6

Effects on the Physical Environment

Extraction of oil and gas from subsurface deposits involves deliberate alterations of the surface and subsurface physical environments, which in turn affect organisms living on the North Slope. This chapter focuses on the effects of industrial activities on the physical environment.

Most of the effects on organisms that are caused by changes in the physical environment are dealt with in chapters 7, 8, and 9, but some of those effects are mentioned here as well. For example, small areas of vegetation have been contaminated by spills of oil, other petroleum products, and saltwater, and road dust; vegetation has also been damaged by bulldozers, offroad vehicles, and ice roads; and destroyed where it underlies gravel pads and roads, or where it has been removed to make way for gravel mines (Forbes et al. 2001, Jorgenson and Joyce 1994, McKendrick 2000, Walker 1996). Alterations in vegetation can affect other organisms on the North Slope. Physical disturbances can affect fish migrations, the movements of caribou, and—in the marine environment—migration and distribution of animals, especially bowhead whales and fish. Oil-field activities can affect the number and distribution of predators, which can in turn affect the number and distribution of birds and some mammals.

PERMAFROST

The climate of Alaska's North Slope is much colder than that of other U.S. oil fields. As a consequence, the ground is permanently frozen to great depths (about 200-650 m, or 660-2,130 ft) (Lachenbruch et al. 1982a,b). In this permafrost zone natural processes are significantly different from those in unfrozen sediments, and this imposes a wide range of unique constraints on the development of industrial infrastructure and on the preservation of functioning ecosystems (Lachenbruch 2001).

A shallow surface layer, the active layer, thaws in summer to become an extensive wetland. Even though the climate is arid the meltwater cannot filter downward through the underlying impervious permafrost. The active layer contains and sustains the living tundra vegetation mat, which in turn sustains the region's diverse populations of land animals and influences landform processes like runoff, erosion, and soil flowage. Below the active layer, the permafrost generally contains a substantial fraction of ice. The integrity of the surface and any buildings, roads, or pipelines placed on it depends on the strength of that ice for support. Structures can topple or collapse if they upset the heat balance and thicken the active layer. Thus, changes in the thermal condition of the surface in permafrost terrain can have widespread effects that accumulate throughout the physical, biotic, and human systems.

Many of the physical effects of oil and gas development enumerated in Chapter 4 (from gravel roads, heated structures, offroad traffic, oil spills, gravel mining, oil wells, pipelines) can trigger environmentally significant changes in the physical behavior of the permafrost and the active layer. The ultimate environmental effects of such development cannot generally be anticipated without knowledge of the intermediate functioning of permafrost. For example, road dust can cause deep pools on the tundra surface by collecting solar radiation and thawing the underlying permafrost.

The general pattern of the committee's efforts has been to identify effects of the industrial activities described in Chapter 4 on the environment (described in Chapter 3). For permafrost, however, it is important also to consider reciprocal effects of the natural environment on development.

In fact, the most conspicuous physical effect on development could be the effect of permafrost on the industrial infrastructure itself. Structures must be designed to avoid thawing their own foundations. Dealing with this condition establishes the engineering configuration, or architecture, of North Slope oil development, which consists of a conspicuous network of 954 km (596 mi) of roadways elevated on thick gravel berms, and 725 km (450 mi) of pipeline clusters elevated on pilings (Table 4-2). They join more than 2,354 ha (5,817 acres) of thick gravel work pads above which are large heated buildings elevated on pilings, and, more recently, closely spaced oil wells that are cooled by extensive refrigeration equipment to preserve the superficial permafrost remnant that supports them. Some effects of this unique assemblage of thick gravel and associated permafrost-resistant infrastructure are discussed in chapters 7 (plants), 8 (animals), and 9 (people).

To understand the importance of permafrost in the evolution of the oil and gas infrastructure and the effects of physical development on the North Slope environment, it is useful to examine the controlling thermal processes. In this section we discuss natural and artificial processes relevant to oil and gas development. Most are mentioned again in later chapters in connection with specific effects.

Active Layer

The active layer that thaws each summer lies between the top of permafrost and the ground surface. It controls the influence of permafrost on surface processes and the influence of human activity on permafrost. The permanently frozen base of the active layer is impermeable to water and impenetrable to roots. Consequently, the active layer is the growth medium for surface plant communities; the reservoir for their water and nutrient supply; the locus of most terrestrial hydrologic activity; and a boundary layer through which heat, moisture, and gases are transferred between permafrost and atmosphere. The active layer protects the permafrost from summer warmth. Its thickness is a measure of the ground's ability to transmit heat. The active layer varies from as little as 20 cm (8 in.) in some areas of peat or poorly drained sphagnum moss to more than 2 m (80 in.) at some well-drained inland gravel sites. The thickness varies with the active layer's properties as well as with the locally variable thermal properties of the permafrost it protects (Lachenbruch 1959).

Disturbance to the surface, whether anthropogenic or natural, can affect the thickness and mechanical nature of the active layer and ultimately the composition of its plant communities. Such disturbances might include disruption of peat and living vegetation, changes in radiation properties, or alterations in the abundance of water. Disturbances can be initiated by off-road vehicular traffic, removal of vegetation, addition of gravel, paving, oil spills, and saltwater spills, deposition of airborne dust, or the modification of surface drainage (Chapter 7).

Ice-Wedge Polygons and Thermokarst

Typically, permafrost is cemented by ice that, in the upper few meters at least, occupies more space than the water-filled pores that would remain after thawing. Melting of such ice-rich or thaw-unstable permafrost results in thaw settlement and disruption of the surface and whatever is on it. The ice in permafrost, or ground ice, can be mainly in the pore space or it can be in large segregated masses. Ice content varies greatly from one North Slope location to another and so consequently does the potential for thaw settlement. Ice content increases sharply from Prudhoe Bay to Alpine on the Colville delta (Hazen 1999) and between many locations on the Arctic Coastal Plain and in the Brooks Range foothills.

The most troublesome disturbances are those for which a thickening of the active layer is not self-arresting; that is the thawed increment from permafrost flows off as a slurry rather than remaining in place to augment the active layer's insulation. This unstable process, called thermokarst, can lead to deepening pits and trenches, retreating scarps, and mud flows (Lawson 1982). It occurs commonly on the North Slope where the active layer is disturbed over ice-wedge polygons—widespread patterns of troughs shaped like giant mud cracks omnipresent on the coastal plain and much of the foothills (Figure 6-1). Below each trough is a wedge of almost pure ice a meter (3.3 ft) or more wide and several meters deep (Figures 6-2 and 6-3). The wedges form over centuries in recurring contraction cracks, opening during the winter and filling with ice each spring by downward percolation and refreezing of melted snow (Lachenbruch 1962). A roadway, heated building, or pipeline that thaws the underlying permafrost will soon be unsupported in a free span across the melting ice wedges. This thermokarst condition is illustrated by early roads on the North Slope that consisted of gravel laid 1 m (3.3 ft) thick on the tundra (Figure 6-4). Because the natural active layer in North Slope gravels is about 2 m (6.5 ft), the roads soon became impassable, even to foot travel. Compression by the gravel destroyed the insulating capacity of the organic mat, and the too-thin gravel disappeared into a network of deepening trenches left by thawing ice wedges (Ferrians et al. 1969, Lachenbruch 1966).

Heated Buildings

On the North Slope the typical result of a heated building constructed on the ground surface is a surface patch the shape of the foundation maintained at a temperature 25 °C (45 °F) or so above the ambient mean temperature of approximately -10 °C (14 °F). The shape of the thawed basin that grows in the permafrost under a building depends on these two temperatures, the width of the building, and its age, and it is easily estimated (Lachenbruch 1957b). Substantial thawing can develop quickly, leading to destructive thaw settlement, a fact well known to Alaskan cabin dwellers. This process leads to a conspicuous constraint on North Slope development—heated structures, even very large ones, generally must be elevated above the surface to let the cool air circulate below. The load that can be carried by their pilings depends on the temperature of the enclosing permafrost. If necessary, building design could be revised to accommodate a warming climate by refrigeration with thermo-siphons (e.g., Kinney et al. 1983) like those used to maintain the mechanical integrity of closely spaced oil wells. Where heated

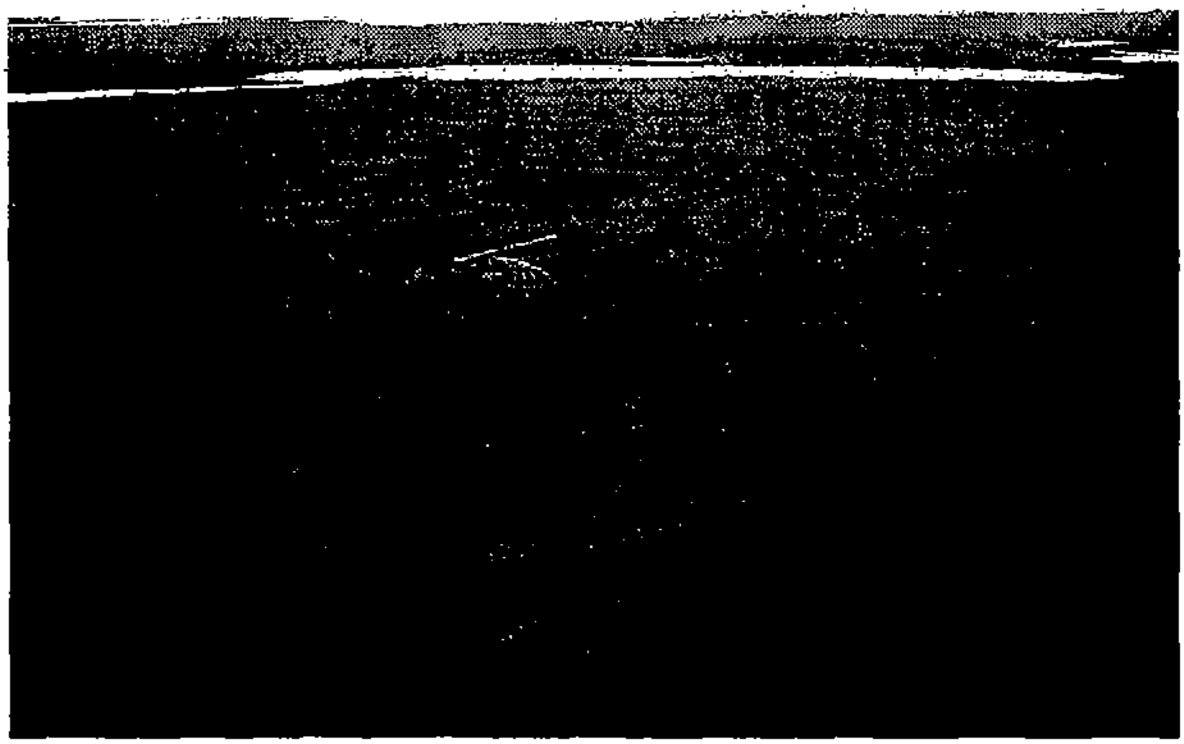


FIGURE 6-1. Ice-wedge polygons on the Arctic Coastal Plain; troughs are underlain by ice wedges. Peripheral ridges represent material displaced from permafrost by ice-wedge growth. Photo taken by George Gryc.

FIGURE 6-2. Intersection of three small ice-wedges exposed in an undercut bank of Elson Lagoon, near Barrow. Photo taken by Gordon Greene.

FIGURE 6-3. Upper portion of an ice-wedge exposed in a riverbank on the Colville Delta near Nuiqsut, Arctic coastal plain. Photo taken by H. J. Walker.

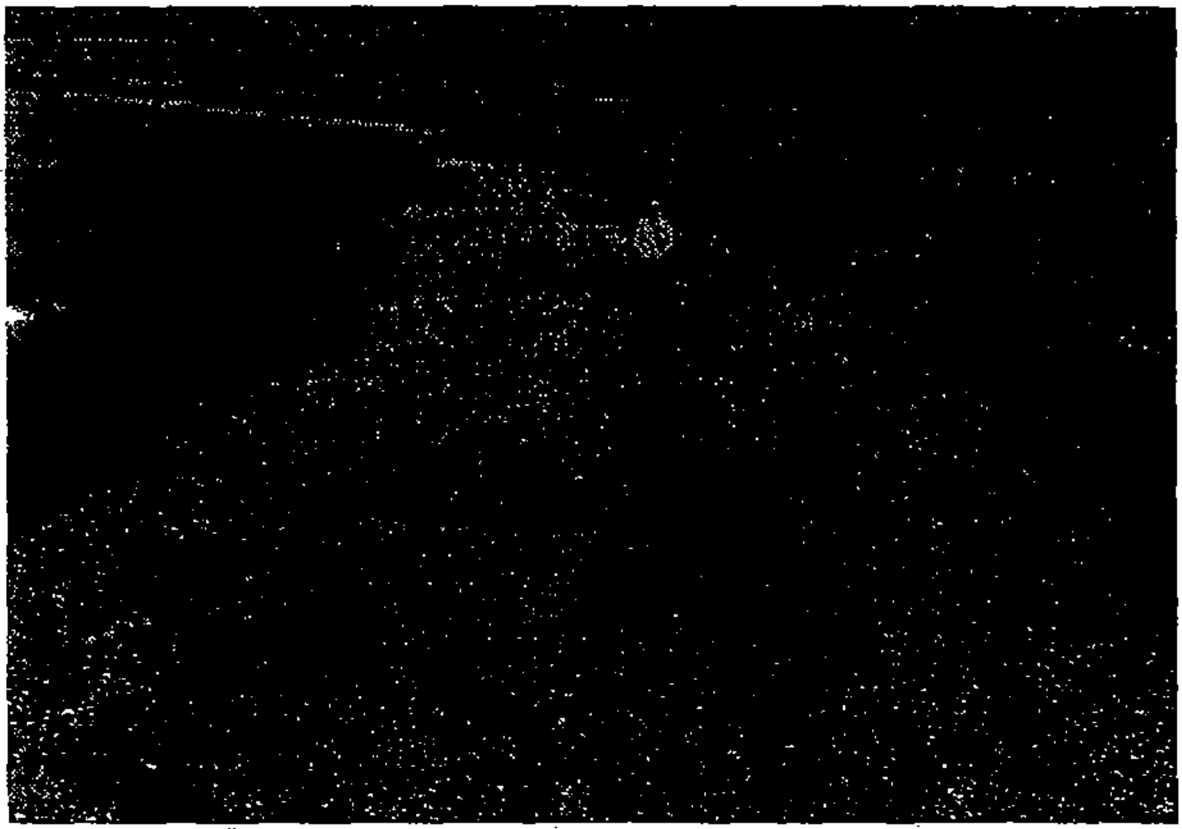


FIGURE 6-4. Roadway destroyed by thawing ice-wedges near Umiat. Gravel fill was not thick enough to replace insulating effect of the organic mat, which it destroyed. Photo taken by Gordon Greene.

buildings must be placed on the surface it is generally necessary to insulate and refrigerate their foundations; insulation alone only delays thawing. Although heated buildings generally are not built on grade, local warm surface patches from snow drifting against structures, or the above-freezing temperatures of well houses can be significant. If those disturbances are superimposed on others they must be considered in thermal design to avoid destructive thermokarst (see the section on "Well Pads" below).

Modified Lakes and Gravel Mines

Winters on the North Slope are cold enough to freeze lakes to a depth of about 1.8 m (6 ft). Most lakes and ponds on the North Slope are shallower than that, so they freeze solid to the bottom, and are part of the active layer. However, lakes that are deeper cross an environmental threshold—the bottom remains unfrozen, and a permanently thawed basin, or talik, grows downward into the permafrost under the lake bed. An inverted dimple of unfrozen ground grows upward from below the base of permafrost. If the lake area is large with respect to the natural depth of permafrost, and if the lake is old enough (thousands of years), the basin and dimple can join to form a thawed hourglass shape through the permafrost. Typically, the mean lake-bottom temperature is 1-2 °C (34-36 °F), or about 10 °C (18 °F) warmer than its surroundings (Brewer 1958b). In this sense deep lakes behave like heated buildings, and the same predictive theory for the thawed basin applies. When the lake is drained, refreezing of the sediments in the thawed basin beneath it often creates a pingo, a mound formed by ice expansion like the bump formed in the middle of an ice cube as it freezes.

If a shallow lake is deepened for a winter water supply, as is done occasionally, for example at Kuparuk, it will generally continue to deepen on its own from thaw settlement as its thawed basin grows. Once the lake no longer freezes to the bottom it works differently in the ecosystem. Gravel mines that become deep lakes behave similarly.

Gravel Roads

To prevent thermokarst, the gravel placed under roads must be thicker than its depth of summer thaw to ensure that the subgrade remains frozen as the road crosses a variety of thaw-unstable permafrost materials (Lachenbruch 1959). On the Arctic Coastal Plain this requires that roads be placed on gravel berms up to 2 m (6.5 ft) above the tundra surface. Like the elevated pipelines, this network of elevated roads has a conspicuous visual impact on the landscape. Additionally, the continuous berms intercept natural drainage, creating ponds that collect solar radiation, thicken the active layer, and initiate thermokarst (Walker 1996). Road dust also can perturb the thermal balance of the active layer and underlying permafrost. The effects of these processes on vegetation are described in Chapter 7.

Pipeline Burial

Permafrost poses severe obstacles to pipeline burial, the preferred mode of construction in nonpolar environments. The principal difficulty is that subsurface heat from the transmission of warm fluids thaws the surrounding permafrost, causing differential settlement, which strains the pipe. This consequence of permafrost leads to one of the most conspicuous impacts of oil and gas development on the North Slope—a network of elevated pipelines. They can impede free overland travel by subsistence hunters (newer ones are higher to permit passage) and they constitute an imposing visual alteration of the landscape (see Chapters 8 and 9).

The Northstar pipeline is buried in the seabed in a shallow trench that extends to an artificial island 10 km (6.2 mi) offshore. The pipeline has a planned operating temperature of 29 °C (85 °F); warm oil started to flow through it late in 2001. Special problems are posed by its burial in ice-bearing permafrost in the seabed within 3 km (1.9 mi) of shore (Intec Engineering 1998)—heat from the oil will eventually thaw the permafrost and strain the pipe. Although it has been carefully designed, such an offshore-buried pipeline is without precedent in the Alaskan Arctic; its performance will be instructive.

Well Pads and Annular Thawing

The layer of gravel used for roads is also generally adequate to protect large work pads from seasonal thaw settlement. However, different thermal designs may be necessary if there are additional sources of heat, such as the heated foundations of well houses, snow drifts that insulate pads from winter cold, or subsurface sources like heat in a "thawed chimney"—the annular region thawed through permafrost around a warm production well (see "Effects of Fluid Withdrawal").

