal carriers, geophone trucks, a recording vehicle, and D-7 Caterpillar tractors pulling ski-mounted trailers for camps. Altogether 2000 km of trails were arranged on a 5- × 10-km grid. **e** Gravel mine occupying the entire floodplain of the Putuligayuk River in the Prudhoe Bay oil field. The mine has altered the river's

Long-term (>30 years) recovery on small disturbance patches was also studied at Fish Creek (Komárková 1985), Oumalik (Ebersole 1985), Cape Thompson (Everett et al. 1985), and along the Canol pipeline in Canada (Kershaw and Kershaw 1986). Recovery of nondegradable and degradable solid-waste surfaces, such as barrels, boards, and other debris, is extremely slow in the arctic climate. For low pieces of debris, e.g., boards and cans, found in moist and wet tundra, vegetation mats eventually envelop them. After 30 years at Fish Creek, only a small percentage of larger solid-waste surfaces, such as barrels and pilings, were colonized by bryophytes, lichens, or vascular plants (Komárková 1985).

3.3.2 Contaminants

Contaminants are sometimes spilled during exploration and development. These include drilling mud, waste water, used crankcase oil, dust-control chemicals, reserve pit fluids, diesel fuel, glycol (antifreeze), crude oil, and salt water. These substances contain a wide variety of chemicals that are toxic to plants.

3.3.2.1 Hydrocarbon Spills

During the early exploration of NPR-A, and construction of the Dalton Highway and trans-Alaska pipeline and operation of the North Slope oil fields, numerous spills of crude and refined petroleum products occurred. At the Fish Creek site spills of crude oil, crankcase oil, and diesel fuel occurred between 1948 and 1949. From 1974 to 1977, when the trans-Alaska pipeline was first built and operated, more than 16 000 oil spills – totaling more than 2 650 000 l – occurred along the pipeline route (Johnson 1981). During 1985–1986, 952 oil spills were reported on the North slope, totaling 731 800 l (Speer and Libenson 1988). Most of these spills consisted of refined petroleum products. Although most took place in water or were confined to gravel pads, some occurred on terrestrial vegetation.

channel and eliminated riparian and bluff habitat on both sides of the river. **f** Roadside environment along the Prudhoe Bay Spine Road. Note the barren areas caused by dust and thermokarst on the ice-wedge polygons. This site was an area of low-centered polygons that has been converted to high-centered polygons by erosion of the polygon troughs after the road was constructed in the early 1970s. **g** Flooded drained-lake basin along a road in the Prudhoe Bay region. The photo was taken in early summer before ice in the culverts thawed. By late summer the large oval impoundment drained, but the vegetation remained changed. Notice the lack of elevated microsites for bird-nest sites in the flooded area compared with the other side of the road. Also note the other impoundment along the road (*arrow*), which does not drain all summer. **h** A portion of the Prudhoe Bay Oil Field showing a complex of pipelines, roads, and gravel pads in the Deadhorse service area. The large *rectangular gravel pad* on the left side is a drill site with 14 well heads and two reserve pits. Complex cumulative impacts are associated with such large developments. (Photos **a–d**, **f**, and **h** by D. A. Walker; photo **g** by L. F. Klinger; photo **e** courtesy of US Fish and Wildlife Service)

Large spills of crude oil from the trans-Alaska pipeline are rare, but five occurred between 1974 and 1977 (Johnson 1981). On the North Slope, the largest tundra area affected by a spill was a Check Valve 7, north of Franklin Bluffs, where more than 1900 bbl of crude oil were sprayed over approximately 8 ha of primarily wet sedge tundra (Walker et al. 1978; Johnson 1981). Other large documented spills occurred at Check Valve 23 (Brendel and Eschenbach 1985) and at oil-well sites at Prudhoe Bay (Pope et al. 1982; Jorgenson et al. 1991a; Jorgenson and Cater 1991).

Numerous studies have examined the recovery of soils and vegetation after small oil spills (e.g., McCown et al. 1973a; Wein and Bliss 1973b; Deneke et al. 1975; Mackay and Mohtadi 1975; Freedman and Hutchinson 1976; Johnson et al. 1980; Linkins et al. 1984). Most of these addressed general recovery trends related to moisture at the site. For example, at Prudhoe Bay, the recovery from crude oil and diesel spills was generally poor in dry and moist sites after 7 years, although a few taxa colonized the spills. In aquatic tundra sites, sedges and mosses recovered well on oil spills, but virtually not at all on diesel spills (Walker et al. 1985a). Spills on saturated soils or areas with shallow standing water disperse quickly as a film from which volatiles are lost. Wet sites may recover completely within a year or two after light spills. Oil does not penetrate deeply into saturated soils, but spills on dry sites are absorbed by mosses and the underlying organic material and mineral (Linkins and Fetcher 1983). Toxic volatiles are released very slowly in these spills, and the microbial decomposition may take decades without bioremediation. Some components of the vegetation are more susceptible to oil-spill damage; for example, mosses and lichens are easily killed. These forms may also be the first to recolonize the spill area, but colonizing moss taxa generally differ from those in unaffected areas (Walker et al. 1985a). Sedges and willows are the first vascular plants to reappear following an oil spill. At Prudhoe Bay regrowth of some sedges had occurred 1 year after an oil spill of 12 l m^{-2}; but 7 years after the spill, very little vascular plant cover had grown in either the moist or dry spill areas (Walker et al. 1985a). At a more southern site near Fairbanks, cottongrass (*Eriophorum vaginatum*) was successfully established, despite oil-saturated soils in the root zone (Johnson et al. 1980).

Areas receiving a heavier application of oil (as much as 60 l m^{-2}), which is typical of many oil spills, have soil-oil concentrations greater than 100 000 ppm, and are much more difficult to revegetate. The most effective means of revegetating these sites is an initial combination of tilling, to increase soil aeration, and a heavy application of high nitrogen and phosphorus fertilizer (Westlake et al. 1978; Atlas 1985; Brendel and Eschenbach 1985; Jorgenson and Cater 1991; Jorgenson et al. 1991a). These techniques increase the microbial action in the soil. Once the soil-oil content is reduced, then the area can be seeded with grasses. Recent advances in oil-spill cleanup techniques were used on two heavily oiled sites at Prudhoe Bay (Pope et al. 1982; Jorgenson et al. 1991a,b,c). These techniques include:

1. Initial containment with sandbags and absorbent material, surface flushing with warm and cold water, removal of oil and water with a vacuum truck, physical removal of contaminated debris by raking and swabbing with absorbent material, and use of plank walkways to limit trampling
2. Removal of oil-contaminated snow during winter
3. Cross-ripping, bulldozing, and scraping of frozen contaminated soils
4. Incineration of heavily contaminated soil in special furnaces
5. Bioremediation, consisting of deep tilling, fertilization, and control of site hydrology to promote microbial degradation of oil
6. Tundra rehabilitation with commercially available native grass-seed mixes and locally obtained mixes of sedges and legume seeds (Jorgenson et al. 1991a).

The effects of oil spills on permafrost are highly variable. Several investigators have reported that the depth of seasonal thaw in areas of oil spills differs little from unaffected areas (Freedman and Hutchinson 1976). At the Franklin Bluffs site, however, there was a marked difference in thaw 6 years after the spill. Within 80 m of the spill point, thaw deepened to more than 100 cm, whereas thaw depth in undisturbed sites was about 50 cm. Subsidence was apparent in a few areas, but was not severe, mainly because the entire spill area was underlaid by thick alluvial gravels (Walker et al. 1985a).

Recovery from diesel spills is extremely slow. At Fish Creek, 28-year-old diesel spills showed little vegetation recovery, significant depression of the permafrost, and strong diesel odors to a depth of at least 40 cm. Gas chromatography showed that a toxic component persisted in the soil after 28 years (Everett 1978). In contrast, spills of crankcase and crude oil showed good recovery after 28 years, except in the areas of heaviest impact.

Natural oil seeps offer analogues to anthropogenic oil spills. Studies of seeps at Cape Simpson (McCown et al. 1973b) found increased thaw and thermokarst in association with oiled areas. Lush patches of *Eriophorum scheuchzeri* and *Carex aquatilis* were found in association with the seeps. The warmer microclimates near the edge of dark oil pools apparently produced larger plants, advanced phenology, and more abundant fruiting in *Carex aquatilis*. Although the studies noted succession of plant communities in association with active seeps, they gave no details of the species involved. Studies of seeps in a variety of climate regimes and vegetation types could provide useful background information regarding long-term exposure to petroleum.

3.3.2.2 Seawater and Reserve-Pit Spills

Secondary recovery of oil at Prudhoe Bay involves transporting large quantities of seawater in elevated pipelines across the tundra for injection into wells to maintain pressure within oil-bearing strata (Simmons et al. 1983; Jorgenson et al. 1987). Small (2000 l) experimental seawater spills in dry, moist, and wet tundra sites at Prudhoe Bay showed an inverse relationship between soil moisture regime and absorption, and retention of salts (Simmons et al. 1983). In wet sites conductivities approached prespill levels within 30 days; salt water was quickly diluted and flushed from the soil. In contrast, dry sites tended to retain the salts, concentrating them at or near the seasonal thaw line.

ARCO Alaska Inc. conducted studies of a large (ca. 63600 l) accidental spill in the Kuparuk oil field (Barker 1985; Jorgenson et al. 1987). The spill, which originally covered about 0.3 ha before freezing in December 1982, spread downhill, eventually affecting about 4.5 ha. All vegetation within 90 to 140 m of the spill point was killed (Barker 1985). After 3 years of recovery, *Eriophorum angustifolium* and *Dupontia fisheri* were the most common colonizers on areas of high impact. The only forbs returning in these areas were *Cochlearia officinalis* and *Stellaria laeta*. In moderately affected tussock tundra sites, *Eriophorum vaginatum* recovered well. Thaw depths were significantly greater in the brine-affected areas than in the control areas. Woody shrubs (*Dryas integrifolia* and *Salix* spp.) were strongly affected in all spill areas. Sedges, particularly *E. angustifolium*, showed the most resistance to impact. After 3 years, salts appeared to have leached from the high-impact zone and accumulated in lower soil layers downslope of the original spill. For the four common vegetation types at the Kuparuk spill, vegetation cover was reduced 20–80% where electrical conductivities were about 2–3 mmhos cm^{-1}, and cover was reduced more than 80% where conductivities rose above approximately 8 mmhos cm^{-1} (Jorgenson et al. 1987).

Natural analogues of seawater spills can be found along the coast in areas affected by storm surges. These areas are often colonized quickly by salt-tolerant taxa such as *Braya purpurascens, Cochlearia officinalis, Puccinellia andersonii, Salix ovalifolia, Stellaria humifusa, Fulgensia bracteata*, and *Thamnolia subuliformis*.

Salts are also major constituents of old reserve-pit fluids (French 1985). The primary cation in reserve-pit fluids at Prudhoe Bay is sodium, and the major anions are sulfate, chloride, and bicarbonate. The toxicity of these fluids varies considerably during the summer and among reserve pits (Myers and Barker 1984), which tend to decrease with the age of the pit because they become diluted by snow. At Prudhoe Bay the plant species most affected by reserve-pit fluids were the same as those plant species affected by salt-water spills (Simmons et al. 1983; Myers and Barker 1984). All sedges and most forbs examined were little affected, whereas woody plants, most noticeably *Salix reticulata* were most sensitive to elevated salt levels. High soil salinities also pose a problem for revegetating disturbed sites in the Prudhoe Bay area, where soil calcium carbonate salt levels are naturally high and summer precipitation is low. Initial investigations suggest that pore-water conductivities above 10 mmhos cm^{-1} severely restrict plant growth on all substrates (Jorgenson 1988).

The effects of summer and winter seawater spills can be considerably reduced by flushing with freshwater. For example, one spill that occurred in December 1989 had salt-contaminated snow scooped from the site. During the following spring and summer, the site was repeatedly flushed with fresh water, resulting in negligible damage (M. T. Jorgenson, pers. comm.).

3.3.3 Fire

Lightning-caused tundra fires in the Alaskan Arctic have been described from the Yukon–Tanana uplands (Wein and Bliss 1973a; Wein 1975), the Seward Peninsula (Racine 1981), the Noatak River area (Racine et al. 1985), and the Arctic Foothills–Kokolik River area (Hall et al. 1978; Johnson and Viereck 1983). The size and importance of tundra fires (based on 25 years of records) varies widely within the Arctic. Tundra fires are rare on the Arctic Coastal Plain and in the Arctic Foothills and central and eastern Brooks Range, but are more common in northwestern Alaska (Gabriel and Tande 1983; Racine et al. 1985).

Recovery patterns vary considerably with local climate, vegetation type, and soil pH. Along a south–north gradient of decreasing temperature and lightning frequency, vascular plant cover plays less of a role in the recovery, and bryophytes increase in importance in both tussock tundra and low-shrub tundra (Racine et al. 1987). Within tussock tundra plant cover increases rapidly following light and moderate fires (Wein and Bliss 1973a; Fetcher et al. 1984; Racine et al. 1987). In one study plant regrowth produced 10–30% cover of vascular vegetation by the end of the first summer following a fire, 50% cover by the fifth year, and 100% cover by the tenth year (Racine et al. 1983, 1987). The recovery was rapid because the leaves of fire-resistant cottongrass (*Eriophorum vaginatum*) tussocks regrow quickly. Low shrubs resprouted more slowly than sedges and contributed less to early recovery. When severely burned, both cottongrass tussocks and shrubs may be killed, and recovery of the vegetation is slower (Johnson and Viereck 1983). Lichen-dominated tundra is predisposed to burning because of the high surface-to-volume ratio of lichens and rapid desiccation because of lack of roots. Lichens are slow to regrow in comparison with most vascular taxa and may require 50–80 years to redevelop a continuous cover (Auclair 1983).

Species involved in recovery vary with substrate pH. For example, *Rubus chamaemorus*, an acidophilous taxon, plays an important role in recovery on acidic sites on the Seward Peninsula, whereas willows are much more important at alkaline sites. A greater diversity of vascular plant species are involved in postfire succession on alkaline sites than on acidic sites including *Potentilla fruticosa, Gentiana propinqua, Equisetum scirpoides*, and *Thalictrum alpinum* (Racine et al. 1987).

Subsidence and thermal erosion following a fire in tussock tundra is usually minimal, because this tundra type generally occupies gentle slopes. Thaw stabilizes within 10 years; erosion and thermokarsting did occur at two areas on the Kokolik River burn site where massive ice was exposed as a result of fire (Johnson and Viereck 1983).