The chimneys have become much more critical with the recent emphasis on decreasing the footprint using directional drilling from closely spaced wells on small well pads. In the process of drilling a well or extracting oil, natural gas, or formation waters, fluid circulating through a borehole transfers heat advectively from warm formations at depth to the colder ones near the surface. The drilling targets are generally at depths where the formation temperatures are 40-90 °C (104-194 °F). Heat from the warm fluid is conducted radially through the borehole wall (the well casing), quickly thawing annular zones, or chimneys in the surrounding permafrost (Lachenbruch et al. 1982a). The radius of the chimney is calculated by using properties of the permafrost and borehole specifications. For typical Prudhoe Bay production wells, Perkins and colleagues (1975) estimated a thawed chimney radius of about 2-6 m (6-20 ft) after a year or two and about 6-11 m (20-35 ft) after a decade of production. The smaller values apply near the surface where the permafrost is colder.

During the early Prudhoe Bay development, wells were drilled about 50 m (160 ft) apart (BP 1998a). Even after decades of production, thawed chimneys were relatively unconnected to one another, and most of the permafrost remained intact and able to resist damaging settlement (sometimes aided by insulating the well casings). In the current design, which is used for pads at the Alpine oil fields, wells at 43 °C (109 °F) are spaced only 3 m (10 ft) apart (Hazen 1999). Accommodating such a concentration of heat in permafrost requires sophisticated design with extensive refrigeration by passive heat pipes (or thermo-siphons) and insulation. Hazen (1999) calculated that, without refrigeration the thaw chimneys would coalesce at all depths, and all of the permafrost—about 300 m (1,000 ft) thick—under the row of wells would thaw. Then, the natural surface, gravel pad, and well houses would settle nonuniformly from 2 to 6 m (6.5-20 ft). With refrigeration to a depth of 15 m (50 ft) and insulated conductor pipe to 24 m (80 ft), Hazen (1999) estimated that all of the permafrost except for the top 12 m (40 ft) will thaw. That layer will remain intact to form a supporting arch that will deform slowly and smoothly, with only 30-60 cm (12-24 in.) of thaw settlement at the surface.

SUBSURFACE ENVIRONMENT: POSSIBLE EFFECTS OF THE WITHDRAWAL AND INJECTION OF FLUIDS AND OTHER MATERIALS

The subsurface physical environment in an oil field consists of the layers of sediment and rock and the fluids that naturally fill their fractures and pore space. Potential effects in this environment generally relate to its possible invasion by gas or oil along unintended flow paths through failed oil well casing and cement seals or through artificially fractured rock. Hydrocarbons—gas and oil—degrade two principle receptors: tundra surface habitats and subsurface water sources. On the North Slope oil fields the consequences are complicated considerably by the presence of permafrost and to some extent by waste-disposal practices. Problems related to the thawing of permafrost are mainly controlled by fluid withdrawal, the subject of the next section. However, in the North Slope oil fields fluids are injected into the wells in volumes comparable to those that are withdrawn; they too can have environmental consequences for the tundra surface and for subsurface water sources. Injection serves two purposes: It enhances production by restoring lost pressure in a waning reservoir, and it is used to dispose of drilling mud and other wastes by placing them in previously undisturbed porous rock strata. The first procedure has a long history of worldwide use; the second is relatively new and used most intensively on the North Slope. The first requires neither new flow paths nor injection pressures above natural ambient values—the second requires both. They are treated separately below.

Fluid Withdrawal and Its Effects

The fluids produced by a well are oil, gas, and formation water. In a typical reservoir, the shallowest portion can be filled with gas resting on oil that, in turn, rests on saline-to-brackish, rarely fresh, formation waters. As oil or gas is extracted, formation water moves up into the portion of the reservoir previously filled with oil and gas.

Those fluids are at temperatures and pressures that are largely controlled by the natural thermal gradient, the pressure gradient, and the depth of burial. The North Slope reservoirs are "normally pressured"; the rate of pressure increase and the pressure at any given depth are close to the hydrostatic gradient—0.427 kg/cm^2 per m (0.445 psi/ft). The initial reservoir pressure at Prudhoe Bay was 309 kg/cm^2 (4,390 psi) at 2,682 m (8,800 ft). In the shallower Kuparuk River field, the original reservoir pressure was 229 kg/cm^2 (3,250 psi) at 1,890 m (6,200 ft). The pressure gradients were 0.48 kg/cm^2/m (0.50 psi/ft) and 0.50 kg/cm^2/m (0.52 psi/ft), respectively, at Prudhoe and Kuparuk.

The thermal gradient determines the temperature of the fluids in the reservoir. It affects their viscosity, corrosiveness, and tendency to melt permafrost. The thermal gradient in the Prudhoe Bay Area is variable—its average is about 5.6 °C per 100 m (30.7 °F per 1,000 ft). The original temperature of the oil at the Prudhoe Bay Field was 97 °C (207 °F) at 2,682 m (8,800 ft); the temperature of the Kuparuk oil was 71 °C (160 °F) at 1,890 m (6,200 ft) (AOGCC 1998).

The withdrawal of subterranean fluids from oil fields in the Arctic causes thawing of the permafrost in the neighborhood of the wells. Ground that had been frozen solid loses its rigidity. This results in potential environmental and structural disruption.

Thawed chimneys create three potential problems that are specific to oil production in permafrost:

- *Annular path to the surface.* The thawed chimney is more permeable to infiltration by fluids than the same area is before disturbance. To the extent that permafrost might be expected to form a barrier to uncontrolled borehole fluids, the relatively permeable thawed chimney provides a possible path outside the casing for broaching to the tundra surface (ARCO/BP/Exxon 1997). Such a fluid path to the surface could affect natural plant communities, although no such effects have been observed.
- *Stress on the well casing.* The formation of the thawed chimney leads to two sources of stress on the well casing (Wooley & Associates 1996). The first is caused by thaw settlement when the annular region loses strength and settles against the casing adding axial (i.e., vertical) drag forces and radial pressures to the pipe. The second is caused by increased radial pressure as ice reforms during freezeback of the chimney after drilling or production ceases.

Alterations in casing design and cementing procedures seem to have solved problems of casing failure caused by external forces in the permafrost chimney (BP 2000, Perkins et al. 1975). A fluid with a freezing point below ambient temperature is commonly used inside the casing to prevent the internal forces caused by refreezing.

- *Surface subsidence.* When permafrost thaws, its volume decreases, leading to subsidence of the overlying ground and damage to structures on it. Producing oil wells on the North Slope thaw a chimney through the entire 300-600 m (1,000-2,000 ft) permafrost column beneath the pad that supports those structures. Understanding and controlling the surface effects are important. If the chimney were only a pinhole through permafrost, the surface material would not sink far into it before it would be supported by shearing stresses from the chimney walls. But if a chimney were wider than its height (thickness of permafrost) the walls could not support the slumping mass, and surface subsidence would be extreme.

In the older development areas where wells were drilled 36.5 m (120 ft) apart (BP 1998a), thawed chimneys did not coalesce and most of the permafrost remained intact and able to resist damaging settlement, especially if casings were insulated. However, wells are now being drilled so close together that, without additional mitigating measures, their thawed chimneys would coalesce to cause destructive differential settlement of the pads (see "Well Pads").

Injection for Enhanced Recovery

Fluids are injected into the subsurface for two purposes. The first is to increase the production of oil. The second is to facilitate more environmentally sound disposal of wastes produced during exploration and development. Several kinds of wells are used to inject fluids either for enhanced recovery or for disposal of wastes. Those wells must meet specific design requirements to isolate the injected fluids from the surface and to place them in specific horizons (Wondzell 2000).

The return of some produced fluids and the introduction of others to the producing formations is designed to improve the recovery of oil from the reservoir, either through maintaining pressure or through increasing the fluidity of the oil. To achieve this, produced fluids, such as formation water and gas, can be re-injected into the original oil-producing reservoirs. Other fluids, such as treated seawater and natural gas or CO_2 from other sources, also can be introduced to the reservoir.

Enhanced recovery requires that the fluid be beneficial for increasing the ultimate recovery of oil, that it be injected at pressures that will not propagate fractures through the confining zones that protect fresh waters, and that it be chemically compatible (for example, not to cause precipitation) with the formation water.

Formation water and treated seawater are used principally to maintain pressure. The water is placed in the reservoir by a series of injection wells to "push" the oil toward the producing wells. Natural gas and miscible injectants also are used to maintain pressure, but they have the added ability to increase the fluidity (decrease the viscosity) of the oil and strip it from sand grains (DOE 1999). The fluids generally are injected at depths below the oil-water contact surface to allow them to sweep through the entire oil column with maximum effect on any remaining mobile oil.

Potential environmental consequences would be the risk of escape of fluids to the surface either through fracturing of the overlying stratigraphic section (a highly improbable event) and the permafrost or around the casing through failure of the cement job or the casing itself. This could result in a spill on the tundra.

Injection for Waste Disposal

Environmentally sound disposal of oil-field wastes has long been a problem. A relatively recent innovation, the down-hole injection of fluid wastes and slurries, has been used for the disposal of large volumes of waste on the North Slope. These drilling by-products and other wastes are now injected into otherwise undisturbed, confined geological formations. Down-hole injection eliminated the use of reserve pits for surface storage of drilling waste (Gilders and Cronin 2000), and although it is superior in most respects to older methods, it is not without potential environmental effects.

Class I and II Wastes

Because of the presence of gas and oil, other volatile organic compounds, and metals, Class II (exempt) wastes present a considerably higher risk to the environment than do Class I (nonhazardous wastes), should there be a spill on the surface (API 1987, BP 1992). Such an event might result from a failure in the cement of the well, a pipe collapse, or through a nearby, poorly plugged or monitored, abandoned, or shut-in well. The actual down-hole effects of these fluids are unimportant if they are not injected into an underground source of drinking water (USDW).

Grind and Inject

The grind-and-inject process is used for Class II waste disposal of substances associated with reserve pits and drilling mud and cuttings from drilling wells. The process involves mining materials from the reserve pits, transporting them to a central grinding facility, grinding the solids finely enough to facilitate injection, and injecting them as a slurry into disposal zones (BP and ARCO 1993). The reserve pit solids contain a wide range of metals and some hydrocarbons, some of which present a potential hazard. (See Appendix D.)

Drilling mud and cuttings from active drilling wells also are ground and injected. More than 42 million barrels (bbl, 7 trillion L, 1.8 trillion gal) have been disposed of this way. This method of waste handling has greatly reduced the possibility of environmental damage caused by reserve pit materials. The hazards associated with subsurface injection of these materials are discussed below.

Annular Injection

Annular disposal is the process of pumping drilling mud and cuttings from drilling operations down the annulus formed when another casing is cemented inside the surface casing. Annular disposal requires porous intervals below the confining zone at the bottom of the surface casing and above the probable top-of-cement depth of the production casing. Only the drilling muds and cutting materials from the drilling operations compatible with disposal horizons can be injected. The ground and slurried materials are combined with water, if necessary, and pumped down the annulus and injected out of the bottom into the disposal formation. The result is a controlled fracturing of the disposal formation that creates more storage space and pushes the particulate material out into the porous formation. The water tends to separate from the cuttings and penetrates more deeply into the unit.

Alaska Oil and Gas Conservation Commission regulations limit the disposal volume to 35,000 bbl (5.7 million L, 1.5 million gal) per well to encourage the construction and use of disposal wells on drill pads and to reduce the possibility of the disposal stream eroding the production casing in the wellhead (Wondzell 2000). The amount is equivalent to the production of disposable materials from three wells.

At least 158 wells have been used for annular disposal of drilling muds and cuttings. A total of 3 million bbl (477 million L, 126 million gal) has been injected as depths of 820-1,340 m (2,690–4,400 ft). The potential hazards are discussed below.

Possible Effects of Injection for Waste Disposal

Pressure Fracturing and Broaches to the Surface

A potential concern is that the pressure required to inject wastes into a selected horizon might be enough to fracture the confining overburden stratum and allow waste to escape toward the surface. In the enhanced-recovery process this does not seem to be a serious problem because the injection augments the falling reservoir pressure and it takes place at pressures below the original ambient reservoir value. By contrast, waste injection is done in previously undisturbed subsurface environments and it requires pressures above ambient values. Where the waste includes ground rock cuttings, the target reservoir must be fractured to receive the slurry. This requires injection pressures that exceed the ambient by the fracture strength of reservoir rock, and poses a substantially greater potential for fracture of the confining overburden than is the case for enhanced recovery. Risk to confinement is much greater if the pressure fracture is vertical (not horizontal), an outcome predictable from a knowledge of the formation's stress state (Abou-Sayed et al. 1989).

Pressure profiles for several Prudhoe Bay wells confirm that the porous disposal formations now have pressures of 7-18 kg/cm^2 (100-250 psi) above the original hydrostatic

Ground Water Degradation by Waste Injection

In recent years, drilling wastes, which previously were stored in environmentally undesirable surface pits, have been injected into subsurface aquifers for permanent disposal. Although much of the water in aquifers below the impermeable permafrost is too saline to meet standards for a legally protected USDW, some is not. Because the sub-permafrost hydrologic system is poorly understood and incompletely sampled, the possibility of contaminating a potential water resource by waste injection should be considered.

The North Slope of Alaska is largely classified as wetlands underlain by permafrost, which separates the surface-water system—active layer, lakes, streams—from the relatively isolated and little understood groundwater system of sub-permafrost formations (Sloan 1987, Williams 1970). Although water appears plentiful on the surface, the North Slope has an arid climate, and if a significant supply of fresh water exists in deep aquifers it could be a valuable resource.

Extensive federal and state regulations are designed to identify potential USDWs and exclude them from waste-disposal programs. The federal Safe Drinking Water Act defines USDW as groundwater that contains less than 10,000 ppm (parts per million) total dissolved solids (TDS). Disposal in USDW is allowed only under special conditions (e.g., CFR144.3). The act essentially prohibits disposal in water with less than 3,000 ppm TDS (e.g., 40 CFR 146.4, 20 Aac 25.080(e)(1)). In aquifers where TDS exceeds 10,000 ppm there is no conflict regarding waste disposal. The TDS values needed to apply these regulations are generally inferred from well logs and are poorly known in detail. Relatively few direct chemical analyses are available from the North Slope.

Much but not all of the sub-permafrost groundwater in production areas is known to have salinities in excess of the 10,000 ppm limit. A map (Fink 1983) of West Sak Sandstone sub-permafrost water salinities shows that they range from > 50,000 ppm TDS in the northeast corner of the Prudhoe Bay unit to < 5,000 ppm TDS in the southwest corner of the Kuparuk River unit. Although those concentrations are generally based on estimates from down-hole resistivity logs, the low values in the Kuparuk River unit were confirmed by extensive chemical sampling showing TDS generally < 3,000 ppm (Fink 1983). Similar low values have been reported from widespread sub-permafrost chemical sampling elsewhere on the North Slope (Collet et al. 1988, Table II-9). Such results suggest that it might not be uncommon for sub-permafrost groundwater to meet the regulatory definition of USDW, but the extent is unknown and data on known occurrences have not been systematically compiled and published (see Chapter 10).

Findings

- Enhanced recovery procedures have not damaged the reservoir or other subsurface formations because of relatively low injection pressures and compatible chemistry.
- Production of fluids has not caused significant local or regional subsidence but the thermal effects of warm fluids promote thawing of the permafrost (creating thaw bulbs and chimneys) and could provide potential pathways for the escape of fluids to the surface around boreholes.
- There have been approximately 20 instances of broaching to the surface, primarily resulting from poor cement packages that cause leaks and from wellhead leaks. Engineering solutions have been effective to date.

- Groundwater resources—and the effects of waste injection on them—are inadequately examined and considered. Injection of drilling wastes into porous horizons has eliminated the problem of surface waste storage but has raised problems of possible groundwater contamination.

Recommendation

It should be confirmed that existing subsurface waste disposal practices are not depleting a groundwater resource intended for legal protection. Rigorously measured total dissolved solids profiles should be routinely acquired, compiled, and used to identify patterns of freshwater distribution as a tool for planning and for evaluation and conservation of the groundwater if appropriate.

ESCAPE OF INJECTED WASTE FLUIDS IN THE MARINE ENVIRONMENT

One concern regarding the effects of industrial activities on the marine environment is that injected waste fluids might travel laterally through a disposal zone to intersect the ocean floor. This is highly unlikely, however, because neither the producing reservoirs nor the disposal intervals intersect the ocean floor. Those units are buried hundreds to thousands of meters under younger rock and sediment. If such an occurrence were possible, one would expect numerous active large oil and gas seeps offshore from the major oil fields. They do not exist because the injection horizons are often as deeply buried as a number of the producing intervals, or as at Alpine, Kuparuk, and several of the satellite fields, the injection zones are deeper than production ones.

Surface Ballooning

Surface ballooning, or rebound, is a phenomenon that can be caused by injection of fluids. The possibility of this occurring on the North Slope has generated some concern. Surface rebound is known to have occurred in areas where a reservoir is relatively shallow compared with its lateral extent, there is a significant reduction in reservoir pressure, and the reservoir is relatively unconsolidated. Studies of the Cretaceous disposal intervals on the North Slope indicate that surface rebound is insignificant.

AIR QUALITY

Air quality on the North Slope has been affected by industrial activities there and elsewhere. The most important potential accumulation of effects is likely to be a reduction in visibility and an increase in direct human exposures to pollutants caused by synergistic interactions between locally generated and globally transported contaminants. Ecological degradation also could result from deposition of dust and pollutants on terrestrial and aquatic ecosystems.

Air quality on the North Slope meets state and national standards. Ambient concentrations of measured pollutants are often near detection limits at monitoring stations.

However, although local air quality does not appear to have been seriously degraded by emissions from oil and gas production facilities (AOGA 2001), emissions from local facilities result in observable haze, increased atmospheric turbidity, and decreased visibility (AOGA 2001).

The most conspicuous air quality problems on the North Slope are the widespread arctic haze, which occurs at higher elevations, and locally produced smog. Research confirms that arctic haze is a common phenomenon in polar climates and that it is the result of distant rather than local emissions. Fugitive emissions from industrialized areas in the temperate zone are transported long distances. There has been no research to determine how local and regional air masses and their contained contaminants interact. The lack of pre-development baseline data further hampers assessment of the effects of local or distant pollution on North Slope air quality.

If additional fields are developed, air emissions will increase. If more energy is required to maintain production in declining fields as waterflood or gas-lift injection are used to enhance oil recovery, air emissions could increase as well.

Findings

- The only areawide monitoring program on the North Slope has been for priority pollutants as defined by the Clean Water Act, from 1986 through 2002, at a limited number of sites. No large-scale, long-term monitoring system has been established to provide a quantitative baseline of spatial or temporal trends in air quality on the North Slope. The lack of adequate information limits the accuracy and precision of assessments of both past and future accumulation of effects.
- The quantity of air contaminants reaching the North Slope from distant sources is unknown.
- Little is known about the nature or extent of interactions between locally produced and globally transported air contaminants on the North Slope.

Recommendation

Research and monitoring should be implemented to distinguish between locally derived emissions and those that arrive by long-range transport, to determine how they interact, and to monitor potential human exposure to air contaminants.