Seeding by vascular plants is an important revegetation mechanism at most burned sites. On the Seward Peninsula, sedges (*Carex* spp.) established from seed covered 50–100% of better-drained sites within 6 years after a fire (Racine et al. 1983). On other well-drained, willow-dominated sites on the Noatak River and Seward Peninsula, dense stands of fireweed (*Epilobium angustifolium*) developed within 2 years following a fire and have persisted for at least 10 years. Grasses (e.g., *Poa* spp., *Calamagrostis* spp., *Arctagrostis latifolia*) are locally important following fires in tussock tundra. Total primary production recovers quickly after most fires, but restoration of the original abundance of species is still not complete after 13 years at a burn site in interior Alaska (Fetcher et al. 1984). Further studies on the distribution of buried seeds and the nature of tundra plant perennating organs are needed for better prediction of recovery following fire.

3.3.4 Transportation Corridors

3.3.4.1 Bulldozed Tundra and Related Disturbances

During early oil exploration on the North Slope from the 1940s to the 1960s, most of the vehicles and road construction methods were borrowed from temperate regions and adapted to the cold climate. Long trails, such as the Oumalik trail from Barrow to Umiat and the Hickel Highway from the Yukon River to the North Slope (Fig. 3.3b), were commonly bulldozed across the tundra during both summer and winter (Reed 1958). These trails eventually formed deep ruts as ground ice melted and water formed ponds in the depressions. Bulldozing was also done locally for excavations, foundations, drill pads, aircraft runways, sewage disposal, and clearing snow (Lawson et al. 1978; Lawson 1982, 1986). Bulldozers were also used in building peat roads, which were made by removing peat from both sides of the road and piling the material in the center to form a raised surface (Fig. 3.3c). This construction method is used extensively in temperate areas, but was abandoned on the North Slope, because the scraped margins of the roads quickly subsided due to thermokarst along ice wedges. Extensive thermal erosion can be triggered by off-road vehicle movement on hill slopes (Mackay 1970; French 1974; Lawson and Brown 1979; Berg 1980; Lawson 1982). On the North Slope successional processes involved with recovery of bulldozed trails and thermokarst caused by oil development were studied at Fish Creek, Cape Thompson, and Oumalik. (Johnson et al. 1978; Komárkova and Webber 1978; Lawson et al. 1978; Lawson 1982; Ebersole 1985; Everett et al. 1985).

The severity of bulldozer damage ranges from compression of microtopographic irregularities to removal of the entire vegetation mat and near-surface sediments. Bulldozing in ice-rich areas inevitably causes the permafrost to melt, the ground surface to subside, and depressions to fill with water, with virtually no possibility of returning the site to its original state. The amount of subsidence is a function of the ice volume, local topographic relief,

and parent material (Lawson 1982). At Fish Creek and Cape Simpson, where there are relatively small amounts of massive ground ice and sandy materials, subsidence after 30 years was 0.4–2 m. At East Oumalik, where there are large amounts of ground ice and mainly silty sediments, the amount of subsidence after 30 years was 3–5 m. Hydraulic erosion commonly accompanies subsidence on slopes. At Fish Creek degradational processes probably diminished within 5–10 years after bulldozing had ceased. At East Oumalik, however, thermokarst is still expanding laterally in some areas because of hydraulic and thermal erosion and continued thawing of sediments. After 30 years, the disturbance covered at least twice the area of the initial disturbance (Lawson 1982). Similar expansion has also occurred along many bladed trails throughout the foothills (Fig. 3.3b).

Recovery on bulldozed sites depends largely on local climate and moisture regimes. At Cape Simpson, located within the cold littoral zone near the coast (mean July temperature <7 °C), recovery has been slow in the 30 years following disturbance, whereas sites inland have a lush growth of willows, grasses, and forbs (Ebersole 1985). Thirty years after wet meadows were bulldozed at Fish Creek, Oumalik, and many other old drill sites inland across NPR-A, subsidence has generally stopped, and vascular plant cover is nearly complete (Ebersole and Webber 1983; Komárková 1983). *Carex aquatilis* and *Eriophorum angustifolium* provide essentially all the cover where the soils are still very wet by the end of the summer, except at the arctic coast, where *Dupontia fisheri* is important. In moist tussock-sedge and mixed-shrub tundra, bulldozing often removes the tussocks and the underlying organic mat, which causes water to accumulate and converts the vegetation to wet sedge tundra composed of *Carex aquatilis* and *E. angustifolium*; there is little tendency toward a return to the original community (Johnson et al. 1978). In less severely disturbed areas where the bases of the tussocks and intertussock plants are intact, however, the tussocks slowly regrow. Seedlings establish slowly where the moist vegetation has been scraped away, leaving a thick organic mat. Seedling establishment is especially slow near the coast (Racine 1977; Johnson et al. 1978; Ebersole and Webber 1983; Ebersole 1989). At inland sites, willow seedlings are common. For example, willows are an important component of the vegetation cover on 30-year-old bulldozed areas at Oumalik (Ebersole 1985).

In many areas another consequence of bulldozing was the creation of mounds of vegetation and soil adjacent to the bulldozed sites, with habitats very different from the adjacent tundra. Mounds of bulldozed material up to 1.5 m high form well-drained microsites with higher soil temperatures than the surrounding tundra and thick active layers. Decomposition rates and nutrient availability are consequently higher (Lawson et al. 1978). For example, at Oumalik temperatures at a depth of 10 cm during 1 day averaged 9.4 °C in bulldozed material compared with 2.4 °C in adjacent tussock-sedge, dwarf-shrub tundra and 5.6 °C in wet sedge tundra (Ebersole and Webber 1983). Where the material forming the berms was mixed with mineral soil, plant cover is high, often composed mainly of nitrophilous grasses (*Arctagrostis latifolia, Poa arctica, Festuca brachyphylla*; Ebersole and Webber 1983). After 20–30 years, grasses and erect willows, particularly *A. latifolia, Salix alaxensis, S. glauca, S. lanata*, and *S. pulchra*, form a complete cover and grow more vigorously than in the surrounding undisturbed tundra (Ebersole 1985).

Animal dens and digging sites of bears are possible analogues of some bulldozed tundra sites (Wiggins and Thomas 1962; Peterson and Billings 1978; Gersper et al. 1980; Walker 1985). Many species occurring on these sites are nitrophilous (e.g., *Arctagrostis arundinacea, Festuca baffininsis, Phippsia algida, Poa glauca, Leymus villosissimus, Trisetum spicatum, Draba hirta, Artemisia tilesii, Arnica griscomii, Androsace septentrionalis, Polemonium acutifolium, Valariana capitata, Chrysosplenium tetrandrum, Saxifraga cernua, S. caespitosa, Rumex arctica*, and others) and are not common zonal tundra communities (Matveyeva 1979). The vegetation associated with such disturbances is distinguished by great vegetative vigor, dominance of herbaceous plants, lack of dwarf shrubs, and increased diversity of vascular plant species (Yurtsev and Korobkov 1979).