FRESHWATER ENVIRONMENT

Industrial activities on the North Slope have to some degree affected the chemistry, flow patterns, and drainage patterns of the area's fresh waters. Effects could accumulate as a result of withdrawal or redistribution of water for construction of ice roads and pads, gravel mining in rivers, and blockage of drainage caused by gravel roads. Deposition of air contaminants also could alter water chemistry. Industrial activities to date have been concentrated in areas where lakes are common and there are abundant supplies of gravel. Those conditions do not characterize the foothills of the Brooks Range, many parts of the National Petroleum Reserve-

Alaska, or the Arctic National Wildlife Refuge. Therefore, the effects of future development on fresh waters in those regions could differ from those of the past.

Water Chemistry

During summer, inland lakes tend to have low concentrations of dissolved ions, but lakes near the coast that receive nearshore brackish waters have elevated concentrations of dissolved ions. As the ice grows in winter, electrolytes are excluded from the ice matrix and ion concentrations increase. By late winter or early spring, at maximum ice thickness, ion concentrations in unfrozen water can be more than four times greater than those observed during summer. Evidence suggests that no significant changes in seasonal patterns or concentrations of chemicals in lakes and streams have resulted from industrial activities on the North Slope.

Flow Patterns

Much of the gravel used for construction of roads and pads has been obtained from deposits within the floodplains of rivers. Concerns arising from this practice prompted the U.S. Fish and Wildlife Service to study the effects of floodplain gravel mining on physical and biological processes (Woodward-Clyde Consultants 1980). The study identified numerous examples of habitat modifications, including increased braiding and spreading of flows. The study also set forth guidelines on how to mine gravel to reduce floodplain effects (Joyce et al. 1980). As a result, gravel mining largely has been restricted to deep mining in upland pits, some of which are flooded on abandonment to create aquatic habitat.

Drainage Patterns

Much of the gravel used for roads and pads has been deposited in wetlands. During spring break-up there are substantial sheet-flows across the wetlands of the Arctic Coastal Plain into lakes and streams. When long stretches of gravel road interrupt flows, the difference in water surface elevation from one side of the road to the other can produce high flow rates in the cross-road drainage structures. An opposite effect can occur in mid-to late summer when stream flow is low.

Findings

- Gravel mining in rivers during the early years of development substantially altered flow patterns and distribution of unfrozen water in winter, but recent restriction of gravel mining to upland pits has reduced those effects.
- Gravel roads and pads have often interrupted both sheet flow and stream flows. Proper construction and placement of culverts can greatly reduce but not eliminate those effects.
- Development in areas where surface water is less abundant could result in effects on fresh water that differ from those in the freshwater-rich Prudhoe Bay region.

MARINE ENVIRONMENT

Offshore activity in the Beaufort Sea has been limited. Activities that affect the quality of marine waters and flow patterns have included construction of gravel islands and causeways and discharges of materials. Only a few small spills have occurred in marine waters to date, but mechanical recovery—the method allowed by current regulations—is not efficient and only removes a small fraction of the spilled oil, especially in broken ice. Concerns about contamination of marine waters center primarily on the potential effects on marine organisms. Those effects are discussed in Chapter 8.

There have been three permitted types of discharges to the Beaufort Sea over the life of the oil fields. First, individual facilities have discharges permitted under U.S. Environmental Protection Agency (EPA) NPDES (National Pollution Discharge Elimination System) program. Second, small or localized discharges have been permitted under the North Slope General NPDES Permit (under EPA). Third, exploratory drilling discharges were permitted under the Arctic General (or Beaufort General) NPDES Permit under either coastal effluent guidelines or offshore effluent guidelines (Wilson 2001b).

Permitted NPDES discharges include effluents from seawater-treatment plants, desalination plants, sanitary-waste-processing units, deck drainage sumps (from offshore production facilities, such as Northstar), temporary construction dewatering, and occasional tests of fire suppression with water. These discharges are permitted for a specific facility, and there are monitoring and reporting requirements. Four facilities currently have NPDES permits: Northstar, the Prudhoe Bay seawater treatment plant (STP), Kuparuk STP, and Endicott. The largest discharges under this program are ocean water and peat detritus from the two STP operations (Wilson 2001b).

A North Slope General Permit was issued by EPA for small operations other than those covered under individual NPDES permits. Permitted discharges include small volumes of water pumped from gravel mine sites and wastes from temporary camps. Industry must apply to EPA for coverage under the general permit. Discharges are small, localized, and infrequent.

Exploratory drilling discharges are covered under the EPA Beaufort Sea General Permit and include disposal of drill cuttings and fluids from well-drilling operations. Which effluent guidelines are in effect depends on whether the well is drilled near to the shore or off shore. The coastal effluent guidelines in effect since the mid-1990s prohibit discharge of muds and cuttings. Offshore guidelines still allow discharges of muds and cuttings.

Monitoring is frequently required as a condition of discharge permits to ensure that discharges do not exceed water quality standards, are not toxic to marine organisms, do not degrade water quality, and do not pose a threat to human health. Most of the records of the monitoring programs are retained by EPA, the principal permitting agency, and are not readily available. Records also are kept by individual operators, but those records are not summarized, and few annual reports have been produced.

NPDES Monitoring

Until recently, NPDES stipulations have called for environmental monitoring for all operations covered by the permits. The studies have included monitoring the waste stream as well as the receiving water. Topics include effluent mixing and dispersion, and the effects of effluents on fish, benthic organisms, sediments, and water quality. Permits generally required that water, sediment, or biological samples be obtained seasonally from within and outside of the outfall mixing zone. Required monitoring of fish and benthic communities has been discontinued in recent years because effects were found to be minor or not measurable (Wilson 2001a).

Water-quality monitoring has included measurement of several variables in the receiving water, including currents, salinity, temperature, pH, dissolved oxygen, total suspended solids, total residual chlorine, and chlorine reaction products. Sediment studies have measured grain size distribution, total volatile solids, and concentrations of organohalide compounds. Biological monitoring has included collection of fish and benthic organisms and toxicity studies that use commercially available test organisms (Robilliard et al. 1988, Wilson 2001b).

Results of monitoring water quality, sediments, and species for the Kuparuk STP outfall were summarized by Montgomery Watson (1994). The results of winter and summer measurements of temperature, salinity, dissolved oxygen, pH, total suspended solids, and total residual chlorine showed values that were within permitted ranges both within and outside of the mixing zone. Sediment monitoring at the Kuparuk STP outfall revealed no adverse effects of the discharge on sediment grain size. Some variability was noted in silt, clay, and other grain sizes at some sampling stations. Total volatile solids showed a pattern of increasing concentrations from west to east across the study area. This was attributed to variations in natural peat detritus across the sampling-station array.

Finding

Physical effects of discharges and spills have been small and infrequent and have not accumulated. The effects of causeways are discussed in Chapter 8.

7

Effects on Vegetation

As a result of oil and gas exploration and development, vegetation on Alaska's North Slope has been affected by diesel fuel, oil, and saltwater spills; by disturbances related to roads and gravel pads; and by damage attributable to seismic exploration (Forbes et al. 2001, Jorgenson and Joyce 1994, McKendrick 2000b, Walker 1996). These direct physical effects can reduce the insulating quality of the vegetation and cause additional disruption of the surface ("thermokarst") by thawing the underlying ice-rich permafrost (Chapter 6). Because most industrial activity has been concentrated on the Arctic Coastal Plain, data about the accumulation of effects on vegetation come primarily from that region. However, as industrial activity spreads south into the foothills of the Brooks Range, it will affect vegetation types not previously influenced. In addition to summarizing those specific classes of effects this chapter examines areas of special biotic importance and the challenges that attend removal of facilities and rehabilitation of gravel areas, including regulatory issues.

SPILLS AND CONTAMINANTS

Oil spills on the North Slope have been smaller than have been spills in other oil producing regions of the world. The largest spill in the North Slope oil fields covered 1,700 m^2 (18,300 ft^2) of tundra, and no other spill has exceeded 500 m^2 (5,400 ft^2) (McKendrick 2000b, Appendix F). For comparison, the 1994 Usinsk oil spill in Russia covered about 70 km^2 (27 mi^2) of terrain and released some amount between 93-114,000 metric tons (102-126,000 tons) of oil, causing an estimated $15.5 million in damage to aquatic resources in three large rivers, destroying 200,000 m^3 (262,000 yd^3) of forest, and sparking large polluting fires (Vilchek and Tishkov 1997). Spills of that magnitude have been avoided in Alaska because of the system of monitoring and check valves in all pipelines. To date, most North Slope contaminant spills have occurred on gravel pads, which have minimized the extent of the effects. Contaminant spills on tundra, however, can cause significant damage to vegetation. The effects of spills vary by the season, the vegetation, and the substance spilled. A winter spill on frozen tundra is easier to clean up than is a spill in warmer periods because the contaminants can be removed as frozen material from the surface (McKendrick 2000b). As would be expected, some plants are more sensitive than others: The most sensitive vegetation is found in dry areas, and some plants, such as *Dryas* and *Sphagnum*, are particularly sensitive.

Generally one of three substances would be spilled: oil as it is drilled or transported for processing, diesel fuel stored for or in use by oil and gas exploration and development equipment, and saline water (seawater used in oil recovery operations or for testing pipelines or saltwater produced as a by-product of oil extraction). The damage can persist: Diesel fuel can remain in tundra soils for more than 20 years with little recovery of plants in affected areas (Walker et al. 1978).

Saltwater spills, although uncommon, are especially problematic. Salts are not biodegradable and they are toxic to many plant species (Simmons et al. 1983): *Dryas* and deciduous shrubs that grow in wet ground, including dwarf willows (*Salix* spp.), are the most sensitive, and sedges that grow in wet places (*Eriophorum* and *Carex*) are the most resilient to saltwater. The standard response to saline water spills is to flush the spill site with fresh water, which reduces effects and promotes more rapid recovery. Colonization by salt-tolerant species, such as *Dupontia* grass, eventually occurs (Jorgenson and Joyce 1994), but recovery of the most sensitive plants can take several years. The extent of a seawater spill is difficult to detect at the time of the spill without chemical testing of the soils.

Old reserve-pit fluids also contain salts (French 1985). The toxicity of the fluid varies seasonally and from one pit to another (Myers and Barker 1984), but it tends to decrease as pits age because of dilution by snowmelt waters. The plant species most affected by reserve-pit fluids are the same as those affected by saltwater spills (Myers and Barker 1984, Simmons et al. 1983). Recent grind-and-inject techniques have largely eliminated new contamination by reserve-pit fluids. Soil salinity also contributes to the difficulty of rehabilitating disturbed sites in some areas at Prudhoe Bay, where calcium carbonate concentrations are naturally high and summer precipitation is low (Jorgenson and Joyce 1994).

Studies of the effects of oil contamination of vegetation in the Prudhoe Bay region indicate that moderate concentrations—about 12 l/m^2—can result in the death of most plant species (Walker et al. 1978). Several common species of deciduous shrubs (*Salix* spp.) and sedges (*Carex* spp. and *Eriophorum* spp.) and a few aquatic mosses (e.g., *Scorpidium scorpioides*) are more resistant. Recovery in areas where the soils are saturated with oil to a depth of more than 10 cm (4 in.) is very poor after 12 years (Walker et al. 1978). Long-term recovery from light to moderate oil spills is usually better because the toxic components break down over time.

Oil spilled on wet tundra kills the moss layers and aboveground parts of vascular plants, and sometimes kills all macroflora in the affected area (McKendrick and Mitchell 1978). Because tundra acts like a sponge, spreading is limited and generally only small areas are affected (BLM 1998). But those effects can be severe, and recovery from tundra spills can take 10 years or more (McKendrick 1987). In general, spills that saturate the tundra produce severe, long-lasting effects and recovery is slow. Walker (1996) reported that recovery from diesel fuel spills also proceeds slowly. Twenty-eight years after a spill at Fish Creek, little vegetation recovery was evident and the fuel was still present in the soil. Places where crude oil and crankcase oil had spilled showed better results after 28 years, except in the areas of heaviest effect. In experimental spills (Walker et al. 1978) of crude oil and diesel fuel, tundra plant communities on diesel fuel plots showed no recovery after 1 year. There was some recovery of sedges and willows after 1 year on the crude oil plots. However, mosses, lichens, and most dicots showed almost no recovery. Walker and colleagues (1978) suggested that vegetation spill-sensitivity maps can be developed. Natural seeps also can affect vegetation; sedges seem to be among the most tolerant plants (McCown et al. 1973).

Many bioremediation techniques have been used within the oil fields (Jorgenson and Joyce 1994): Microbial degradation has been enhanced by fertilizer treatment, aeration, and hydrologic manipulation (Jorgenson et al. 1991). Burning of spilled oil and thermal remediation also are used (Jorgenson and Joyce 1994). The oil industry has developed technology to prevent, clean up, and rehabilitate most terrestrial contaminant spills, but techniques for optimizing the microbial degradation of hydrocarbons in tundra soils still needs development. Although the effects of contaminant spills could accumulate if the size and frequency of spills were to increase, their effects have not accumulated to date on North Slope vegetation. Oil and saltwater spills are described in detail in appendixes F and G.

Most of the literature on the response of tundra vegetation to contaminant spills has been from short-term observations, 1-3 years. Longer term studies are needed to determine the recovery potential of various plant communities and for use in developing maps that will show areas of sensitivity to spills and those in which there would be a good possibility of recovery from a spill.

ROADS AND GRAVEL PADS

There is an extensive, increasing network of roads and gravel pads on the North Slope (Figures 4-3–4-6). The effects of gravel pads on vegetation are usually localized, but roads (especially old roads and those more heavily traveled) have a variety of sometimes far-reaching effects on plants and animals and can cause broad changes to ecosystem structure and functioning. Roads directly cover and kill tundra vegetation, but their effects extend beyond their footprints. Roads can displace wildlife, impede wildlife movement, and increase human access to an area. They are visually conspicuous, change hydrological patterns, and assist in the dispersal of nonnative plants (Ercelawn 1999). Road-related changes that are unique to cold regions include alterations of snow distribution patterns and creation of thermokarst (irregular depressions caused by melting and heaving of frozen ground) (Walker et al. 1987a).

The Prudhoe Bay region has a variety of road types. Roads to remote drill sites are rarely traveled; roads that link oilfield structures are heavily used. As would be expected, wide, more heavily traveled roads cause more severe indirect effects: heavy road dust, hydrology changes and flooding, altered snow distribution, thermokarst, increased accessibility to associated off-road-vehicle trails, and greater opportunity for invasion by nonnative plant species. Hunters, tourists, and other users cause additional effects in a broad area along the Dalton Highway corridor. The effects of dense networks of roads and gravel pads are complex—several roads can influence the same piece of ground. Roadside structures, such as pipelines, power lines, power plants, and industrial centers, can make large areas of land unavailable or undesirable to wildlife, subsistence hunters and wilderness travelers.

Old Roads, Exploration Trails, and Drill Sites

When exploration of the North Slope began, knowledge about of the effects of exploration and construction techniques on permafrost was limited. From early exploration through the 1950s, trails often were cut directly into frozen ground. Large tractors and tracked vehicles traveled over thawed ground in the summer, often leaving deep ruts, and sometimes road builders removed the vegetation mat completely, causing deep thermokarst (Bliss and Wein 1972, Chapin and Chapin 1980, Hernandez 1973). Trails commonly became wetter than the natural habitat and were colonized by species more adapted to wet sites. Higher biomass and changes in nutrient concentrations occurred in the trails (Chapin and Shaver 1981). At times, subsidence and erosion created trails as deep as 5 m (16 ft) (Lawson et al. 1978). Some old trails and seismic surveys made by government contractors in the 1940s are still clearly visible because they are deeply rutted, often flooded, and filled with vegetation that is quite different from the surrounding tundra (Hok 1969, 1971; Lawson et al. 1978).

In the 1960s, peat roads were built by scooping the active layer from two sides of an area and piling it in the center to form an elevated surface. This method also resulted in severe thermokarst. By the 1970s, gravel had replaced peat in road construction. Now in many cases, ice is used.

There has been a parallel evolution in the techniques used to build drill sites. Many of the early exploration wells were drilled without gravel pads. In some cases the drilling wastes were deposited directly on the tundra. As environmental awareness increased, drilling wastes were contained in reserve pits, which often leaked. The consequences for those old reserve pits on the arctic vegetation pose special challenges for rehabilitation.

Modern Roads and Gravel Pads

The currently preferred method for road and site development is to build a thick gravel pad, often more than 2 m (6.5 ft) thick, to insulate the underlying permafrost. Sometimes polyethylene insulation is placed below the pads to reduce the amount of gravel needed. If a pad is temporary, a thinner layer of gravel or sand is used. Thick gravel pads that protect the permafrost cause other environmental effects: They create dry elevated areas that are difficult to rehabilitate after a pad is abandoned, they require gravel mines whose sites also must be rehabilitated, they block natural drainage channels, and they alter snow-drift patterns. The direct and indirect effects of the Dalton Highway, the Prudhoe Bay roads, and the Trans-Alaska Pipeline Corridor have been studied extensively (Auerbach et al. 1997, Brown and Berg 1980, Klinger et al. 1983b, McKendrick 2002, Pamplin 1979, Walker 1996, Walker et al. 1987a).

Road Dust

Dust is an inevitable by-product of the use of gravel roads on the North Slope (Figure 7-1). Dust loads are highest along the Spine Road and, until 2002, when it was chip-sealed, the Dalton Highway, where traffic is heavier and faster than on other area roads. One study showed that as much as 25 cm (10 in.) of dust had been deposited in some areas along the Spine Road (McKendrick 2000b). Earlier studies reported that all vegetation was eliminated within 5 m (16 ft) of the most heavily traveled roads at Prudhoe Bay. Mosses were eliminated to about 20 m (66 ft) (Auerbach et al. 1997, Everett 1980, Walker and Everett 1987). Dustfall 1,000 m (3,280 ft) from the road was several times higher along the Spine Road than at the other sites because of the heavier traffic (Everett 1980). In acidic tundra regions, the normally high buffering capacity of the tundra was neutralized by the heavy dustfall. At an acidic tundra area in the foothills, the pH in roadside areas has shifted from acidic to alkaline (pH 4.0 to pH 7.3) (Auerbach et al. 1997).