3.3.4.2 Off-Road Vehicle Trails

Although recent oil exploration and development was accompanied by a trend toward more permanent transportation corridors, all-season off-road transportation is still needed (Radforth and Burwash 1977; Abele et al. 1984). Industrial off-road vehicle (ORV) designs have become increasingly sophisticated to minimize the damage to tundra landscapes, but permanent damage is still possible unless sound guidelines are followed. Another concern is the cumulative effects of recreational one-passenger snow machines and motorized three- and four-wheel off-road vehicles. An estimated 15000 of these vehicles are currently in use in central and northern Alaska (Slaughter et al. 1990).

3.3.4.2.1 Summer Travel

The ORVs are involved in a wide range of summer activities, including seismic operations, drilling, mining, scientific research, reindeer herding, subsistence activities, and recreation. Vehicles vary in type and size and include tracked "weasels" and bulldozers, four-wheel-drive trucks, and vehicles with low-pressured tires, such as "Rolligons" and lightweight three-wheeled all-terrain cycles. Air-cushioned vehicles showed great promise for low-impact transportation on flat tundra (Abele et al. 1972; Sterrett 1976), but they have not been widely used on land, because they are expensive to operate and cannot traverse hilly areas.

Vehicle impact and recovery were monitored for up to 10 years following tests at Barrow, Lonely, and Prudhoe Bay (Abele et al. 1972, 1978a,b, 1984; Walker et al. 1977). At Cape Thompson, vehicle trails, which were used for research between 1959 and 1961 and then abandoned, were examined in 1981 (Everett et al. 1985). In addition, a variety of 25- to 30-year old off-road-vehicle trails were studied at Fish Creek, Oumalik, and elsewhere on the North Slope (Hok 1969; Lawson et al. 1978; Lawson 1982; Ebersole 1985).

Abele et al. (1984) analyzed 10 years of observations involving six vehicle types (three low-tire-pressure Rolligon vehicles, two lightweight tracked vehicles, and one air-cushioned vehicle) at Barrow and Lonely, Alaska. The air-cushioned vehicle generally produced the least impact. All three Rolligons produced a longer-lasting impact than lightweight-tracked vehicles, mainly because the ground pressure for the Rolligons (0.25–0.35 $kg\,cm^{-2}$) was higher than for small-tracked vehicles (0.07–0.1 $kg\,cm^{-2}$). Recent studies of lightweight all-terrain vehicles (ATVs; 0.1 to 0.7 $kg\,cm^{-2}$) at Anaktuvuk Pass show that terrain damage in the mountains is less than on the coastal plain because of better draining soils with less massive ground ice.

Site moisture is particularly important to predict initial impact and recovery. At Prudhoe Bay and Lonely, single-pass Rolligon tracks through wet tundra were initially very visible, but recovered fully in 7 years (Walker et al. 1977; Abele et al. 1978b). In contrast, single-pass trails of overloaded Rolligons in wet tundra are still apparent after 10 years. After 20–30 years, deeply rutted tracks in wet tundra at Cape Thompson, Oumalik, Fish Creek, and Barrow seem to have reached thermal equilibrium and support typical wet tundra plant species (Abele et al. 1972; Lawson et al. 1978; Ebersole 1985; Everett et al. 1985). In some areas, this wet tundra differs in composition from the initial vegetation. In moist tundra at Prudhoe Bay, single-pass tracks of Rolligons compressed hummocks and ice-wedge polygon rims, causing damage that persisted for 5 years (Walker et al. 1985b). Moist tundra generally resists disturbance better than wet tundra, but it is less resilient once disturbed. Nutrient fluxes tend to increase, particularly in wet vehicle trails (Challinor and Gersper 1975; Chapin and Shaver 1981; Shaver and Chapin 1984).

The depth of summer thaw often increases after impact, but tends to rebound in later years. At Barrow the initial depression of a wet meadow surface was 15 cm in a 50-pass weasel track test. Seasonal thaw increased an average of 10 cm after 2 years, but returned to predisturbance levels within 10 years (Abele 1976). In wet meadows at Cape Thompson no significant differences in thaw depths were found in severely disturbed trails and adjacent controls after 20 years (Everett et al. 1985). The depressed surface of tracks in wet sedge tundra at Barrow and Cape Thompson have rebounded, presumably because of subsurface ice buildup (Abele 1976; Everett et al. 1985). Nearly complete vegetation recovery from vehicle traffic is likely within 10 years on flat tundra if the vegetation mat is not broken. This likelihood holds even for apparently serious damage to wet tundra vegetation as long as root systems are not damaged. However, if the mat is broken, or if runoff water is channeled into the track, recovery is likely to be slow. Where off-road vehicle tracks break and churn the organic mat over ice wedges, thaw and melting of the massive ice lead to subsidence and thermokarst formation (Abele 1976; Lawson et al. 1978; Lawson 1982; Abele et al. 1984).

Recent research on 20-year-old vehicle trails in the High Arctic has shown important differences from Low Arctic recovery patterns because of the High Arctic's shorter growing season and lower summer temperatures. Differences included limited reinvasion among rhizomatous graminoids in all but the wettest sites, and minimal seedling establishment. Moreover, strips wider than about 1 m remain mostly unvegetated, except for occasional clumps of mosses and small tufts of invading grasses (Forbes 1992).

3.3.4.2.2 Winter Travel

Snow and Ice Roads. In winter temporary roads are prepared by smoothing or compacting the snow surface to form a snow road or by spraying water on the surface to build up an ice layer that forms the roadway (Gas Arctic-Northwest Project Study Group 1973; Adam and Hernandez 1977; Johnson and Collins 1980; Johnson 1981). Such roads have been used in a variety of situations in northern Alaska. Explorations of NPR-A, for example, took place during the winter over unprepared snow trails, and prepared snow roads and ice roads. In another situation, a snow pad was built adjacent to the TAPS (trans-Atlantic Pipeline System) haul road during construction of a 230-km gas line during the winters of 1975–1976 and 1976–1977 (Brown and Berg 1980; Johnson 1981). Aircraft landing strips have also been prepared using packed snow or ice. Disturbances and recovery resulting from winter trails and snow and ice roads have been studied at Prudhoe Bay, Inigok in NPR-A, Seward Peninsula, along the TAPS haul road, and in the Arctic National Wildlife Refuge (ANWR; Buttrick 1973; Racine 1977; Johnson and Collins 1980; Johnson 1981). If left in place for only 1 year, ice roads are a good technique for minimizing damage, especially considering the alternatives.

A heavily traveled 40-km ice road was used to construct the drill pad at Inigok in spring 1978. When viewed from the air in summer 1978, the impact of the road seemed slight. In part, this impression was because the road traversed mostly tussock-sedge, dwarf-shrub tundra, where the compression of standing dead vegetation is less obvious than in wet sedge tundra. Ground observations 3 years after the disturbance, however, revealed a variety of vegetation impacts ranging from abraded and crushed tussocks to willows with broken or abraded terminal stems. Especially apparent was the alteration or destruction of the intertussock plant community, particularly the mosses (*Sphagnum* and *Dicranum*) and lichens. These species are apparently very susceptible to compression and breakage when frozen (K. R. Everett, unpubl. data). An ice road in the Arctic National Wildlife Refuge (ANWR) was kept in place for two winters, and one summer killed almost 100% of the vegetation (M. T. Jorgenson, pers. comm.).

Where snowpads are used for construction, considerable debris is deposited on their surfaces. For example, along the snowpads used for excavating the TAPS fuel-gas pipeline and for constructing a section of TAPS as much as 90% of the pad along the fuel-gas line was covered with debris, and 25% of the TAPS snowpad was covered (Johnson and Collins 1980; Johnson 1981). Thaw depths under the pads increased for at least 3 years, reaching maximums of 22 cm deeper than controls along TAPS and 28 cm deeper along the gas line. The total vascular plant cover was reduced under the area of the snowpad during the first growing season after use, with erect shrubs (*Salix* spp. and *Betula nana*) and mosses showing extensive damage (Johnson 1981). Under the TAPS snowpad, many *Eriophorum vaginatum* tussocks were compressed or sheared off. Most of the vascular plants recovered after 3 years, but the amounts of mosses, lichens, and evergreen shrubs were still reduced compared with control areas (Johnson 1981).

Seismic Trails. All seismic activities on the North Slope are now conducted in winter, and most of the recent studies involving vehicle impact have been related to the effects of winter seismic operations (e.g., Reynolds 1982; Densmore 1985; Felix and Raynolds 1989a,b; Raynolds and Felix 1989; Felix et al. 1992). An area where winter vehicle trails are of particular concern is the 60 000 ha coastal plain portion of the ANWR, which was opened to winter seismic surveys in the winters of 1984–1985 and 1985–1986. More than 2000 km of trails were traversed within the refuge (Fig. 3.3d). The U. S. Fish and Wildlife Service (USFWS) studies of ANWR trails showed that 29% of the trails sustained medium-to-high levels of impact (Raynolds and Felix 1989). The most noticeably affected areas were river terraces dominated by *Dryas integrifolia*, terrain with considerable microtopographic relief caused by mounds, tussocks, hummocks, or high-centered polygons (Raynolds and Felix 1989). In places where there was little winter snow cover, as much as 87% of the vegetation cover was destroyed in swaths 10 m wide and up to 50 m long. Riparian shrub tundra was also heavily affected, mainly by breakage of the shrub canopy. Wet or partially vegetated areas were the least affected. Surface depressions to 15 cm deep occurred in wet areas (Felix and Raynolds 1989a). Evergreen shrubs (*Vaccinium vitis-idaea, Ledum palustre* ssp. *decumbens*) were among the most sensitive species, showing little recovery potential. In dry sites *Dryas integrifolia*, *Oxytropis* spp., *Astragalus* spp., *Equisetum variegatum*, and numerous mosses were strongly affected (Felix and Raynolds 1989a). Little resilience was seen in any of the vegetation types 4–5 years after the disturbance. The active layer remained deeper on plots in all nonriparian vegetation types, and most areas still had visible trails (Felix et al. 1992).

Disturbance and snow depth are generally inversely related; the amount of snow required to buffer disturbance also varies with vegetation type and impact intensity (e.g., seismic line vs camp move; Felix and Raynolds 1989b). Areas where tracks crossed local snow accumulations, such as the base of low terraces, show none of the damage noted in less-protected sites. During the seismic operations in ANWR, government regulations required an average snow depth of 15 cm before vehicles were permitted on the tundra, but more than 25 cm of snow is needed to minimally protect tussock tundra vegetation (Felix and Raynolds 1989b).

Follow-up studies in ANWR indicate that, despite efforts to minimize damage during the 1984–1985 seismic operations, long-term damage to the tundra did occur and is likely to remain for many years (Felix et al. 1992). Approximately 25% of all the trails showed little recovery between 1985 and 1988, and thaw settlement had not stabilized after 5 years. Once a track is present, a positive feedback is established such that the tracks become wetter, causing more heat gain, melting more ground ice, and further deepening the track. Avoidance of areas with low snow cover, use of lightweight vehicles, dispersed traffic patterns, and minimizing sharp turns and steep grades are the main recommendations to minimize damage (Felix et al. 1992). Revised government regulations regarding minimum snow depths for seismic operations would be effective. Aesthetics is a major consideration in highly protected areas such as national parks, refuges, and wilderness areas. The visible impact of traffic is the most prominent, long-lasting, and difficult-to-measure consequence of current seismic operations (see Fig. 3.3d).

3.3.4.3 Permanent Roads and Pads

The present approach to building roads and construction sites in northern Alaska is to create a thick – often more than 2 m thick – gravel pad to prevent thawing of the underlying permafrost. Although this design maintains the integrity of the permafrost, it causes other environmental impacts including (1) creation of dry elevated sites that are difficult to revegetate once the road or pad is abandoned, (2) creation of gravel-mine sites that also need to be revegetated, (3) blockage of natural drainage patterns, and (4) alteration of snow drift patterns. Other impacts associated with roads include gravel and dust spray, toxic spills, debris, and other disturbances. Sometimes the pads are constructed with rigid polyethylene insulation underneath to reduce the amount of gravel needed to insulate the original ground surface. If the pad is temporary, only a thin layer of gravel or sand is commonly used.

Elevated pads constructed on the open tundra are likely to remain unaltered for many hundreds of years and, for all practical purposes, represent a permanent change to the environment unless intensive site preparation provides adequate soils. Some of the older pads that have been abandoned at Prudhoe Bay with no revegetation efforts have developed very sparse vegetation communities with many of the same taxa that grow on gravel river bars and coastal beaches, e.g., *Arctagrostis latifolia, Artemisia alaskana, A. borealis, A. tilesii, Astragalus alpinus, Cochlearia officinalis, Deschampsia caespitosa, Epilobium latifolium, Equisetum arvense, Festuca rubra, Oxytropis campestris, Papaver lapponicum, Poa glauca, Sagina intermedia, Salix ovalifolia, Saxifraga cernua, S. oppositifolia,* and *Trisetum spicatum* (Walker et al. 1987a,b; Jorgenson 1988).

Revegetation of gravel pads at Prudhoe Bay is limited by cold summers, low rainfall during summer, and thick gravel fill that limits plant access to groundwater and nutrients (Johnson 1981; Jorgenson et al. 1991b). Revegetation with seeded grasses has been the most common form of gravel pad rehabilitation. Revegetation on gravel pads seeded with commercially available grasses was generally more successful in the southern portion of the coastal plain and in the foothills (Johnson 1981). Fertilization increases plant colonization rates. At test sites in NPR-A, which were drilled and abandoned in 1976, drill pads, runways, and roads have been revegetated with a mix of exotic and native grasses (*Festuca rubra, Arctagrostis latifolia, Poa glauca, Poa pratense*), and most sites were fertilized (McKendrick 1987). Considerable vegetation cover was observed between 1977 and 1984 at sites that were reseeded and fertilized repeatedly. At Prudhoe Bay, recolonization rates increased from 0.05% cover per year without fertilization to 3.7% after fertilization (Jorgenson 1988). The best development of artificial vegetation cover occurred in depressions on the pads where moisture is more available.

Plant cover is inversely related to fill thickness; it is very low on sites with more than 1 m of gravel, because groundwater availability is low (Jorgenson 1988). Recent rehabilitation of abandoned gravel pads at Prudhoe Bay has incorporated a variety of hydrological manipulations to improve the arid conditions on raised gravel surfaces including (1) creation of 1-m high gravel berms to capture drifting snow to increase water input to the soil, (2) adding organic matter to improve water-holding capacity, and (3) applying mulches to reduce evaporation (Jorgenson et al. 1991b, 1992a). Sewage sludge from wastewater treatment plants is also being considered (Jorgenson et al. 1991b).