Several road-related phenomena interact to increase the depth of the tundra's active layer. The elimination of the moss carpet reduces insulation, and deep snow drifts accumulate near the

(a)

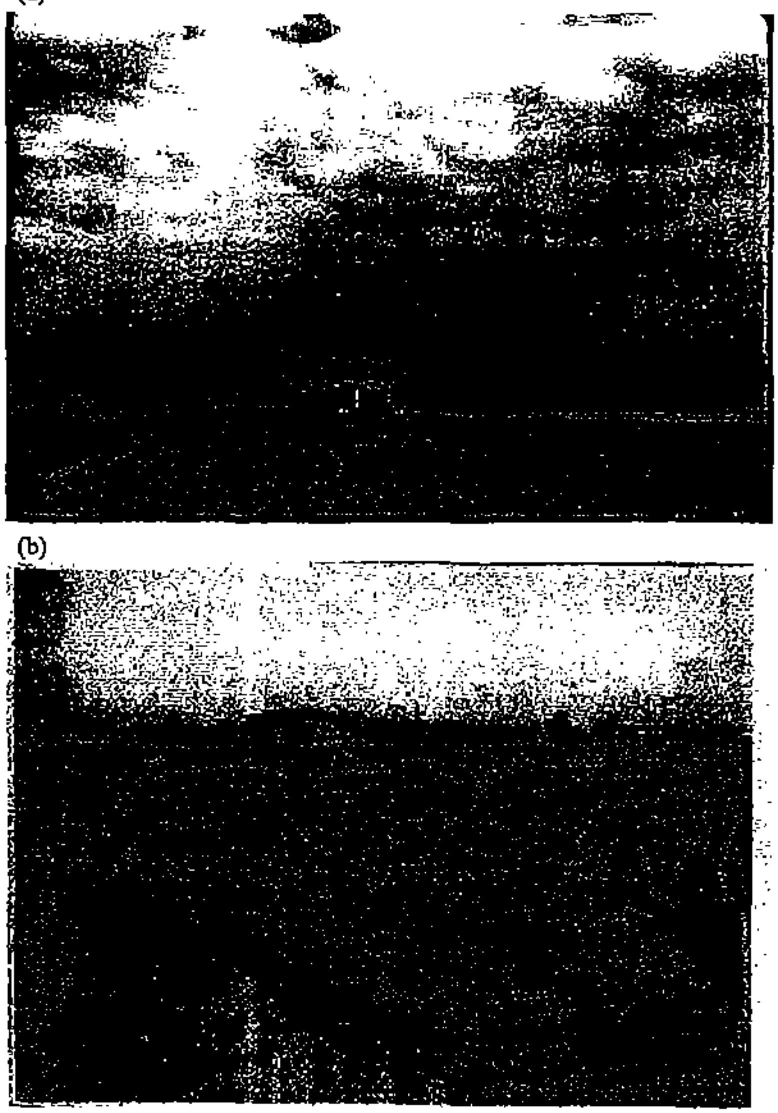


FIGURE 7-1. (a) Trucks raising dust plumes along the Dalton Highway. Truck speeds often exceed 60 mph, and winds can distribute the dust to distances of more than 1 km from the road (Everett 1980). Chip sealing, which is now being done, reduces dust along the Dalton Highway. (b) Environment along the Prudhoe Bay Spine Road. Barren areas are caused by thick dust, and ponded areas are caused by thermokarst. This was formerly an area of low-centered polygons that was converted to high-centered polygons by erosion of the polygon troughs. Source: Walker 1996. Reprinted with permission, copyright 1996, Springer-Verlag.

roads, increasing the wintertime soil surface temperature. Despite the deeper snow associated with elevated roads, the snow melts earlier because the darker, dust-covered snow surfaces absorb more heat. Ponds near roads also absorb more heat. All of these factors combine to warm the soil, deepen the thaw, and produce thermokarst adjacent to roads. The earlier snowmelt near roads also can open these areas to wildlife several days or weeks before adjacent snow-covered tundra areas become accessible (Walker and Everett 1987). Tracts of dust-killed vegetation have expanded from those observed in 1980s, and thermokarst, which was spreading rapidly during the 1980s (Walker et al. 1986b, 1987b), continues to spread along ice-wedge polygon troughs. Changes along the roads have not been documented consistently, and detailed long-term studies are needed. Paved roads produce far less dust, and chip-seal treatments (an application of asphalt followed with an aggregate rock cover) have reduced dust along the Dalton Highway and some other roads.

Roadside Flooding

Flooding, another major effect, is generally confined to wet and aquatic tundra vegetation. Most road-related flooding occurs where roads cross low-lying, drained thaw-lake basins. Drainage patterns on the flat tundra are complex, and there are many unconnected drainage systems. In areas where there is an intersecting web of roads, such as around the Prudhoe Bay development, flooded areas are more common and often difficult to drain (Figure 7-2). The road to West Dock, constructed in 1980-1981, is 7 km (4 mi) long, crosses four drained lake basins, and caused flooding to about 131 ha (324 acres) of tundra (Klinger et al. 1983a). It is difficult to position culverts along such roads because the routes of melt water drainage often are not detectable at the time of road construction. Even if culverts are located appropriately, they generally are frozen at the time of the spring melt. In deeply flooded basins, elevated microsites, which are important nesting areas for some bird species, are submerged and thus unavailable during the nesting season (Walker 1997).

Invasion of Nonnative and Native Species

Nonnative species have sometimes been introduced in seed mixtures and mulches during rehabilitation efforts (Johnson 1981, Kubanis 1980). Surveys along the Dalton Highway during the late 1970s showed that 13 plant species had been introduced, and 9 of them were reproducing (Kubanis 1980). However, none of those species has been documented as successfully invading native-plant communities. Climate change could cause more species to invade the North Slope. Current rehabilitation research focuses on natural revegetation with minimal application of nonnative seed mixes (Jorgenson et al. 1997a). Vegetation patterns also can be altered when native species that grow naturally in other areas move into disturbed sites (e.g., dusted areas, seismic trails, snow pads) (Emers et al. 1995, Johnson 1981, McKendrick 2000b). The grass *Arctagrostis latifolia* often invades those areas, but others species do as well depending on the severity of the disturbance. Coastal and dune plant species can colonize severely dusted areas well inland (McKendrick 2000b). Overall, invasion by nonnative species has not been an important problem.

FIGURE 7-2. One of the four lake basins along the Waterflood road at Prudhoe Bay. The photo was taken in early summer before ice in the culverts thawed. By late summer the large oval impoundment drained, but the vegetation changed over a period of 3 years. Notice the lack of elevated microsites for bird nests in the flooded areas compared with the other side of the road. Also note the other impoundment along the road (arrow), which does not drain all summer. Source: Walker 1996. Reprinted with permission, copyright 1996, Springer-Verlag.

Estimates of Indirect Effects

Few detailed analyses of the growth of the oil-field infrastructure assess indirect effects such as dust, flooding, and thermokarst. Nor do they address the various types of habitat lost to direct and indirect effects. Such analyses require a time-sequence of detailed photo-interpreted maps that show the ecological communities of a region before development and maps of the direct and indirect effects for several years during development. One such an analysis was performed for three heavily disturbed portions of the Prudhoe Bay oilfield. Figure 7-3 illustrates one section (Walker et al. 1987b).

Although there are no data to delineate the extent of the indirect physical effects of the North Slope's road network, historical mapping studies from the 1980s showed that wide margins on both sides of roads were affected by dust, thermokarst, intermittent flooding, gravel spray, vehicle trails, and trash (Walker et al. 1987b). The width of the margins varied according to the amount of traffic and the terrain type. Very flat portions of the oil field with many drained thaw lake basins and many roads had extensive areas of roadside flooding that greatly exceeds the gravel-covered areas of the roads and pads (Figure 7-3).

Effects of ground excavations were most widespread in the floodplains, whereas effects of dust and thermokarst were most extensive on the upland areas. In a very wet area of a heavily affected portion of the oil field, the ratio of indirect effects (roadside flooding, dust, debris, thermokarst) to the area of the gravel road was 8.6:1. In dry areas of the same heavily developed portion of the field, the ratio was 2.4:1, and the mean for all mapped areas (mostly in heavily developed portions of the field) was 6:1 (data derived from Walker et al. 1986b).

Walker and colleagues (1987b) focused on some of the most severely affected areas of the oil field—areas that were developed first but that no longer represent development practices (Robertson 1989). Their study is, however, an important reference for changes within the oldest, main part of the oil field. Their methods could be used again to examine more recent changes and used elsewhere to assess effects in areas where newer technology has been used.

SEISMIC EXPLORATION

Some seismic trails from the 1940s are still visible on the North Slope. There are no maps that show all of the early trails, so an estimate of their total length cannot be calculated. Many studies of the effects of off-road vehicles have noted critical factors that determine the amount of damage to the tundra (Abele et al. 1978, 1984; Radforth 1972, Walker et al. 1977):

- ground pressure
- total weight of each vehicle
- number of passes by the vehicles
- terrain
- type of vegetation

The development of new methods for seismic exploration might reduce damage by reducing the weight, tracks, or the number of vehicles used.

Nearly all of our knowledge about long-term recovery from seismic exploration comes from a single U.S. Fish and Wildlife Service (FWS) study of a 2-D (two-dimensional) seismic survey in the Arctic National Wildlife Refuge in 1984-1985 (Emers and Jorgenson 1997).

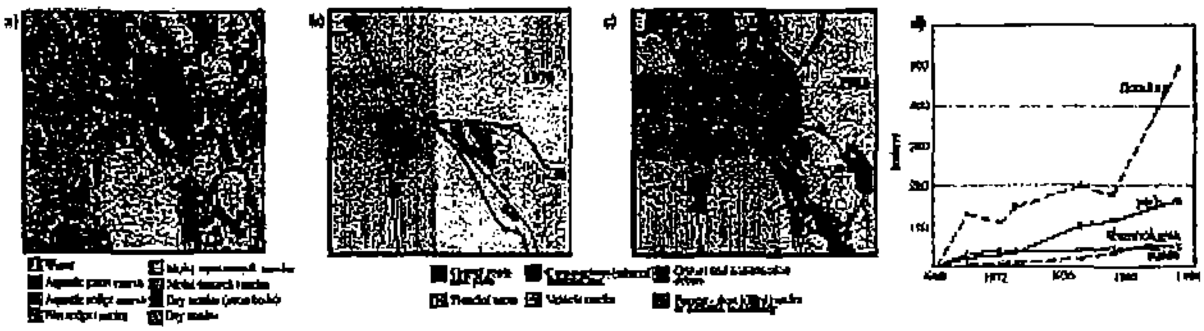


FIGURE 7-3. Geobotanical and historical disturbance mapping. The area shown is among the most heavily developed portions of the oil field. (a) Vegetation map shows the terrain as of 1949, before development. Soils and landforms also were mapped. (b) Infrastructure as of 1970, with a few roads and drill sites. Some flooding (violet) and roadside disturbances (red) are evident. (c) Infrastructure as of 1983. Source: Walker 1996. Adapted from Walker et al. 1987b. Numerous large pads include the processing facility at GC-1 (center) BP base operations camp (lower right), a construction camp (northwest of GC-1), and several production pads. The roads and pads inhibit drainage, and there is extensive flooding in the drained thaw effects in lake basins. (d) Progression of direct (solid lines) and two indirect effects (dashed lines). The area of indirect effects in this portion of the oil field was nearly triple the area of the direct effects. Source: Alaska Geobotany Center, adapted from Walker et al. 1987b.

Although technology changes since then limit the applicability of its results, the study does provide valuable information on different types of effects and on the recovery rates of tundra.

According to Emers and Jorgenson (1997), the 1984-1985 seismic exploration consisted of more than 2,000 km (1,200 mi) of seismic lines, arranged in 5 x 20 km (3 x 12 mi) line spacings. Another 2,000 km of trails was associated with moving the support camps. Most seismic lines consisted of a multitude of trails caused by multiple passes by a variety of vehicles (Figure 7-4). Camp-move trails caused more damage than the seismic lines did, however, particularly when the snow cover was insufficient to protect the ground and the tractors scraped the tundra as their treads sliced through the vegetative mat.

Effects were estimated from an aerial photo survey that examined a random sample of 20% of the trails a year after disturbance. About 14% of the trails showed no detectable disturbance; 57% had low disturbance; 27% had moderate disturbance; and 2% had high disturbance (Raynolds and Felix 1989). Eight years after the exploration, only about 3% of the seismic and receiver line trails were still disturbed, but camp-move trails showed more disturbance—about 10% were disturbed, including 4% that showed medium disturbance and 1% that showed high disturbance (Emers et al. 1995).

Figure 7-5 shows examples of damage caused by seismic-exploration vehicles. Effects are rated on a 4-point scale with 0 indicating no damage and 3 indicating extensive disturbance of vegetation.

Although the typical effects of individual seismic trails in the Arctic National Wildlife Refuge generally were minor, they were extensive and varied greatly with vegetation type, terrain, vehicle type, operator vigilance, and amount of snow cover. Minor effects and rapid recovery occurred in flat areas of wet tundra, which are common on the Arctic Coastal Plain. Damage was greater in areas with more microrelief and in areas with taller shrubs that were not covered by snow, which is more common in hilly portions of the North Slope. Tussock tundra and frost-boil tundra were particularly susceptible because of higher microrelief.

The greatest damage occurred where the vegetative mat was destroyed and the underlying soil was exposed. This was infrequent and usually result from tracked vehicles or sleds on skids cutting into hummocks or other raised areas or from Caterpillars operators making a tight turn or dropping a blade too deeply into the snow. High disturbance also occurred where vehicles became mired in deep snow and their operators tried to extricate the equipment instead of being pulled out (Shultz 2001). The most common sites of high disturbance were in areas with low snow cover and where vegetation is easily disturbed—river terrace plant communities or plant communities on stabilized sand dunes.

The plant species that are most sensitive to disturbance and that have poor potential for recovery are among the most common. Cottongrass tussocks (*Eriophorum vaginatum*) are susceptible and often are crushed or cut open by the grouser bars on tracked vehicles, as are evergreen shrubs (*Rhododendron decumbens, Vaccinium vitis-idaea, Dryas integrifolia*), some deciduous shrubs (*Betula nana, Arctostaphylos rubra, Salix phlebophylla, S. reticulata*), some mosses (particularly *Sphagnum* and *Tomentypnum nitens*), and all lichens (Felix et al. 1992). Some affected species, such as Labrador tea (*Rhododendron decumbens*) and low-bush cranberry (*Viburnum edule*), are used extensively by the Inupiat, who have concerns about the effects of seismic trails on their subsistence harvests. The physiological reasons for the sensitivity of certain species are not known.

In 1998, 14 years after the original survey, 7% of the plots assessed on the ground were still disturbed, and 15% showed disturbance that was visible from the air (J. Jorgenson, FWS,

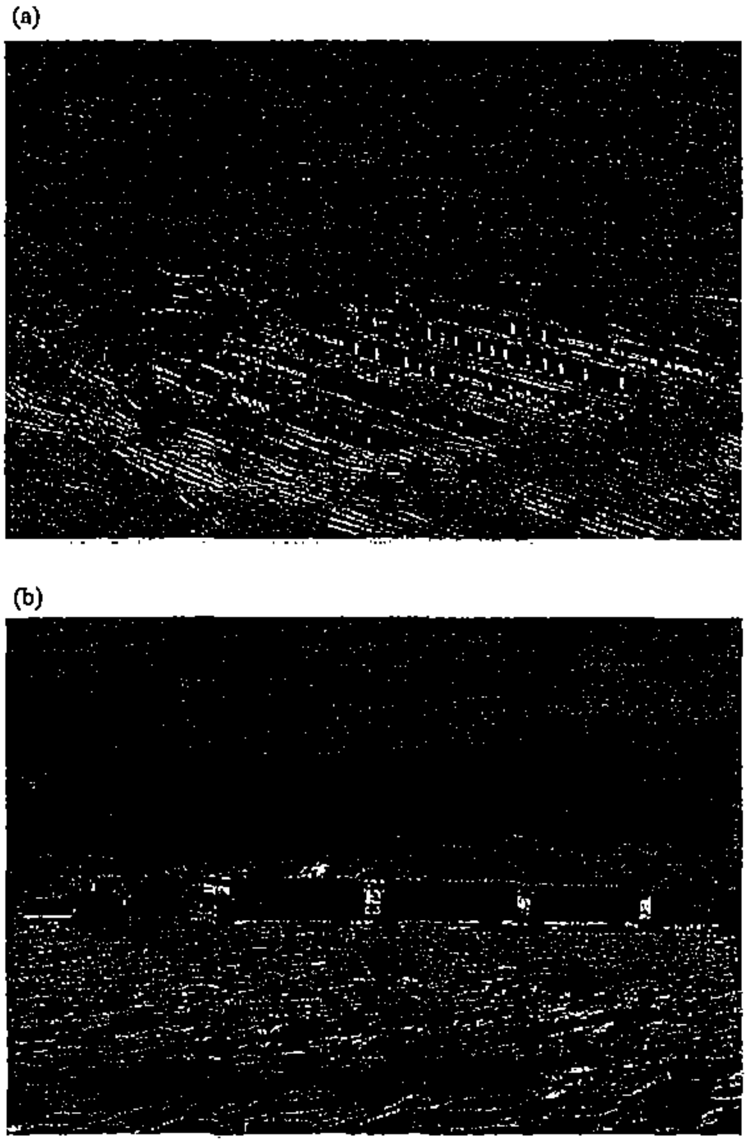
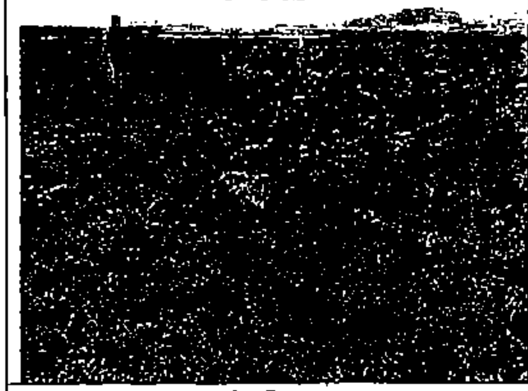
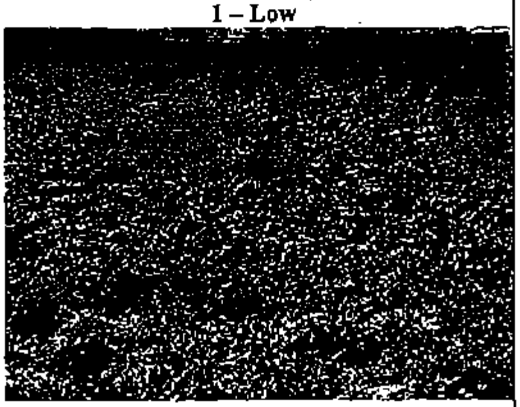


FIGURE 7-4. (a) Trailers on skids make up Camp 794 on the tundra of the National Petroleum Reserve-Alaska. Photo courtesy of the *Anchorage Daily News*. (b) Tractors towing camp trailers during a camp move. Source: U.S. Fish and Wildlife Service.

0 – None 	No effect of slight scuffing of higher microsites. *Trail goes through photo from foreground to background, passing between the two wooden stakes in the distance. Note slight color difference in tussocks on trail (light brown color rather than gray), due to scuffing of tops of tussocks.*
1 – Low 	Less than 25% decrease in vegetation or shrub cover; less than 5% soil exposed. Comparison of standing litter and slight scuffing in wet graminoid and moist sedge-shrub tundra. Tussocks or hummocks scuffed. Trail evident only with tracks on Dryas terrace sites. *All of the foreground and much of the background of this photo show tussocks disturbed by dispersed vehicle traffic. Note the flattened, brown-topped tussocks, compared to the tussocks with level 0 disturbance pictured above.*

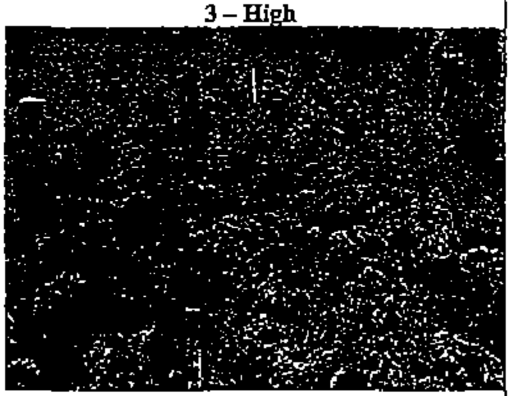
2 – Moderate 	Vegetation or shrub cover decrease 25-50%, exposed soil 5-15%. Compression of mosses and standing litter in wet graminoid and moist sedge-shrub tundra; may have increase in aquatic sedges. Tussocks or hummocks crushed but show regrowth. Portions of trail may appear wetter than surrounding area. Some disruption of vegetative mat within tracks of riparian shrublands and Dryas terrace. May be some change in vegetative composition. *Note the two vehicle tracks going from foreground to background. Tussocks in the tracks are crushed.*
3 – High 	Over 50% decrease in vegetation cover or shrub cover; over 15% soil exposed. Obvious track depression in wet graminoid and moist-shrub tundra; standing water is apparent on trail that is not present in adjacent areas in wet years; moist sedge-shrub tundra changing to wet graminoid. Crushed tussock or hummocks nearly continuous; general depression of the trail is evident; change in vegetation composition. In riparian shrub and Dryas terrace vegetative mat and ground cover substantially disrupted. *Note the exposed soil and crushed tussocks on the trail.*

FIGURE 7-5. Examples of seismic-exploration disturbance on tussock tundra vegetation.
Source: U.S. Fish and Wildlife Service.

personal communication, 2001). The active layer was deeper on about 50% of the disturbed plots than it was in adjacent control areas after 10 years (1984-1994). By 1998, differences in thaw were still noticeable on many of the trails. Based on the current recovery rates, the long-term trends each disturbance category can be illustrated (Figure 7-6). Overall, the vegetation recovery reaches a plateau after about 8 years. Some trails are likely to be visible from the air for decades after that (Jorgenson, unpublished, 2001) (Figure 7-7).

Few studies have examined the effects of current three-dimensional (3-D) seismic methods. One study of the Colville River delta detected the trails left from repeated 2-D exploration in 1992, 1993, and 1995 and from 3-D work in 1996, but it reported generally minor disturbance (Jorgenson and Roth 2001). High disturbance occurred on only 1% of the sites surveyed, mostly dry dune areas. Maps of those survey lines show the much higher density of trails associated with the 3-D operations, which can be spaced as close as 200 m (660 ft), or rarely even closer. It was difficult to quantify the numerous random stray trails that were not part of the seismic lines or camp-move trails (for example, see Figure 7-7a). Some areas were surveyed several times by different companies, resulting in a maze of seismic trails, camp trails, and ice roads, which are difficult to separate or identify by type and year of origin. Some repetition is caused by the need for new or better seismic information, but it also occurs because the data are proprietary and companies will not share information that might help competitors, thus setting the stage for each to gather data and conduct analyses independently.

The Importance of Snow Cover

The Alaska Department of Natural Resources (DNR) issues tundra travel permits for seismic crews based on their examination of several sites each December and January. The permits allow tundra travel for seismic camps when there is an average minimum of 15 cm (6 in.) of snow and 30 cm (12 in.) of frozen soil, which is determined by the number of times a hammer must strike a stake to drive it into the soil. Conditions are monitored throughout the winter. DNR closes tundra travel in April or May, again depending on conditions.

The only published study of seismic disturbance in relation to snow cover suggests that measurable, low-level disturbance occurs at depths of as much as 45 cm (18 in.) in tussock tundra, and 72 cm (28 in.) in sedge-shrub tundra (Felix and Raynolds 1989b). Moderate disturbance occurs at snow depths to 25 cm (10 in.) in tussock tundra and 35 cm (14 in.) in moist sedge-shrub tundra.

Knowledge of the distribution and ecological significance of snow in arctic ecosystems has grown considerably in the past 20 years (e.g., Jones et al. 2001, Liston 1999, Olsson et al. 2002, Sturm et al. 2001). The structure of the snowpack is critical to maintaining the relatively warm winter microclimate at the base of the snowpack (Pomeroy and Brun 2001). The subnivian layer, the highly porous granulated layer of snow at the base of the snowpack, acts as insulation and is important to many wintertime processes, such as soil microbial activity and wintertime carbon dioxide flux (Oechel et al. 1997), and to the movement of small mammals (Aitchison 2001). Plants are sensitive to the thermal conditions at the base of the snowpack (Walker et al. 2001a). Ice roads and pads and vehicle trails alter snowpack structure and can physically disturb vegetation and soils if the snowpack is thin.

Small amounts of snow in northern Alaska are a particular problem for wintertime exploration activities. Near the coast, the average April wind-packed snow depth is 30 cm (12

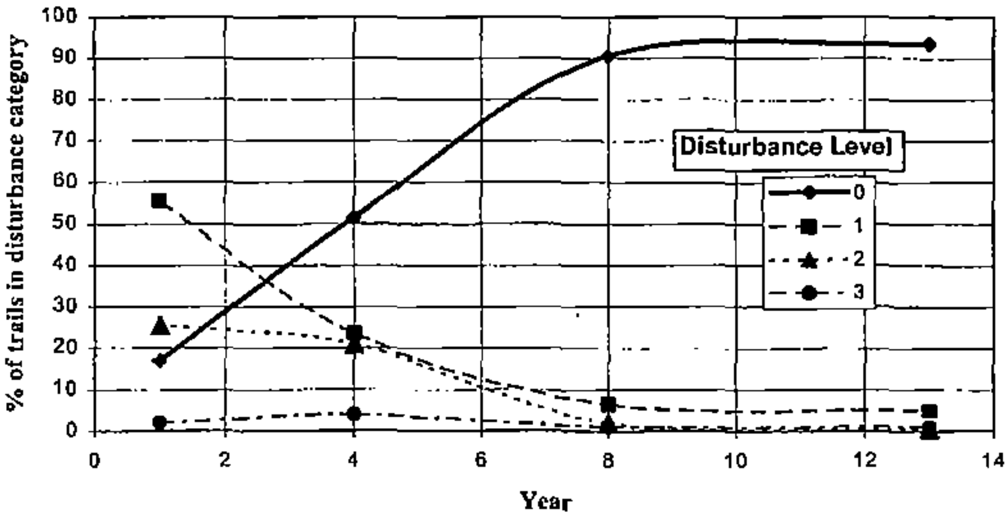
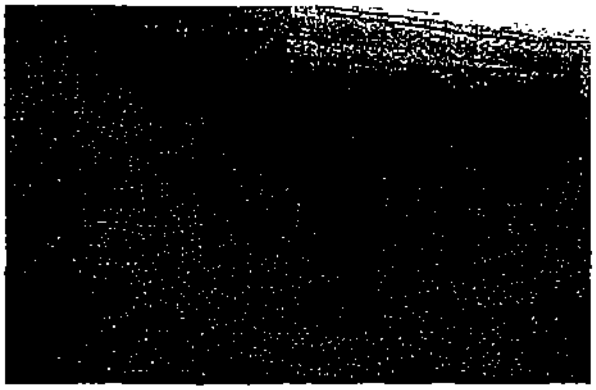
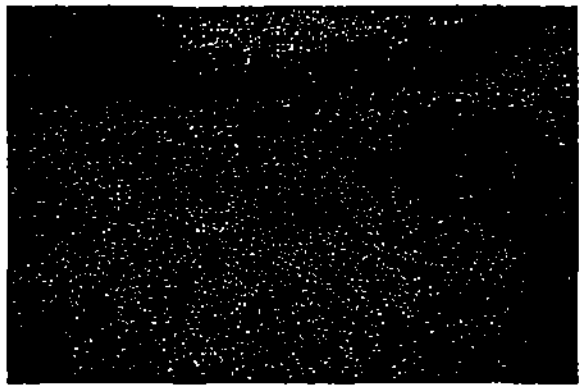


FIGURE 7-6. Recovery after seismic disturbance. Sources: Data from Felix et al. 1992, Emers et al. 1995, FWS 2002.

(a)



(b)



(c)

FIGURE 7-7. Aerial views of seismic trails. (a) Intersecting seismic-exploration and camp-move trails, Arctic Foothills, 2001. The heaviest trail (center) near Kavik in the tussock tundra is a camp-move trail. The intersecting trails (left) are seismic lines. Also shown here are numerous stray trails that are not part of the camp-move or seismic trails. Tan colors show damaged cottongrass tussocks *(Eriophorum vaginatum)* and dead dwarf shrubs. Source: U.S. Fish and Wildlife Service. (b) Heavily impacted tundra in hill slope with frost boils, sedge-dwarf-shrub tundra, and high microrelief. Source: U.S. Fish and Wildlife Service. (c) Camp-move trail from 1985 exploration in the Arctic National Wildlife Refuge, photographed in 1994. This trail remained visible because of trail subsidence, a decrease in shrub and mosses, and an increase in standing dead sedge leaves. Source: Jorgenson et al. 1996.

in.). The snowpack normally builds up to about 20 cm (8 in.) within 10-20 days after freezeup and then increases slowly through the rest of the winter (Dingman et al. 1980). Several factors affect the local and regional distribution and characteristics of snow, including increasing snowfall from east to west and from north to south across the North Slope, gradients of wind across the North Slope, and differences in snow cover associated with topography. The use of average snowpack and frost thickness by regulatory agencies to determine when to open and close the tundra travel season does not consider such differences.

If snow cover increases in the future, as some climate-change models predict, the effects of seismic trails could be reduced. Snow cover also affects the depth of frost penetration. Generally, snow insulates the tundra, so if the snowpack accumulates earlier or to greater depths, the timing of the opening of the seismic season could be affected. Less snow would shorten the seismic season. Earlier warming in spring could mean the cessation of seismic activities earlier in the year. The length of the season for off-road tundra travel has decreased (Figure 7-8). The change in the off-road season is mainly the result of later opening dates for the season rather than earlier closing dates. A more complete understanding of just how much snow and frost penetration are needed to adequately protect the tundra from seismic operations is needed.

Potential Accumulation of Effects of Seismic Trails

According to the best estimate of the committee on the Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities, 32,000 line miles of seismic trails, receiver trails, and camp-move trails were made between 1990 and 2001, and if current trends continue another 27,000 line miles will be surveyed in the next 10 years. A large percentage of the trails should recover within relatively short periods. Data from the Arctic National Wildlife Refuge showed that after 8 years only about 3% of the seismic and receiver line trails and 10% of camp-move trails were still disturbed (Emers et al. 1995).

Based on these recovery rates and modern ratios of trails in each disturbance category, the committee projected the total seismic line miles in each disturbance category into the future (Figure 7-9). This figure projects cumulative line miles of trails for the next 12 years in each of four disturbance level illustrated in Figure 7-5, and it assumes the same rates of recovery that occurred in the Arctic National Wildlife Refuge. According to this model, about 17,500 miles will recover fully (Level 0, although parts could be faintly visible from the air). About 6,200 miles will have Level 1 disturbance, 3,600 miles will have Level 2 disturbance, and about 300 miles will show Level 3 disturbance.

Although there are no comparable data for modern seismic methods, the Arctic National Wildlife Refuge data provide some useful insights. First, after about 6 years, the recovery of old trails in disturbance categories 1 and 2 about balance the addition of new trails. As long as the rate at which of new trails are added remains constant, the recovery of old trails generally keeps pace, and the total footprint of seismic trails on the landscape at any one time will remain about the same. The sum of trails in disturbance categories 1, 2, and 3 currently is about 10,000 line miles (Figure 7-9), so the posited relationship is valid only if the improved technology does not result in a decrease in the degree and amount of tundra disturbance. However, newer technologies appear to cause less long-term damage. There is a small increment of trails in disturbance category 3 that do not recover, and the total line miles in this category continues to climb slowly. Because of the large number of seismic line miles created each year, even very

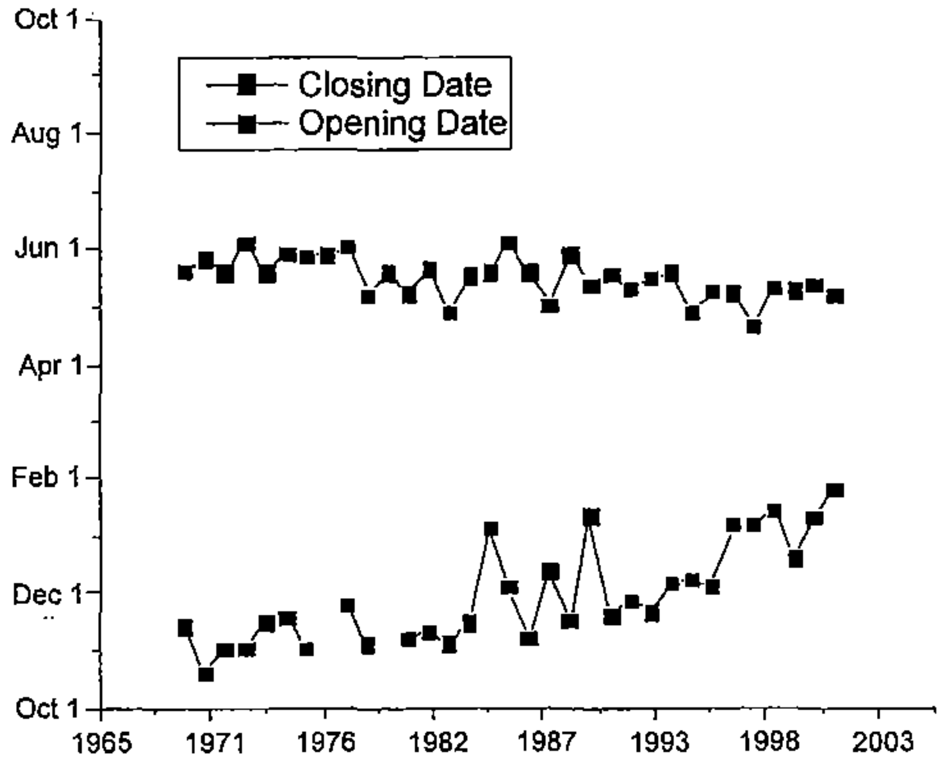


FIGURE 7-8. Opening and closing dates of North Slope off-road traffic. Source: Alaska Department of Natural Resources.

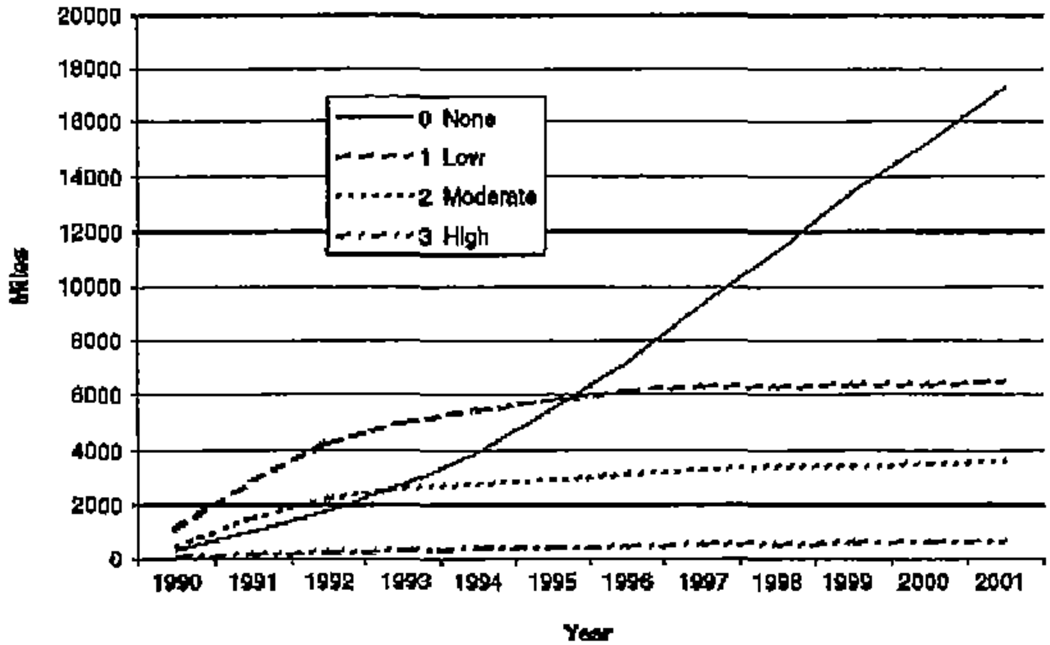


FIGURE 7-9. Hypothetical cumulative line miles of trails during 12 years and totals in the four disturbance levels based on the following: (1) Total seismic line miles equivalent to that during 1990-2001. (2) The ratios of line miles in each disturbance category is the same as that resulting from the 1984-1985 seismic surveys in the Arctic National Wildlife Refuge (Emers et al. 1995). (3) The recovery rate in each disturbance category is the same as that in the Arctic National Wildlife Refuge studies. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

small percentages of trails in category 3 can accumulate to large totals over many years. If this trend were to continue to 2025, then another 29,900 line miles will have been surveyed. If 1% of the trails are in category 3, this would add nearly 300 line miles of degraded land to the North Slope. Trails in this category can deteriorate over time and become worse as permafrost subsidence and erosion occur.

The model used here is based on information from studies that measured recovery rates on the ground. It does not address the question of how much remains visible from the air. About 15% of the trails created in the Arctic National Wildlife Refuge between 1984 and 1985 are still visible from the air (J. Jorgenson, FWS, unpublished, 2001). Those trails affect the visual quality of large landscapes and are a cause for particular concern in pristine areas, such as the Arctic National Wildlife Refuge, especially given that most North Slope travel is by small aircraft. There have been no studies to document recovery rates of trails visible from the air.

Some seismic trails have caused significant changes to plant communities (Emers and Jorgenson 1997, Emers et al. 1995). Although most trails recover to resemble the original plant community within about 8 years, heavily damaged areas do not. The long-term consequences of the changes are unknown, but possibilities include the establishment of weedy species and the subsidence of trails because of thermokarst. Invasive grasses have colonized some highly disturbed trails, making them more visible from the air (Emers et al. 1995).