Other techniques for rehabilitating thick gravel pads being tested at Prudhoe Bay include fertilization and colonization by local native forbs, native grass cultivars, indigenous wetland sedges, and transplanted tundra plugs combined with gravel removal to reestablish the original hydrological conditions (Jorgenson and Kidd 1991). Early results from these studies indicate that land rehabilitation in the Low Arctic is feasible and can be relatively rapid, even on extreme sites, when adequate soil and hydrological conditions are provided (Jorgenson and Cater 1992). Nevertheless, we do not have enough information presently to develop rehabilitation prescriptions for all sites (Wyant and Knapp 1992).

3.3.4.4 Gravel Mines

Gravel used for pads must sometimes be hauled long distances from rivers or open-pit mines. During the construction of TAPS, more than 78 500 ha of land were disturbed; 31 700 ha, or 40%, was for gravel borrow sites (Pamplin 1979). River bars have historically been the primary gravel source for most of the roads and gravel pads in northern Alaska (Fig. 3.3e). Because they are high-energy environments with a predominance of early successional communities, they can recover relatively quickly from disturbance if proper guidelines are followed (Woodward and Clyde Consultants 1980). Four factors relating to changed hydrology constitute impediments to reestablishing vegetation in mined riparian areas: (1) permanent or annual flooding, (2) increased frequency and duration of temporary flooding, (3) long-term channel changes (increased braiding and channel width and decreased channel stability), and (4) new or increased formation of riving icings (Joyce 1980). Factors that promote recovery of the vegetation and faunal communities include (1) siting the mines in large and medium-width channels flowing in a braided pattern, (2) shallow scraping of surface layers over broad areas, and (3) using organic-rich soils to enhance recovery either by broadcasting it over the ground or forming piles that can become temporary small-mammal and passerine habitat (Joyce 1980).

Gravel borrow pits have many of the same site characteristics as roads. Both nutrients and moisture are frequently limiting, but unlike roads, borrow pits are rarely elevated above the general tundra surface, so revegetation is somewhat easier. If fine-grained material is placed over the gravel, the areas can usually be revegetated (Johnson 1981). Temporary pads and borrow pits in areas with frequent natural disturbance, such as floodplains, are more quickly revegetated, because local seed sources are able to colonize river gravels (Johnson 1981).

Johnson (1987) emphasizes the importance of planning gravel sites carefully, including: (1) selecting the site to minimize visual impacts and promote reinvasion by native species, (2) limiting the area of impact, (3) reducing the need for gravel through innovative engineering designs, and (4) reclamation plans that both ensure erosion control and reestablish as natural a vegetation cover as possible. Important aspects of the reclamation effort include reconstructing soil by spreading stockpiled organic matter and fine-grained mineral soil over the site and seeding or transplanting adapted, preferably native, species.

3.3.4.5 Native Species in Revegetation of Gravel Pads and Mines

Use of native species is increasing for reclamation of gravel pads, mined areas, and disturbed roadsides (Chapin and Chapin 1980; Johnson 1981, 1984, 1987; Shaver et al. 1983; Densmore and Holmes 1987; Densmore et al. 1987; Jorgenson 1988; Jorgenson and Kidd 1991). Early revegetation efforts in the Arctic attempted to identify commercially available grass species that were best adapted to the cold climate to help control erosion (Younkin 1972, 1976; Hernandez 1973; McKendrick and Mitchell 1978). Later consideration focused on native species (Mitchell 1979; Johnson 1981; Jorgenson and Kidd 1991).

Most commercial seed mixes are designed to create a fast-growing cover of grasses, but establishment of native species can be restricted, at least in the

short term, by competition from commercial grasses (Johnson 1981; Densmore et al. 1987; Densmore 1992). Recent studies of the long-term effects of seeded grasses in floodplain mines suggest that the grass treatment alters the pattern of succession (Densmore 1992). A gravel mine site on a floodplain of the Atigun River that was scarified, fertilized, and seeded with a commercially available seed mix had only about 5% cover of *Festuca rubra* after 4 years and 1.5% cover after 11 years. Invasion by native species was greatly reduced on seeded areas. Many species, particularly nonlegume forbs such as *Epilobium latifolium*, failed to establish on the seeded areas, and shrubs such as *Salix glauca* and *S. alaxensis* were severely inhibited. Leguminous plants, such as *Astragalus alpinus*, were apparently unaffected by the treatment. Factors contributing to the differences were thought to be (a) initial competition by the grasses for soil moisture and nutrients, and (b) the high moss cover on the fertilized areas, which dried the surface, raised soil temperature, and prevented seedling establishment. Densmore (1992) suggests that seeding be used only on tundra sites where immediate stabilization is needed to prevent erosion. Revegetation is generally best achieved on untreated floodplain sites that are allowed to recolonize by natural riparian successional processes (Bliss and Cantlon 1957; Viereck 1966; Peterson and Billings 1978, 1980; Moore 1983).

Recent studies at Prudhoe Bay have used a variety of native plants including plugs from wet sedge meadows, seed from hydrophytic sedges and grasses, native legumes, and cuttings of *Salix ovalifolia* and *S. arctica* (Jorgenson and Cater 1991; Jorgenson and Kidd 1991). Willows (*Salix alaxensis*) have also been used to restore moose habitat lost to pipeline construction along the Sagavanirktok River (Densmore et al. 1987). Some attempts were made using willows on abandoned TAPS gravel pads, but these attempts were mostly unsuccessful (Johnson 1981).

Surveys of abandoned gravel pads and disturbed sites along the Dalton Highway, Dempster Highway, Canol Pipeline, and Denali National Park have identified several other native species that conceivably could be useful for revegetation efforts on gravel sites. Particularly good candidates include *Arctagrostis latifolia, Artemisia arctica, A. borealis, A. tilesii, A. glomerata, Astragalus alpinus, A. aboriginum, A. eucosmus, Braya purpurascens* (in alkaline coastal areas), *Calamagrostis canadensis, Deschampsia caespitosa, Epilobium latifolium, Festuca altaica, Festuca brachyphylla, Hedysarum alpinum, Oxytropis campestris, O. nigrescens, Potentilla fruticosa, Salix alaxensis, S. ovalifolia*, and *Trisetum spicatum* (Everett et al. 1985; Walker 1985; Densmore and Holmes 1987; Kershaw and Kershaw 1987; McKendrick 1987). There is considerable local variation in the pool of species colonizing disturbed riparian sites and gravel pads. Summer temperatures are particularly important. In a survey of 12 revegetated pads in NPR-A, an average of only three native species was found on pads at the cold coastal sites. An average of 10 native species was found on inland coastal-plain pads, and an average of 24 native species occurred on relatively warm foothill sites

(McKendrick 1987). Few willow species occur near the coast, and slow growth of all woody species limits the height and recovery potential of shrubby communities at the coast (Walker 1987). Detailed studies of the dynamics of succession in relation to the coastal temperature gradient and alkaline vs acidic substrates would be useful.