An average of about 1,300 line miles of seismic trails is added each year. The total area likely to be affected annually can be estimated by multiplying by the width of trails—on average, 30 m (100 ft)—and adding the areas of the associated camp-move trails. This was done for the environmental impact statement for the northeastern portion of the National Petroleum Reserve-Alaska, in association with the first lease sale. Assuming the same ratio of 2-D to 3-D exploration for the entire North Slope, the predicted 13,000 line miles over 10 years would translate to a total affected area of 1,114-3,421 km^2 (430-1,321 mi^2). This estimate does not include areas affected by receiver lines perpendicular to main lines or to the many stray vehicle trails on the tundra. The estimate also does not include the areas between the trails, which often are visually affected, especially in areas of 3-D seismic exploration, nor does it include recovery that would occur within the 10-years period. It also does not address the fact that a good portion of the seismic line kilometers will occur in areas already surveyed using older seismic technologies. And it does not take recent technological improvements into account. But the estimate does give some impression of the extent of the areas that are likely to suffer effects caused by seismic activities in the near future, although the degree of effect is difficult to judge given that effects are less if the tundra is adequately protected by snow.

In the future, seismic-exploration is expected to increase in the foothills region, and effects are likely to be different from those documented on the coastal plain. Research will be needed to identify and monitor those effects. The committee is not aware of data that can be used to assess the ecological significance of the persistence of disturbed linear segments of tundra.

Ice Roads and Pads

Ice roads, airstrips, and drilling pads have been built in recent years to reduce costs and environmental effects of gravel construction (Hazen 1997, Johnson and Collins 1980). Extended-season ice pads have many environmental and economic advantages for exploration

(Hazen et al. 1994, Stanley and Hazen 1996). The ice pads are covered with reusable insulated panels that help preserve the ice in the summer, allowing drilling to resume nearly two months earlier the next season.

There have been some studies of the short-term ecosystem effects of ice roads (Johnson 1981, Johnson and Collins 1980, Walker et al. 1987a), but there have been no long-term studies. Most of the effects of ice roads involve the direct physical disturbance of vegetation, the effects of debris from the road, and destruction of the subnivian layer (Walker et al. 1987a). The biotic effects of ice roads are substantially less than those of gravel roads and pads but more severe than those of seismic trails. Studies of vegetation recovery at an extended-season ice drilling pad showed a 34% decrease in vascular plant cover 2 years after the pad melted; the effect was greatest on raised microsites (Noel and Pollard 1996). Climate warming could restrict the use of ice roads and pads in the future.

AIR QUALITY

The effects of air quality on vegetation near industrial facilities on the North Slope appear minimal: for example, concentrations of NO_x and SO_2 from 1989 to1994 were below those generally expected to be harmful to plants (Kohut et al. 1994). High concentrations of NO_x occurred only during a small percentage of monitored hours. The NO_x and SO_2 monitoring revealed no effects on vegetation that could be attributed to pollution. The researchers (Kohut et al. 1994) recommended continued monitoring at 2-year intervals to ensure that any changes in vegetation could be detected relatively quickly. This monitoring is not being conducted (Taylor 2001).

Lichens are known to be vulnerable to SO_2, and concentrations as low as 12 $\mu g/m^3$ for short periods can depress photosynthesis in several species, with damage occurring at 60 $\mu g/m^3$ (National Petroleum Reserve-Alaska FEIS IV(5)(b)(3)). (The National Ambient Air Quality Standards maximum 3-hr limit for SO_2 is 1,300 $\mu g/m^3$). Sensitivity of lichens to sulfates is greater under the moist and humid conditions that are common on the North Slope. Air monitoring that was conducted from 1989 to 1994 showed maximum 3-hr concentrations of SO_2 above 12 $\mu g/m^3$ at 11 of the 12 sites monitored; 1 site exhibited concentrations greater than 100 $\mu g/m^3$ (BLM 1999, Northstar FEIS Table 5.4-5). Thus, even though air quality meets national ambient-air-quality standards, it is not clear that those standards are sufficient to protect arctic vegetation.

Similarly, although most monitored concentrations of ozone were reported by Kohut and colleagues (1994) to be below those thought to injure temperate vegetation, little is known about the sensitivity of arctic vegetation to ozone.

The FWS has studied the effects of atmospheric deposition of contaminants on snowpack on the moss, *Hylcomium splendens*, at Prudhoe Bay and in the Arctic National Wildlife Refuge (FWS 1995a). The report documented enrichment of nutrients and several trace elements in the Prudhoe Bay snowpack compared with sites in the Arctic National Wildlife Refuge. "Significant inputs of major and trace elements, including heavy metals [were found] at Prudhoe Bay at two sites, one near drilling operations and the central processing facility, and the other near the North Slope Borough solid waste incineration facility." Effects appear to be local, however (FWS 1995a).

AREAS OF SPECIAL IMPORTANCE

Several features of the North Slope vegetation deserve special mention because they are important focal points for wildlife activity; nonacidic tundra, bird mounds, pingos, river corridors, salt marshes, and small groves of trees near springs.

Nonacidic Tundra Regions

Most North Slope oil and gas development has occurred on nonacidic tundra. Because it grows on mineral-rich soils, this tundra is especially important to wildlife. It is home to many plants and animals, including four major caribou herds, three of which calve in areas of coastal nonacidic tundra. The nonacidic soils of the region could contribute to this wildlife diversity (see Chapter 3 for additional discussion of soil pH). The digestible, nutrient-rich vegetation could be especially important for caribou and other herbivores. The warmer soils could provide habitat for burrowing mammals, such as voles (*Microtus oeconomus*), ground squirrels (*Spermophilus parryi*), and lemmings (*Lemmus sibiricus*), which in turn could provide favorable hunting grounds for a variety of predators.

River Corridors

River corridors are probably the most biologically diverse and the most affected of the important terrain types in the Prudhoe Bay region. A diversity of plant communities occurs in association with waterways: ground squirrels, bears, and foxes use well-drained valley sites for their dens, and all predators find abundant prey along rivers. Riparian systems vary considerably. For example, riparian communities are different in loess and sandy regions. Communities are more diverse in warmer portions of the North Slope.

Rivers were among the first areas disturbed by oil and gas development because they are sources of gravel and routes for roads and buried pipelines. The lower portion of the floodplain of the Little Putuligayuk River (Figure 7-10) has been intensively mined for gravel and used for waste disposal; in places, it is no longer recognizable as a floodplain (Walker 1995). Fluvial processes are slowed in the Arctic because the highest flows tend to occur when most of the floodplain is frozen. As a result, areas altered by gravel mining take much longer to recover than is the case in lower latitudes. Some components of river floodplains, such as higher terraces, are more sensitive to disturbance and also are slow to recover.

Pingos and Bird Mounds

Pingos, another important landform of the Arctic Coastal Plain ecosystem, attract numerous species of animals, including arctic foxes (*Alopex lagopus*), arctic ground squirrels, caribou, grizzly bears (*Ursus arctos*), lemmings, raptors, buff-breasted sandpipers (*Tryngite subruficollis*), plovers, and ptarmigan (M.D. Walker 1990, Walker et al. 1991). The pingos around Prudhoe Bay are apparently quite old, and they do not erode easily or collapse as do

FIGURE 7-10. Floodplain of the Little Putuligayuk River. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

pingos composed of more fine-grained materials, such as those in the Mackenzie River delta (Mackay 1979, Walker et al. 1985). They consequently have old, well-developed plant communities (M.D. Walker 1990, Walker et al. 1991). Pingos attract people because some animal species, such as arctic foxes, are easily trapped at these sites, and pingos offer good vantage point for hunters and surveyors. Most of the accessible pingos in the Prudhoe Bay region are littered with vehicle trails, trash, and debris from geodetic surveys; a few are scarred with bulldozer trenches formed during the search for gravel.

Bird mounds, which usually are less than 1 m high, are scattered abundantly across the flat coastal plain (Walker et al. 1980). They are thought to have accumulated organic matter over long periods from fertilization by birds and small mammals. Predatory birds use these higher sites to observe the surrounding terrain. Other animals, such as voles and lemmings, take advantage of the relatively dry habitats. The importance of bird mounds to coastal plain ecosystems has never been evaluated, but they support diverse plant communities. They are easily damaged by ice road construction and camp moves during seismic operations.

Rare and Endangered Plants

Three North Slope plant species are considered endangered or threatened by the Nature Conservancy as listed in the *Alaska Rare Plant Field Guide* (Lipkin and Murray 1997): *Erigeron muirii* (Muir's fleabane), *Mertensia drummondii* (Drummond's bluebell), and *Poa hartzii* var. *alaskana* (Hartz's bluegrass). All three occur in dry habitats associated with dry bluffs, flood plains, river terraces, sand dunes, rocky slopes, outcrops, fellfields, and mountain summits. Those habitats are the primary sources of ballast and fill used for construction projects.

FACILITY REMOVAL, REHABILITATION AND RESTORATION OF GRAVEL-COVERED AREAS

Many industrial activities and their accompanying accidents and consequences—spills or discharges of oil or other materials; tundra travel; the construction and operation of roads, airstrips, gravel islands and pads; gravel mining; dust deposition, and impoundments—disturb surface environments (Walker 1996). The extent to which effects accumulate depends in part on whether efforts are made to ameliorate them. The oil and gas industry generally defines *rehabilitation* as the conversion of a disturbed site into functional habitat for plants and animals without necessarily restoring the original species and processes. *Restoration* means the replacement of lost habitat features, species, and processes that were present prior to disturbance (AOGA 2001).

As noted in Chapter 4, the committee commissioned an analysis of the history of the North Slope road and infrastructure network (also see Appendix E). The analysis included an estimate of the area affected by industrial development judged to be *rehabilitated*. Rehabilitated areas as defined by Aeromap, Inc., included areas that were no longer definable as clearly disturbed in aerial photographs or areas that now provide functional habitat but might be different from the original. In most cases, these areas were not restored to their former condition. Rehabilitation to some degree has occurred on only about 195 acres—about 1%—of gravel pads.

The rehabilitated area includes the gravel mines of the Sagavanirktok and Kuparuk river floodplains rehabilitated by natural river action, engineered rehabilitation that occurred on abandoned exploration pads, and the flooding of the deep gravel mines in the oxbows of the Kuparuk River. According to the analysis, rehabilitation has occurred on about 11 ha (26 acres) of abandoned airstrips, 15 ha (37 acres) of offshore gravel pads, 29 ha (72 acres) of on-shore gravel pads, and 1,841 ha (4,549 acres) of gravel mines. Gravel has been removed from about 79 ha (195 acres); and the sites are in various stages of recovery. About 95% of the rehabilitation has occurred in gravel mine areas.

Some of the shallow gravel mines in the floodplains of the Kuparuk and Sagavanirktok rivers have been allowed to recover by the natural action of the rivers. Before mining, floodplains consisted of a mosaic of barren active channels and barren and vegetated islands. Numerous river bars and islands eliminated by mining have not been restored. The deeper gravel mines are not restored to their previous condition, but they are considered rehabilitated by Aeromap because they provide winter fish habitat even though they are strikingly different from the original habitat.

Although the size of the gravel footprint required to support operations has been greatly reduced (Streever 2000), relatively little progress has been made on restoring existing sites affected by gravel fill. Only about 1% of the roughly 3,733 hectares (9,225 acres) of tundra habitat on the North Slope covered by gravel roads, pads, airstrips, and other facilities, has been rehabilitated, either naturally or from revegetation efforts. The factors that contribute to the low rate of site restoration include technical and natural constraints imposed by the harsh environment of the North Slope; the lack of clear regulatory requirements governing the level and timing of restoration; uncertainty about whether currently unused sites will be required in the future; contamination and liability concerns; and the high cost of removing facilities and restoring sites in the region. Each of these issues is addressed below.

Technical and Natural Constraints

The North Slope presents special technical challenges to restoration and recovery. Extremely cold temperatures, meager precipitation (13-18 cm [5-7 in.] per year), and the short growing season lengthen recovery times substantially beyond those possible elsewhere in the United States. Natural recovery of disturbed sites to original soil and plant conditions has been estimated to require 600-800 years for upland mesic sites and 100-200 years for marsh sites (AOGA 2001).

Recovery of disturbed sites on the North Slope is complicated by the fact that any disturbance of the insulating vegetative mat can melt the underlying permafrost, a process that is extremely difficult to reverse and that can continue long after the initial disturbance ends. Finally, gravel pads and roads, which account for the vast majority of the directly affected habitat on the North Slope, retain moisture and nutrients poorly and so slow recovery processes.

Recovery times in the Arctic, as elsewhere, depend in part on the nature and extent of disturbance and the type of habitat affected. For example, wet sites tend to recover quickly from light oil spills; dry sites affected by diesel fuel spills recover exceedingly slowly, with little recovery occurring after several decades (Walker 1996). Disturbed areas that would recover relatively quickly in more temperate climates (such as those caused by Caterpillar tractor tracks), can persist for many decades because of melted permafrost.

Restoration Research

During the past few decades, considerable industry research has examined the feasibility of rehabilitating areas disturbed by oil-field activities (McKendrick 1997). Until recently, that work has focused on revegetating sites with exotic grasses to avert erosion. More recent efforts have focused on the use of native grasses and forbs and on the restoration of habitat processes and aesthetics, all of which are much more challenging goals (AOGA 2001).

A variety of rehabilitation strategies has been developed, including flooding of gravel mine sites to create overwintering habitat for fish; creation of wetlands in ponds perched on overburden stockpiles; revegetation of thick gravel fill and overburden to compensate for lost wildlife habitat; removal of gravel fill to help restore wet tundra habitats; restoration of tundra on less severely modified habitats; and remediation of areas contaminated by oil spills, seawater spills, and drilling mud (Jorgenson and Joyce 1994). The oil industry is conducting experiments at several sites throughout the Prudhoe Bay oil field and at old well sites in the National Petroleum Reserve-Alaska. Preliminary results indicate that, if cost is not a factor, a productive and diverse vegetative cover can be established even on sites with severe ecological limitations. Most of the studies suggest that natural recolonization occurs relatively rapidly on thin fill and on organic rich fill where moisture and nutrients are not severely limiting (Jorgenson 1997). Low temperatures near the coast, however, reduce the number of species available and the rate at which recolonization occurs. A survey of 12 revegetated pads in the National Petroleum Reserve-Alaska showed that on average only 3 native species were found on pads at the cold coastal sites, 10 were found on inland coastal plain pads, and 24 were found on relatively warm foothills sites (McKendrick 1987). Fertilization and seeding with nonnative species appears to delay natural recolonization (Jorgenson 1997).

More costly methods are required for rehabilitating the gravel roads, pads, and mine sites that dominate disturbed land (Jorgenson 1995). Construction of berms and basins, application of topsoil, and use of various plant cultivation techniques are required on these sites. However, only a very limited amount of topsoil has been stockpiled for future use in the oilfields (Jorgenson 1997). Sewage sludge is being considered as an alternative source of organic material. Native legumes with nitrogen-fixing ability could be essential for sustaining the long-term productivity of those sites.

Removal of gravel fill has recently been done in wetlands, and preliminary studies suggest that wetland mosaics of vegetation can be restored, although the method is expensive and finding acceptable locations for the fill can be difficult.

Gravel extracted from 24 open-pit gravel mines, (ADNR) affects some 2,580 ha (6,364 acres) in various floodplains and deltas on the North Slope (Table 4-4). Rehabilitation typically involves converting mine sites to lakes, with a channel usually cut between the pit and a stream or river so the site can be accessible to fish. Such sites create potential overwintering habitat for fish, but they also result in the permanent loss of the original habitats.

Restoration Standards and Requirements

Existing state and federal laws and regulations governing surface restoration lack clear definitions and standards, and they overlap in potentially conflicting ways. The lack of definitions in the relevant statutes and regulations of clear restoration goals makes it difficult to plan and design restoration activities.

The Federal 404 Program

Section 404 of the Clean Water Act authorizes the U.S. Army Corps of Engineers to issue permits for the discharge of any type of fill material into waters of the United States, including wetlands. Because virtually all of the Arctic Coastal Plain is in wetlands, permanent facilities (roads, pads) require Section 404 permits, as do causeways, gravel islands, gravel mines, pipeline burial routes, and other construction activities, regardless of location on state, federal, or privately held land.

Until 1979, however, the corps did not exercise its Section 404 authority on the North Slope, and it estimates that about half of the area covered by gravel was filled without permits (USACE 2001a). The corps now lacks jurisdiction over those "unpermitted" sites, and no detailed mapping or inventory of them exists (USACE 2001a,b). Since 1979, 1,179 permits have been issued on the North Slope (USACE 2001b,c); 3 have been denied (GAO 2002). The corps has no estimate of the total area affected by its Section 404 permits (USACE 2001b).

Restoration is not mandatory even for gravel roads, pads, and other facilities constructed under Section 404 permits. Restoration upon abandonment is governed by General Condition 2, one of the conditions included in all standard 404 permits, which states: "... Should you wish to cease to maintain the authorized activity or should you desire to abandon it without a good faith transfer, you must obtain a modification of this permit from this office, which *may* require restoration of the area" (emphasis added) (Army Standard Permit). The corps takes the position that the ultimate authority over restoration lies with the landowner (the state for state leases, the Bureau of Land Management [BLM] for the National Petroleum Reserve-Alaska leases, and the Minerals Management Service [MMS] for the Outer Continental Shelf [OCS] leases) (USACE 2001b). Fewer than 1% of the permits issued contain restoration requirements that are accompanied by specific success criteria, principally percentage cover required (USACE 2001b). The requirements do not define methods for estimating cover, specify whether cultivars or native species are to be used, or include specific monitoring methods to determine success (Streever 2000). As a result, different methods of defining percentage cover have yielded very different results (Streever 2000). The corps has reported that the most lenient requirement found in a review of permits for the North Slope—30% cover in 3 years—could not be met for gravel pads.

Recently, the corps has included ecosystem process goals in several of its permits for new facilities. For example, the Alpine permit requires that, upon abandonment, the gravel footprint is to be rehabilitated "in a manner that maximizes benefits to fish and wildlife resources, and restores the natural hydrology of the immediate project area footprint" (404 Permit #2-960874, Special Condition 9). However, specific standards for achieving those goals, criteria to measure performance, the timing of implementation, and the type and amount of monitoring required are not specified.

The corps has required gravel reuse as a special condition of particular permits. The Northwest Eileen permit (USACE permit 4-2000-0041) requires the permit holder to "remove and recover gravel" from 3 abandoned sites. This involves using gravel from existing pads, roads, and other unused facilities rather than mining new gravel and restoring the old sites. Gravel reuse has been required in only 6 permits issued by the corps (USACE 2001b). If gravel reuse is added as a special condition, the permit holder must arrange to have the gravel tested for hydrocarbon contamination and cleaned (by burning hydrocarbons off) if necessary. In the event that the contamination is too severe to be removed effectively removed, the permit holder must identify another site of equivalent size that could serve as a source of gravel. Gravel reuse and revegetation can be expensive, particularly if decontamination is required.

The nature, extent, and timing of restoration required by gravel reuse permits or upon ultimate abandonment is not specified in regulations and is subject to the discretion of the corps' Alaska District. In exercising that discretion, the corps does not appear to have made systematic use of the substantial research conducted by the industry and others on revegetation and restoration. Various experimental trials of different approaches to revegetation have been conducted by the industry at least since 1984. Those studies have yielded important information about the establishment of vegetation on gravel (Streever 2000).

Compensatory Mitigation

National policy and guidelines developed by the Environment Protection Agency (EPA) and the Army Corps of Engineers in 1990 under the Section 404 program require "compensatory mitigation" for the unavoidable destruction of wetlands that can be achieved by restoring existing degraded wetlands or by creating new, artificial wetlands. Because, the corps and EPA have taken the position that the North Slope is exempt from the compensatory mitigation requirement, however, the corps is not required to oblige companies to restore old oil-field sites as a condition of new permits—a strategy that has worked elsewhere to promote restoration.

Other Federal Restoration Requirements

In addition to the Section 404 permitting program, the federal government may impose additional restoration requirements in leases it awards on federal land. Under lease terms awarded in the National Petroleum Reserve-Alaska, no permanent facilities may be established in the exploration phase (National Petroleum Reserve-Alaska FEIS, Stip. # 27). To date, however, BLM has not developed specific dismantlement, removal, and restoration (DRR) requirements to meet its general goal of returning disturbed land to its original primary use (wildlife habitat and wilderness) (GAO 2002).[1]

On the federal OCS, MMS regulations, lease terms, and lease stipulations impose stringent requirements regarding removal of structures and plugging and abandoning wells. In most circumstances elsewhere in the United States, MMS has required platform removal and clearing of the ocean of obstructions to other uses (30 CFR Sec. 250.700); the agency has not specified requirements for abandonment of North Slope gravel islands.

[1] Lessees of land in the National Petroleum Reserve-Alaska are required by the lease terms to "reclaim the land as specified by lessor." The final environmental impact statement specifies no restoration requirements, and it explicitly leaves open the possibility that facilities may be left in place upon abandonment. NPRA FEIS, Stip #58: "Upon field abandonment or expiration of a lease or oil- and gas-related permit, all facilities shall be removed and sites rehabilitated to the satisfaction of the AO, in consultation with appropriate federal, State, and North Slope Borough regulatory and resource agencies. *The AO may determine that it is in the best interest of the public to retain some or all of the facilities.*" (emphasis added).

State Restoration Requirements Applicable to State Land

The Alaska Oil and Gas Conservation Commission (AOGCC) imposes stringent well-plugging and abandonment procedures for all wells throughout Alaska, regardless of land ownership. The Alaska DNR oversees activities affecting the surface (other than spills or other contamination, which is handled by the Alaska Department of Environmental Conservation [ADEC]).[2] Current state lease terms specify removal of all machinery, equipment, tools, and materials within 1 year of the expiration of a lease; older lease terms for most Prudhoe Bay leases allow lessees to leave behind infrastructure with state permission (GAO 2002). Older and newer leases alike leave decisions regarding the nature, timing, and extent of restoration of gravel roads, pads, and other facilities to an undetermined future process (ADNR):

> At the option of the state, all improvements such as roads, pads, and wells must either be abandoned and the sites rehabilitated by the lessee to the satisfaction of the state, or be left intact and the lessee absolved of all further responsibility as to their maintenance, repair, and eventual abandonment and rehabilitation.

Thus, as with the federal government, decisions regarding whether sites must be restored after abandonment and to what extent are largely left to future regulators.

Offshore, artificial islands in state waters have been abandoned under plans approved by DNR, which typically involve removing surface hardware, and debris, providing shore protection to a specific depth, and then allowing the island to erode naturally.

Under the existing unitization agreements approved by the State, nothing within a unit must be officially abandoned until the entire unit is closed. So, for example, even if the state were to decide to impose stringent restoration requirements, the companies are not obligated to implement them on any abandoned sites within the Prudhoe Bay oil field until the entire unit has been closed. The Army Corps of Engineers, however, can require rehabilitation of individual pads within a lease or unit, although it has done so in only a few instances.

Whether the oil companies have a clear, substantive obligation to remediate sites on the North Slope has been examined by a court of law on only one occasion (Exxon 2000). In that case, the Internal Revenue Service challenged Exxon's deduction of expenses related to future restoration. The court held that the standard language of the leases under which Exxon and other oil companies conduct activity in the Prudhoe Bay oil field did not create a clear obligation on the part of the oil companies to undertake restoration in the oil field, with the exception of specific well-plugging and abandonment requirements imposed by the AOGCC.

The almost 76,000 m^3 (100,000 yd^3) of solid waste generated by oil-field operations every year, includes scrap metal, waste insulation, tires, wrecked vehicles and airplanes, and old buildings. Although there have been improvements in waste management, large amounts of scrap have accumulated over time and there is no comprehensive plan for its disposition. At times, scrap is sent out on the return trips of barges that bring supplies to Prudhoe Bay, but often barges are sent back to Anchorage from the North Slope without a load of scrap. Already, the state is facing disposal of abandoned drilling rigs for which corporate dissolution, bankruptcies,

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[2] Alaska statute AS46.03.822 makes owners and operators liable for "damages, for the costs of response, containment, removal, or remedial action" resulting from unpermitted release of hazardous substances. AS 46.03.826 defines hazardous substances to include oil and associated products and byproducts. The statute does not cover rehabilitation or restoration.

and mergers have clouded ownership (ADNR DPF 93-03), and the scrap issue is expected to become more serious as facilities age.

Local Government Restoration Requirements

The North Slope Borough has zoning authority that extends by ordinance to state, Native, and municipally owned land within the borough's boundaries. There is some debate over whether the borough's authority extends to federal land as well. The Coastal Zone Management Act requires consultation with the borough before leasing and development of federal land. The borough issues permits for most activities that affect the land surface. It may exercise its authority to require restoration of existing "orphan" sites (abandoned sites where ownership is unknown), of new-construction sites, or both as a condition of new permits. The committee found no evidence that the borough has exercised its authority to impose specific restoration requirements separately from those of other government agencies.

Local Native villages and corporations also control surface lands and subsurface mineral rights and can establish restoration requirements through contractual arrangements with the industry (GAO 2002).

Overlapping Authority

Because few restoration requirements have been imposed at the local, state, or federal level, overlapping jurisdiction among regulatory agencies has not been a major issue. However, as the fields age and as decisions about restoration begin to be made in earnest, the potential exists for inconsistent or contradictory restoration requirements applying to the same piece of land. For example, the Army Corps of Engineers, the state, and the North Slope Borough all have jurisdiction over activities on state land, and each is free to impose restoration requirements.

The lack of an effective, coordinated regulatory structure is partly to blame for the lack of significant progress in restoring disturbed North Slope sites. Without clear and specific standards, the industry faces significant uncertainty regarding what will and will not be acceptable to regulatory agencies. And without explicit time requirements and performance standards, there is little incentive for the industry to undertake expensive and complex restoration efforts. Finally, the absence of standards makes monitoring and enforcement difficult. In developing standards, flexibility must be built in to advance standards as restoration research advances.

Uncertainty Regarding Future Need for Sites

One obstacle to restoration and rehabilitation is uncertainty about whether old gravel roads, pads, airstrips, and other facilities might be needed in the future. As technology advances and the economics of production change, abandoned pads could become economically profitable to operate. Thus, there is some reluctance on the part of the industry to commit to restoring currently unused sites.

Contaminated Sites

The ADEC maintains a database of contaminated sites throughout the state. The database lists more than 90 contaminated sites associated with oil and gas activities on the North Slope. The extent and nature of contamination on those sites varies considerably.

As part of the charter agreement governing BP's acquisition of ARCO, the two companies agreed to assess and clean up 43 of their sites by the end of 2007 (Charter Agreement, II.A.3. and Exhibit D.2). BP and ARCO agreed to spend $10 million to assess and clean up another 14 orphan sites (Charter Agreement, II.A.1. and Exhibit D.1). ADEC confirmed that the 14 are the only known orphan sites, but that others are likely to be found (Judd Peterson, ADEC, personal communication, 11/13/01). The companies also agreed to work with ADEC to develop a database of contaminated and solid-waste orphan sites to identify the nature and location of the sites, the responsible parties, and the relative priority for cleanup of each based on an evaluation of risk to human health and the environment (State of Alaska et al. 1999).

Finally, as part of the charter agreement, ARCO and BP agreed to clean up 170 exploration and production reserve pits (Charter Agreement, Exhibit D.3.A. and D.3.B). This includes pits being cleaned out and closed pursuant to a 1993 consent agreement between environmental groups and ARCO. Another 158 pits in the area from the Canning River to Point Lay are being closed under the state's closeout regulations (J. Peterson, ADEC, personal communication, 2001). The contents of all production pits, and some exploration pits, are being ground and injected. The rest of the exploration pits are being closed using "freezeback," whereby below-grade pits are capped and allowed to freeze in place. One-hundred-eighty-four of the 328 reserve pits on the North Slope are now officially closed (ADEC 2002) but this does not necessarily mean that the sites have been restored. The fate of those sites, some of which could be affected by shoreline erosion, and of 5 "regional" drilling-waste disposal sites on the North Slope that used freezeback as the closure method is uncertain. Between 115,000 and 183,000 m^3 (150,000 and 240,000 yd^3) of waste was buried at each regional site (ADEC 2001a,b).

In addition to sites and reserve pits that are known to be contaminated, industry is concerned about the potential liability and expense associated with recycling possibly contaminated gravel from roads and pads. The ADEC has not studied the extent of contamination in gravel roads and pads (ADEC 2001b).

Economic Considerations

There have been no comprehensive estimates of the cost of dismantling and removing the roughly $50 billion worth of infrastructure installed over the past three decades on the North Slope or of restoring the thousands of square kilometers of tundra habitat affected by development (GAO 2002). Estimates for different projects indicate that the total cost will run into the billions of dollars.

Phillips Petroleum has estimated that it would cost between $50 million and $100 million to remove facilities and restore the Alpine area (Ryan 2001). With 30 million bbl (4.77 billion L, 1.26 billion gal) of oil produced to date, that cost is equivalent to $1.67–$3.33 per barrel. Alpine covers an area of 39 ha (97 acres) (MMS Liberty DPP Plan DEIS Table U.B-3), yielding an average restoration cost of between $1.2 million and $2.5 million per hectare ($500,000 and $1 million per acre). Assuming roughly similar costs to remove facilities and restore the estimated 3,600 ha (9,000 acres) of gravel-covered tundra on the North Slope, the overall cost of restoration could range from $4.5 billion to $9 billion.

In the context of litigation brought in 1989 and 1990, Exxon estimated that fieldwide costs to plug and abandon wells, dismantle and remove facilities, and close reserve pits using the freezeback method would be $928 million for the Prudhoe Bay field (not including gravel removal, revegetation, or grind-and-inject costs) (Exxon case 2000). The company calculated its share as $204 million. Exxon also estimated that well-plugging costs alone amounted to $132,000 per well (Exxon case 2000).

The Phillips 2000 *Annual Report* indicates that the estimated total future DRR costs stemming from its acquisition of ARCO Alaska amounted to more than $1.5 billion (Phillips 2000). Virtually all of Phillips holdings acquired from ARCO in Alaska are on the North Slope.

About 80 wells drilled on federal land in what is now the National Petroleum Reserve-Alaska were improperly plugged and abandoned, and some are leaking oil and other substances. The BLM estimates the cost to restore the sites at upwards of $100 million (GAO 2002).

The estimated cost to abandon two platforms in Cook Inlet is $31 million (VanDyke and Zobrist 2001).

The Army Corps of Engineers estimates that the average cost of gravel decontamination, reuse, and revegetation on the North Slope is approximately $2.5 million per hectare ($1 million per acre) of gravel picked up. With a total gravel footprint of 3,755 ha (9,225 acres) (see Chapter 4), the total cost is slightly more than $9 billion. However, that assumes that all the gravel would need decontamination, which is not the case.

The anticipated high cost of restoration on the North Slope raises concerns about whether adequate funds will be available to undertake restoration when production ceases. Most North Slope leases are now held by large, multinational, integrated oil and gas companies that clearly have the wherewithal to pay for abandonment and restoration.[3] However, if the North Slope follows the pattern exhibited by the rest of the industry in the United States, ownership is likely to change over time as production declines.

As large companies no longer find it economical to maintain leases, they could sell out to smaller companies with fewer expenses that can operate these leases profitably. A shift in ownership from large to small companies as fields age has already begun at Cook Inlet, where 14 of the 16 current offshore platforms began operations before 1969 (Van Dyke and Zobrist 2001). As production declined from 83 million bbl (13.2 billion L, 3.5 billion gal) per year in 1970 to 11 million bbl (2.75 million L, 462 million gal) per year in 1999, one large multinational company offered all of its Cook Inlet infrastructure for sale, and another sold 2 platforms to a much smaller independent business. A third sold its oil production facility to a smaller independent firm, although it retains its gas interest (Van Dyke and Zobrist 2001). A recent oil discovery in Cook Inlet has revived interest in the region.

If leases on the North Slope are transferred from the large multinational companies to smaller independent firms, the smaller concerns are less likely to have the resources to pay for restoration when production ceases. Existing state and federal bonding requirements are not remotely sufficient to cover the costs of restoration. The state DNR requires bonds of $500,000

[3] Following conventional accounting practices, the major companies that operate on the North Slope report amounts on their books that will be used for DRR. However, there is no actual money set aside for those purposes. DRR funds are, like depreciation, an accounting procedure, not actual cash accessible by subsequent leaseholders or government agencies.

per company statewide, whereas restoration of the Alpine oil field alone is estimated as $50 million to $100 million. The BLM requires bonds of $300,000 for the National Petroleum Reserve-Alaska, but the Army Corps of Engineers require no bonding for activities conducted under section 404 permits. Existing bond requirements also are intended to serve several purposes (among them to ensure royalty payments), further diluting the amount that would be available if needed for restoration.

The MMS bonding requirements are much higher: each company must have a $3 million statewide production bond. However, even this amount is sufficient to cover only a small fraction of estimated restoration costs. The MMS may require companies to post supplemental bonds equal to the estimated abandonment costs at the facility, but it has not yet done so on the North Slope.

The BLM, MMS, and DNR all specify that original lessees retain liability arising from activities that occurred before any lease transfer to other entities. In theory, this means original lessees would retain responsibility for restoration expenses.[4] However, it is not clear whether this will occur in practice. To date, there has been only one such transfer in Alaska, involving an offshore lease in Cook Inlet from a large multinational corporation to a smaller company. Because the multinational did not guarantee liability, the state raised the bond required of the new owner as a condition of the transfer (Van Dyke and Zobrist 2001). There are no formal criteria governing when additional financial assurances should be required (GAO 2002).

FINDINGS

Effects on Vegetation

- Effects of contaminant spills on North Slope vegetation have not accumulated because the spills have been small and cleanup and rehabilitation efforts at spill sites generally have been successful.
- Some 1,540 km (956 mi) of roads, 350 gravel pads, and the extensive gravel mining have combined to result in 7,011 ha (17,324 acres) of tundra and floodplains being directly covered by oil development. The total does not include the Trans-Alaska Pipeline and the Dalton Highway.
- Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to covering tundra with gravel, indirect effects on vegetation are caused by dust, roadside flooding, thermokarst, and roadside snow accumulation. The effects accumulate and interact with effects of parallel pipelines and with off-road vehicle trails. The measurable direct effects covered approximately 4,300 ha (10,500 acres) in the developed fields, not including indirect of effects of the Dalton Highway.
- The indirect effects associated with roads, reducing roadside flooding, dust-killed tundra, and thermokarst, are estimated to cover at least 4,300 ha (10,500 acres). This does not include areas affected by off-road vehicle trails, including seismic trails.
- Dramatic progress has been made in minimizing the effects of new gravel fill by reducing the size of the gravel footprint required for many types of facilities and by substituting ice for gravel in some roads and pads.

[4] Transfer of Section 404 permits does not require Army Corps of Engineers approval. The new owner assumes the permit obligations of the permit holder upon transfer.

- Roadside dust has resulted in the loss of mosses and in earlier snow melt along many roads. Acidic tundra areas along the Dalton Highway with abundant *Sphagnum* moss are particularly sensitive to dust. Chip-seal treatment of roads could dramatically reduce generation of roadside dust.
- Impoundments next to raised roadbeds and pads have caused extensive habitat changes in flat portions of the Arctic Coastal Plain.
- Higher summer soil temperatures near roads and pads results in thermokarst, which is continuing to expand outward from roads.
- Some nonnative species were introduced in seed mixtures and mulches, but most have not persisted and have not spread beyond the sites where they were introduced.
- Networks of seismic trails (as well as ice roads and pads) cover extensive areas of the tundra. The proprietary nature of industry-obtained seismic data made it impossible for the committee to determine the total line kilometers and location of seismic trails for the full period of oil exploration on the North Slope. According to the committee's best estimate, more than 52,000 km (32,000 mi) of seismic trails, receiver trails, and camp-move trails were created between 1990 and 2001, an annual average of 4,700 km (2,900 mi). The committee views seismic trails as producing a serious accumulating visual effect. The significance of ecological effects on vegetation of large areas of the North Slope is unclear.

About 96 % of trails from the 1984-1985 seismic exploration of the Arctic National Wildlife Refuge were not noticeable on the ground after 8 years of recovery, but an estimated 15 % of those trails are still visible from the air after 16 years of recovery. This would be a major concern for proposed future exploration in areas of high wilderness value if similar effects occurred.

- Data from the FWS provide good information regarding the long-term recovery from 2-D seismic exploration on trails that were created 15 years ago. However, the results might not be applicable to the high spatial density of the newer trails and larger camps associated with 3-D surveys. It is open to conjecture whether the continuing evolution in the technology of seismic-data acquisition would reduce effects.
- Current regulations require minimum average snow depth and frost penetration of 15 cm (6 in.) and 30 cm (12 in.), respectively, before seismic activities are permitted on the tundra. Those requirements are not based on scientific evidence. The variations in snow depth and density across the North Slope are not considered in the establishment of opening dates for seismic exploration each year, and 15 cm (6 in.) of snow is not sufficient to protect the tundra in many areas of the North Slope.
- The use of ice roads and ice pads has increased and will continue, but little information is available on how long effects will persist after one or more seasons pass.
- Because the hundreds of onshore spills that occur annually are well reported, they have been the subject of a great deal of concern among North Slope residents and others. However, because most spills have been small, have occurred on gravel pads, and have been cleaned up, the ecological effects of onshore spills have been small and localized and hence have not accumulated. However, such spills contaminate gravel, which impedes its reuse for environmental reasons (and adds liability and financial issues.)
- There have been no documented negative effects of air quality to vegetation in the Prudhoe Bay region, but the potential exists for local, long-term, effects of air pollutants on some types of vegetation, particularly lichens, to accumulate.

Areas of Special Concern

- Several North Slope landscape features are focal points of plant and animal diversity, including pingos, riparian corridors, salt marshes, and small groves of trees.
- The role of the coastal nonacidic tundra regions for wildlife has not been adequately studied.
- None of the three rare plant species found on the North Slope is threatened by current oil-field activities, although all occur in habitats that could be mined for gravel.