The buried seed bank is a potentially important source of native seeds. Large numbers of native plant seedlings appear on recently disturbed sites before any external seeds arrive (Chester and Shaver 1982; Gartner et al. 1983). These seedlings are concentrated on organic soils and probably come from buried seeds held in the organic layer of undisturbed tundra (McGraw 1980; Gartner et al. 1983; Ebersole 1989). Replacement of organic soil matter after a disturbance is particularly important to native plant recovery, because the organic layer contains the principal native plant seed source and because native plant growth rates are higher in organic soils than in mineral soils.

The germination strategies of many arctic plants appear to be useful for seedling establishment on disturbances (Densmore 1979; Gartner 1983). The highest germination rates are at high temperatures (25–35 °C) and in sunlight. This observation suggests that many of these species are preadapted for colonizing disturbances.

Studies at cold coastal sites have not found the buried seed bank to be a useful means for revegetating disturbed sites, possibly because of the reduced viability of the seeds (M. T. Jorgenson, pers. comm.). Weeds are not important in the buried seed bank, but they were observed at a number of seeded sites along the trans-Alaska pipeline, where they were introduced in both straw mulch and in the seed mix. On the North Slope weeds generally do not persist (Kubanis 1980; Johnson 1981). An experiment in which grids of toothpicks were implanted in various substrates showed that the mineral substrate was much less stable than the organic substrate (Gartner et al. 1983). Thus, adding organic matter to an artificial seedbed may increase the success of seedlings by reducing needle ice or other unfavorable physical factors. Fertilizing adjacent strips of undisturbed tundra may also promote seedling establishment, but a dependable strategy for encouraging seed production is currently not available.

3.3.4.6 Road Dust

Road dust on arctic tundra is a relatively recent phenomenon associated with high-speed gravel highways (Walker and Everett 1987; Auerbach 1992). Road dust, like the regional loess, is alkaline; calcium and magnesium are the most abundant cations (Chap. 15, this Vol.). Everett (1980) measured dustfall and wind along the Dalton Highway and Prudhoe Bay Spine Road and found that dust loads 1000 m from the road were several times higher in the Prudhoe Bay region than at similar distances from the road at other sites along the Dalton Highway. This difference is an effect of the dense, heavily traveled road network at Prudhoe Bay with road dust coming from many sources. Over the 5

years of Everett's study, the normally high buffering capacity of this tundra, which is due to large amounts of exchangeable hydrogen and aluminum, was neutralized in some areas of heavy dustfall. In the upper 2–5 cm, soil pH has shifted from acid to alkaline. A less dramatic and somewhat erratic buildup of other cations, such as potassium, was also documented. Soil chemical changes induced by road dust were measurable only after 3 or more years of impact in the high dustfall zone (0–30 m). Changes in areas of lower dustfall will take much longer to become recognizable.

In some areas along the most heavily traveled roads at Prudhoe Bay, all vegetation has been totally eliminated within 5 m of the road. Mosses were eliminated to a distance of about 20 m. A few dune and coastal species, such as *Elymus arenarius*, *Braya purpurascens*, *Puccinellia andersonii*, and *Armeria maritima*, are colonizing these areas. Beyond about 100 m in alkaline tundra, the vegetation, although heavily dusted, appears to have survived with little compositional change (Walker and Everett 1987). The loss of vegetation near the road is partially responsible for the extensive thermokarst features and high-centered polygons that have developed along older roads (Fig. 3.3f). Thermokarst features occur mostly within 25 m of the road at Prudhoe Bay, but in some areas, thermokarst is actively expanding into the tundra within 100 m from the road.

The changes at Prudhoe Bay are occurring in a tundra adapted to high influxes of natural loess (Walker and Everett 1991). In acidic tundra, road dust significantly reduces and often eliminates *Sphagnum* moss, especially in the 0–10 m adjacent to the road (Spatt 1978; Werbe 1980; Spatt and Miller 1981; Auerbach 1992). This effect is due to the toxic effects of calcium in the dust (Clymo 1973) and reduced photosynthetic rates of the moss in heavily dusted areas (Spatt and Miller 1981). Ten years after road construction, *Ceratodon purpureus*, *Bryum pseudotriquetrum*, and *Polytrichum juniperinum* had replaced *Sphagnum* as the most common mosses near the road (Walker et al. 1985a). After 15 years, *Sphagnum* spp. has been replaced by *Aulacomnium turgidum* as much as 100 m from the road near Toolik Lake, Alaska (Auerbach 1992). Other plant species also react negatively to road dust (e.g., *Cassiope tetragona* and *Cladonia* spp.). Some plants, on the other hand, especially several minerotrophic moss species (e.g., *Drepanocladus*, *Scorpidium*, and *Catascopium*), respond positively to the increased nutrients.

3.3.4.7 Roadside Impoundments

Within the Prudhoe Bay region, most instances of road-related flooding occur where the road crosses low-lying, vegetated, drained thaw-lake basins. Drainage patterns on the flat tundra are complex, with many unconnected drainage systems. In areas with an intersecting web of roads, flooded areas are more common and often extremely difficult to drain. For example, a 7.0-km road was constructed in 1980–1981 through a flat coastal portion of the Prudhoe Bay oil field, flooding 134 ha (18 ha km^{-1} of road; Fig. 3.3f; Klinger et al. 1983).

Culverts blocked by snow and ice prolong the flooding period during the spring. Detailed hydrological maps and observations during the melt are helpful in deciding where to place culverts.

Another form of flooding occurs in narrow strips along the margins of most Prudhoe Bay roads. This type of flooding is accentuated if the ground subsides, either when the road settles or thermokarst develops. Numerous roadside areas along the Spine Road are covered by thermokarst features flooded 30–100 cm deep above thawed ice wedges (see Fig. 3.3f). The thermal disturbance results from the flooding and the loss of vegetation buried by road dust.

Most flooding is confined to wet and aquatic tundra vegetation. The most notable effect is a greening of the vegetation (Klinger et al. 1983). Many flooded areas drain by midsummer so major damage may not occur, although the plant communities do change in a manner that corresponds to communities along moisture gradients in thaw-lake basins. Mesic species (e.g., *Eriophorum triste*, *Dryas integrifolia*, *Tomenthypnum nitens*, *Thamnolia subuliformis*) are often replaced by hydric taxa (e.g., *Carex aquatilis* and *Eriophorum angustifolium*). Vegetation is killed in areas of prolonged and deep flooding. In other areas moist microsites, such as polygon rims, hummocks, and strangmoor, are eliminated by flooding. Such features are particularly important nesting sites for several species of birds.

An understanding of vegetation succession in thaw lakes, both during their formation and after drainage, is important for properly managing coastal wetlands in areas of development. Ongoing observations of the dominant species in drained thaw lakes at Barrow (*Dupontia fisheri*, *Carex aquatilis*, *Eriophorum angustifolium*, and *Arctophila fulva*) are helping to establish the time scales and mechanisms involved with succession (Billings and Petereson 1980). At Prudhoe Bay techniques are being tested to establish common aquatic grass, *Arctophila fulva*, along disturbed creeks, lake shores, and artificial ponds (McKendrick 1990; Moore 1990). The patterns of vegetation succession in drained thaw lakes are affected by the substrate, local climate, and manner of drainage. For example, *Dupontia fisheri* is an important colonizer at the coast. Where the climate is warmer, a wide variety of forbs, willows, birch, alders, aquatic taxa, and *Sphagnum* play major roles in succession. Substrate also varies across the coastal plain. Areas that have sandy lake bottoms have very different successional processes than the marine clays and peaty substrates in the Barrow region.

Recent efforts by the oil industry to create wetland habitat in impounded gravel mine sites have applied a suite of rehabilitation techniques to (1) restore the sites as fish habitat, (2) create littoral zones for juvenile fish and shorebirds, (3) create wetlands for waterbird habitat, and (4) revegetate overburdened piles with native grasses and forbs for forage and nesting (Jorgenson et al. 1992b). Much of this work relies on detailed knowledge of life history and habitat characteristics of species involved in wetland succession (McKendrick 1990). More work is needed to document variations in successional schemes, not only of the vegetation, but also of other components, such as invertebrates, fish, and wildlife populations, which contribute to total wetland function.

3.3.5 Cumulative Impacts

Perhaps the most severe long-term effects in northern Alaska are the incremental disturbances to vast areas of undisturbed tundra and the tendency for development to focus on sites that also have high wildlife and vegetation diversity. For example, pingos are high points on the flat coastal plain that are often heavily disturbed because they are frequently used for survey bench marks. They deserve full protection from oil-field activities because they are unique landforms containing concentrations of wildlife habitat, rare soils, and forb meadows (Walker 1990). Severe cumulative impacts also commonly occur in biologically rich riparian areas.

Cumulative effects of North Slope oil fields have only recently been explicitly addressed (U. S. Department of Interior 1983; Meehan 1986; Shideler 1986; Walker et al. 1986, 1987b; Speer and Libenson 1988). Cumulative impacts differ from simple additive effects in five major ways: (1) the disturbances are so close in time that the system cannot recover (time-crowded perturbations); (2) the disturbances so are closely spaced that the effects are not fully dissipated between them (space-crowded perturbations); (3) combinations of disturbances produce effects that are different from those of any single disturbance (synergistic effects); (4) the effects are delayed in time or space from the original disturbance (indirect effects); and (5) large regions are affected by many seemingly insignificant perturbations (nibbling; Beanlands et al. 1986). Cumulative impacts go beyond ecology because socioeconomic, legal, jurisdictional, and policy issues are affected by and control ecosystem impacts (Cline et al. 1983; Lee and Gosselink 1988; Stakhiv 1988). Landscape and regional perspectives are needed to expand the area of concern beyond the immediate site of impact (Preston and Bedford 1988; Wyant and Knapp 1992).

On the North Slope, cumulative impact research has focused on enumerating and mapping the history of development in the region (Walker et al. 1986, 1987b), cumulative effects of development on shorebirds (Meehan 1986), caribou (Shideler 1986), and discharge of reserve-pit fluids into tundra wetlands (West and Snyder-Conn 1987). The problems relating to the development of large oil fields include direct and indirect impacts of water pollution, air pollution, hazardous and other wastes, wildlife impacts, restoration problems, regulatory problems, and lack of aggressive enforcement of existing environmental regulations (Speer and Libenson 1988).

Expanding networks of roads and pipelines (Fig. 3.3h) have many cumulative effects (e.g., Berger 1977; Pamplin 1979; Brown and Berg 1980; Johnson 1981). The Prudhoe Bay Oil Field, Kuparuk Oil Field, and several nearby smaller oil fields affect approximately 1000 km^2, and contain the most extensive road network in the North American Arctic. As of 1991 approximately 12 000 ha had been directly affected by gravel filling or gravel mines (Wyant and Knapp 1992). The physical disturbances related to roads include elimination of habitat beneath the roadbed, dustall, roadside trash, and deposition of plowed material and gravel on the adjacent tundra. In the Prudhoe Bay region, indirect impacts, such as flooding, road dust, and roadside thermokarst, affect an area equal to nearly 60% of the directly affected tundra, and in some parts of the region, exceed the area of planned impacts especially in flat sections of the coastal plain where impoundments are a major problem (Walker et al. 1986, 1987b). Many extreme examples of cumulative impacts to tundra systems have been described for the oil and gas fields in the northern Tyumen Oblast near the Ob River embayment in northwestern Siberia (Vilchek and Bykova 1992). There are currently no accepted scientific or regulatory means for evaluating or predicting cumulative impacts (Wyant and Knapp 1992).

3.4 Conclusions

Many of the scientific issues surrounding direct physical disruptions to tundra ecosystems have been addressed during the past 3 decades (Alexander and VanCleve 1983). The interconnectedness of physical and biological components of the ecosystem has been recognized along with the necessity of first stabilizing the physical system (permafrost and soils) before the biological components can stabilize. Even seemingly minor physical perturbations can alter surface hydrology and energy budgets, resulting in thermokarst or thermal erosion. Nearly all natural disturbances in the Arctic are either directly or indirectly driven by climate and mediated by hydrological processes. Snowpack, soil moisture, and runoff patterns control the vast majority of vegetation patterns, primary production, and the patterns of animals, yet the links between arctic vegetation, permafrost, energy, and water are still poorly understood. Because the physical and biological components are so closely linked in arctic systems, and because both components could be strongly affected by climate change, it is imperative that we develop the means to accurately model the linkages between the vegetation and the physical system.

The advent of environmental laws from the 1960s to the 1990s substantially changed the character of development on the North Slope, substantially reducing many of the impacts common in the early phase of oil exploration. On the other hand, some predictions in the 1970s by environmentalists may in the long-term prove correct. George West, in an early review of environmental problems associated with Arctic Alaskan oil development, wrote:

> Perhaps the greatest impact on arctic ecosystems is simply the increased intervention of the human population. Where native people were previously only sparsely settled or nomadic in the tundra, and on coasts where they tended to congregate, now the economic need for resources has resulted in increased pressure overall which will result in decreasing habitats for wildlife, destruction of wilderness areas, and increased access to humans for further exploration and recreation. (West 1976: 223)

While we have seen a heightening of environmental concern, the development of engineering and planning techniques to minimize small-scale direct impacts to the tundra, and the adoption of rehabilitation techniques to return disturbed tundra areas to their original condition, we have simultaneously seen a many-fold increase in the number of impacts and size of the areas affected. A focus on issues relating to cumulative impacts is needed. Part of this will require identifying and protecting areas of high biodiversity and important corridors of migration, as well as large areas representative of the diversity of arctic landscapes.

Much still needs to be done to fine-tune our knowledge of tundra ecosystem processes and to develop the means to rehabilitate tundra regions disturbed by energy development. Just as we cannot apply methods of revegetation developed in the Low Arctic to polar deserts of the High Arctic (Bliss and Peterson 1973; Bliss and Grulke 1988), we need to critically evaluate the variation that exists within Low Arctic tundra regions in order to develop workable strategies for revegetation and restoration. Revegetation of disturbed sites requires a fuller appreciation of the rates and dynamics of succession on a variety of substrates and climates. Perhaps the greatest need is a better understanding of how arctic landscapes function and how this function can best be maintained in the presence of large-scale development.

Basic research is also needed to understand the natural processes that have created existing arctic landscapes. Most anthropogenic perturbations have good natural analogues, although the scale of the analogues may be very different. Arctic landscapes at all scales are in states of natural succession (Churchill and Hanson 1958), and the North Slope is an excellent place to study these processes because large landscapes still exist that are virtually unaltered by human influence. These landscapes are extraordinarily valuable because they are some of the only easily accessible natural scientific laboratories in the world where natural disturbance processes still dominate.

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