Facility Removal and Restoration

- Tundra sensitivity to disturbance, recovery from disturbance, and the effectiveness of rehabilitation techniques are all affected by local variations in climate, soils, and topography.
- The oil industry and the regulatory agencies have made strides in developing techniques for rehabilitating some disturbed habitats. The most difficult areas to reclaim contain the 3,736 ha (9,225 acres) covered by gravel roads and pads. Some of those are still in use. Only about 1% of that area has been rehabilitated.
- Liability for contaminated sites poses an obstacle to the reuse of gravel.
- State, federal, and local government agencies have largely deferred decisions regarding the nature and extent of restoration (with the exception of well-plugging and abandonment procedures). The lack of clear state or federal performance criteria, standards, and monitoring methods governing restoration is partly to blame for the lack of significant progress in restoring disturbed sites on the North Slope.
- Because the obligation to restore abandoned sites is unclear and because the financial capacity to do so uncertain, the committee judges it unlikely that most disturbed habitat on the North Slope will actually be restored unless those constraints change.
- Comprehensive restoration and landuse planning for the post-oil-and-gas era on the North Slope is lacking.
- No funds have been set aside for dismantling and removing the estimated $50 billion worth of existing infrastructure on the North Slope or for restoring the thousands of hectares of tundra affected by industrial activities. Total costs are likely to be billions of dollars.

RECOMMENDATIONS

Effects on Vegetation

- Long-term studies of the response of tundra plant communities to a variety of contaminants, including oil, diesel fuel, and saltwater, would promote the development of contaminant sensitivity and recovery potential maps.
- Changes in roadside thermokarst over time should be documented and monitored to determine long-term trends in the expansion of those areas.
- Studies are needed to determine the amount of snow and frost penetration required to protect tundra from the effects of seismic exploration. Some plant species are particularly sensitive to seismic trails, so the studies should consider effects at the plant-species level.

- Monitoring of the long- and short-term effects of off-road ice roads and other off-road trails is needed.
- An inexpensive monitoring program focused on lichens should document trends in the accumulation and effects of sulfur and other air pollutants on vegetation.

Areas of Special Concern

- Ecosystem and wildlife studies on the North Slope would benefit from spatial databases that include more detailed information on substrate chemistry, climate, and topography.
- A multiple-scale planning procedure is needed to identify areas of special botanical and wildlife concern, such as riparian systems, nonacidic tundra, coastal wetlands, and pingos, at regional, landscape, and plot-specific scales.

Facility Removal and Restoration

- A comprehensive, slopewide plan should be developed to identify landuse goals after the oil industry leaves. The plan should specify the rehabilitation and restoration objectives needed to achieve the goals, identify specific performance criteria and monitoring requirements tied to rehabilitation and restoration objectives, provide an inventory of facilities on the North Slope and information on ownership, identify contamination status and former habitat type, and discuss whether portions of the site might be likely to have future uses. It should include a mechanism to ensure that adequate financial resources will be available to restore public lands in accordance with the plan.
- Site-specific plans for eventual revegetation should be developed for each developed site, taking into account regional climate, substrate, and topographic setting.

8

Effects on Animals

Animals can be affected directly by oil and gas activities or indirectly via alterations in habitat or food supplies. At sea, animals can be affected by noise, particularly sounds generated by seismic exploration, and by spills of oil and other contaminants. On land, animals can be affected by noise associated with seismic exploration, routine industrial activities, vehicle and aircraft traffic, and disturbance of dens. In addition, animals can be indirectly affected by changes in vegetation caused by industrial activities, contaminant spills, withdrawal of water from lakes and streams, and by the availability of anthropogenic food sources. For obvious reasons, attention has been directed toward animal species such as whales, seals, fish, bears, caribou, and birds that have particular economic, esthetic, or cultural value. Most invertebrates and many smaller vertebrates have not been studied. A review of the fates and effects of oil in the sea (NRC 2003) details much recent information.

POPULATION DYNAMICS

Terrestrial animals are mobile as adults. They can move away from sources of disturbance or find new habitat. Declining populations in areas where local extinction is a danger, can be replenished by the immigration of individuals from other areas. The movements of individual animals, however, make it difficult to assess the effects of industrial activities on the North Slope. Data are needed on the behavior of individual animals and on trends over larger areas than are required, for example, to assess effects of road dust on plants.

Although many studies have examined the responses of various species on the North Slope to roads, ground and aerial traffic, gravel pads, pipelines, and impoundments, for example, it is difficult to assess the implications of the findings for the long-term population dynamics of those species. Rarely are data available with which to compare the quality of the lost or disrupted habitats with that of remaining, undisturbed habitats. There are only inadequate estimates of the total fraction of high-quality habitats affected by commercial activities.

To guide its thinking about effects of industrial activities on animals, the committee on the Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities used basic principles and concepts of population ecology. One process of central importance is habitat selection (Cody 1985). All animals select habitats for various activities (breeding, molting, hibernating) using clues associated with the suitability of habitats for those activities. Because individuals that make good habitat choices reproduce more successfully than those that make poor choices, populations evolve so that individuals prefer to be in habitats that best serve their needs. Thus, individual animals select the regions containing the best, on average, available habitats (Rosenzweig 1981), and use poorer habitats only when better habitats are fully occupied or when the density of individuals in the better habitats is high enough to lower expected success below levels attainable in poorer habitats. At a landscape scale, animals travel to regions that maximize long-term productivity, although in a particular year, those regions might not be the best (Griffith et al. 2002).

Biologists can use habitat selection behavior as an indicator of habitat quality. For example, because some species of waterfowl travel long distances after completing reproduction to molt in particular areas on the North Slope, we can assume that those are the best available molting areas and that their loss would force individuals to molt in less favorable places. Similarly, if caribou typically calve in specific areas, we can assume that those are the best available calving areas. Although data might not be available about the likely suitability of other areas—to which individuals might be displaced—it is prudent to assume that alternative areas are less desirable than the ones currently used.

When patterns of habitat occupancy are constrained by behavioral dominance or population density, a population is likely to have "source-sink population dynamics" (Hanski and Gilpin 1997), which result when reproductive rates are higher than death rates in high-quality habitats. The better habitats are sources of emigrants that disperse into and occupy poorer quality habitats (sink habitats), in which death rates exceed birth rates. Population densities can be quite high in sink habitats even though persistence of the species in those habitats depends on a regular supply of immigrants from source habitats.

An important consequence of source-sink population dynamics is that a substantial proportion of the population of a species can be found in sink habitats. Without detailed demographic data, distinguishing between source and sink habitats can be difficult at best (Pulliam 1988). Loss of source habitats could threaten the viability of a population even though most of the habitat occupied by the species in a region remains relatively intact. Thus, as activities and structures associated with oil and gas development expand into the National Petroleum Reserve-Alaska and into the foothills of the Brooks Range, the result could be an unexpected decline of species even though total habitat loss might be modest. In predicting the effects of expanded activity on the North Slope, the committee attempted to identify those species and areas where source-sink population dynamics are likely to be operating and used the available information to evaluate the likelihood that source-sink dynamics would occur. Although all receptors were considered from this point of view, source-sink dynamics was discussed only for those that appeared to be affected by it.

MARINE MAMMALS

Although primary productivity is low in the freshwater and marine ecosystems of northern Alaska, it is enough to support many species of carnivorous vertebrates. The marine mammal fauna off northern Alaska consists of three truly arctic species: ringed seal (*Phoca hispida*), bearded seal (*Erignathus barbatus)*, and polar bear (*Ursus maritimus*) and four subarctic species: spotted seal (*Phoca largha*), walrus (*Odobenus rosmarus*), beluga whale (*Delphinapterus leucas*), and bowhead whale (*Balaena mysticetus*) that move into the area seasonally from the Bering and Chukchi seas (Ferrero et al. 2000, Frost and Lowry 1984, Lentfer 1988). Beluga whales spend most of their time in the Beaufort Sea in deep offshore waters.

Bowhead Whales

The bowhead whale is large—up to 18 m (60 ft) long. It is a baleen whale that once was common in northern circumpolar waters. Massive exploitation by commercial whalers greatly reduced its numbers to the current five small groups in the Bering Sea, Okhotsk Sea, Spitzbergen, Davis Strait, and the Hudson Bay (Shelden and Rugh 1995).

The Bering Sea stock is found seasonally in the Bering, Chukchi, and Beaufort seas and in parts of the East Siberian Sea. For many centuries bowhead whales have been important nutritionally and culturally to the coastal Native people of western and northern Alaska (Inupiat), the Chukotka Peninsula (Inupiat and Chukchi) of the Russian Far East, and northwestern Canada (Inuit) (for example, see Krupnik 1987, Sheehan 1995, Stoker and Krupnik 1993). This stock was heavily exploited by commercial whalers beginning in 1848 and ending in about 1914 (Woodby and Botkin 1993). Before commercial whaling, the population is estimated to have been between 14,000 and 26,000 (Breiwick et al. 1981) with estimates of 22,000 animals having been taken (Shelden and Rugh 1995). By the end of the commercial whaling period it is thought that only a few thousand remained.

As a result of the 1993 census effort conducted off Point Barrow, Alaska, the Bering Strait stock of bowhead whales is estimated at 8,200 (95% estimation interval from 7,200 to 9,400) (Raftery and Zeh 1998). The estimated annual rate of increase from 1978 to 1993 was 3.2% with 95% confidence interval 1.4% to 5.1%. As described in Chapter 1, accurate censuses of bowhead whales were accepted only after long efforts by Alaska Native hunters to correct earlier work.

The Bering Sea stock of bowhead whales spends the winter (from about late November to about mid-March) in the Bering Sea primarily at or near the ice edge. In the spring, most bowheads move north from the vicinity of Saint Lawrence Island, along the Alaskan coast to Point Barrow and then eastward, with most reaching the Canadian part of the Beaufort Sea by early to mid-June (Shelden and Rugh 1995). Although many spring migrants move in newly forming open areas (leads) in the ice, bowheads also move through ice-covered seas (Clark and Ellison 1988, 1989; Clark et al. 1996), often breaking through ice (to at least 15 cm [6 in.]) to breathe (George et al. 1989). Most spend the summer in the Canadian part of the Beaufort Sea. During fall, (late August to mid-October), they migrate westward through the Alaskan part of the Beaufort Sea, then into the northern part of the Chukchi Sea, and then south along the Chukotka coast. Most return to the Bering Sea by mid-November.

Bowhead whales depend heavily on euphausiids and copepods (Carroll et al. 1987, Lowry 1993, Lowry and Burns 1980, Lowry and Frost 1984, Lowry et al. 2001), small prey (3-4 cm [1-2 in.]). Bowheads feed throughout the year, at least to some extent. There are inadequate data to properly evaluate the importance of the Alaskan portion of the Beaufort Sea as feeding habitat for bowhead whales, especially during their fall migration. Because this is the time when they are susceptible to disturbance by the noise of exploration for oil, the information is needed for a full assessment of the effects of noise on bowheads.

It probably takes about two decades for a bowhead to achieve sexual maturity. Conception likely occurs in late winter or early spring, and calves are usually born during the spring migration (Kenney et al. 1981; Koski et al. 1993; Rugh et al. 1992; Shelden and Rugh 1995; Tarpley et al. 1983, 1999; Tarpley and Hillmann 1999). Bowheads can live 100 years or more (George et al. 1995, 1999).

Oil- and Gas-Related Activities and Bowhead Whales

The activities most likely to affect bowhead whales are marine seismic exploration, exploratory drilling, ship and aircraft traffic, discharges into the water, dredging and island construction, and production drilling. To date there have been documented effects of industrial noise. As was true of early censuses, the current understanding of the effects of noise on bowheads was achieved only after long efforts of Alaska Native hunters to correct early, imperfect studies (Chapter 1). There have been no major offshore oil spills on the North Slope.

Marine seismic exploration produces the loudest industrial noise in the bowhead whale habitat. Some seismic surveys are conducted in winter and spring on the sea ice, but most are done in the summer-autumn open-water period. Thus, bowheads and seismic boats are in the same areas during the westward fall migration. In the nearshore Alaskan Beaufort Sea, nearly all the fall-migrating bowhead whales avoided an area within 20 km (12 mi) of an operating vessel, and deflection of the whales began at up to 35 km (21 mi) from the vessel (Richardson 1997, 1998, 1999; NMFS 2002). Noise levels received by these whales at 20 km (12 mi) were 117-135 dB (NMFS 2002).

Disturbance to fall migrating bowhead whales also has been shown in relation to offshore drilling in the Alaskan Beaufort Sea. At the 1992 Kuvlum site the approaching fall-migrating whales began to deflect to the north at a distance of 32 km (19 mi) east of the drilling platform and bowhead calling rates peaked at about the same distance (Brewer et al. 1993). At the 1993 Kuvlum #3 site the whales were nearly excluded from an area within 20 km (12 mi) of the drilling platform (Davies 1997, Hall et al. 1994).

During the 1986 open-water drilling operations at the Hammerhead site, no whales were detected closer than 9.5 km (6 mi) from the drillship, few were seen closer than 15 km (9 mi), and one whale was observed for 6.8 hours as it swam in an arc of about 25 km (15 mi) around the drillship (LGL and Greeneridge 1987). The zone of avoidance therefore seemed to extend 15-25 km (9-15 mi) from the drillship. Acoustic studies done at the same time provided received levels of drillship noise that can be related to the zone of avoidance. At 15 km (9 mi) from the 1986 Corona, site received sound was generally 105-125 dB (LGL and Greeneridge 1987); at 11 km (6 mi) from Hammerhead, received sound was generally 105-130 dB.

Estimating Future Accumulation of Effects

Industrial Noise

If oil- and gas-related activities continue in the Alaskan waters of the Beaufort Sea, the major noise will be generated with marine seismic exploration. Other significant noise will continue to be produced by exploratory and production drilling, island construction, and vessel transit. The probable consequences are diversion of animals from their normal migratory path, possibly into areas of increased ice cover, and less use of the fall migration corridor as feeding habitat.

If two or more types of disturbance occur at the same time or in the same general area, the effects could be greater than those observed from single sources. The greatest diversion would occur if two or more seismic vessels operated simultaneously with one just offshore of the other.

Such a disturbing influence set across the migratory path could displace the whales seaward into areas where ice conditions are more dangerous for hunters, prevent some whales from passing, reduce use of the area as feeding habitat, and affect the other behavior in the animals.

Spilled Oil

There are no data on Arctic oil spills and bowheads because no major oil spill has occurred in the Beaufort Sea. However, the potential for an oil spill and its likely effects on bowhead whales are viewed by bowhead-dependent hunters as the greatest threat to the whale population and to their cultural relationship with the animal (Ahmaogak 1985, 1986, 1989; Albert 1990). Oil spilled in broken-ice cannot be cleaned up effectively, and it is expected that whales would not avoid oil-fouled waters.

Each environmental impact statement (EIS) relating to industrial activity in the Beaufort Sea contains estimates of the likelihood of an oil spill. For example, the final EIS for Beaufort Sea Planning Area Oil and Gas Lease Sale 170 (MMS 1998 IV-A-12) estimated a 46-70% chance of a spill of 1,000 barrels (bbl) or more. Increasing industrial activity in the Beaufort Sea, coupled with existing production at the Endicott and Northstar facilities, would lead to rising probability of a significant oil spill.

The *Exxon Valdez* experience shows that cleaning up spilled oil is difficult, even in ideal conditions in ice-free waters (Loughlin 1994). An oil spill would be most difficult to control during periods of broken ice—in the fall when bowheads migrate through the area. During this period, new ice is forming, slush ice is often present, ice is in the form of chunks and pans, and ice formed earlier can move into the area with the drifting and shifting ice pack. Mechanical recovery alone would likely be able to clean up only a small fraction of oil in broken ice (ADEC 2000).

An oil spill would pose less risk to bowhead whales if the whales could detect spilled oil and avoid it. Although there is no direct evidence about how bowhead whales would react to oil-fouled waters, Dall's porpoise, harbor porpoise, killer whales, and grey whales moved through waters contaminated by the *Exxon Valdez* accident (Harvey and Dahlheim 1994). Also, fin, humpback, and probably right whales did not avoid an oil spill off Cape Cod, Massachusetts (Goodale et al. 1981, cited in BLM 1982). Bowhead whales regularly surface in slush ice, and easily break through thin ice to breathe, so they are unlikely to avoid surfacing in oil-covered waters. The toxic effects that inhalation of oil vapors and ingestion of oil on bowhead whales would probably be similar to those described for seals and polar bears, below.

A modest amount of attention has been devoted to studying the likely effects of spilled oil on bowheads (for example, see Albert 1981b, Hansen 1985 and Beaufort-Sea-related EISs). One method compares the structure of the various tissues of the whale that are most likely to contact the oil with those of better-studied mammals. Related studies of the bowhead, begun in the late 1970s with examination of subsistence harvested whales and with the collection and examination of tissues from those whales (Albert 1981a, Kelley and Laursen 1980), indicated that the skin, the eyes, the baleen, and the lining of the gastrointestinal tract of bowhead whales are likely to be injured by contact with spilled oil (Albert 1981b).

The Skin

The skin of a bowhead whale is 10-22 mm (0.4-0.9 in.) thick over much of its body (Haldiman et al. 1981, 1985, 1986). Although bowheads have the soft, smooth skin typical of most cetaceans, they also have dozens to hundreds of roughened areas (1-4 cm [0.4-1.6 in.] diameter) of skin surface (Albert 1981b, Haldiman et al. 1985, Henk and Mullan 1996) the cause of which is not yet known (see Figure 8-1). In some of the roughened areas, the epidermal cells between the epidermal rods have been removed. The exposed epidermal rods then appear as tiny hairlike or filamentous projections. The great increase in exposed surface (microrelief) of these roughened areas increases the area to which oil can adhere. In a laboratory experiment, oil adhered, in proportion to the roughness of the skin surface, to formalin-preserved bowhead skin exposed to crude oil on water (Haldiman et al. 1981). The roughened areas of skin had large numbers of diatoms and bacteria, including potential pathogens with varying tissue-destructive enzymes (Shotts et al. 1990). Thus, it is likely that oil contact would be harmful.

The Eyes

The conjunctival sac associated with the eye is so extensive that an adult human's fingers can pass beneath the eyelids and reach approximately two-thirds of the way around the eye (Albert 1981b, Dubielzig and Aguirre 1981, Haldiman et al. 1986). Thus, a large surface exists for an irritant (such as spilled oil) to contact sensitive visual structures (Zhu 1996, 1998; Zhu et al. 2000, 2001).

The Baleen

Bowheads filter prey from the water with their extensive baleen apparatus (Lambertsen et al. 1989). Many of the hair-like filaments that form the margin of the baleen plates break off during feeding and are commonly found in the stomachs of harvested bowheads. Because the bowhead's baleen apparatus is so extensive and the filaments on the margin of each plate are so prominent, the baleen would be fouled if a whale fed in oiled waters (Albert 1981b, Braithwaite 1980, 1983).

A laboratory study (Braithwaite et al. 1983) showed that crude oil strongly adhered to isolated bowhead baleen and interfered with filtration efficiency for approximately 30 days. Less of an effect on filtration was found on isolated baleen (fin, sei, humpback, gray whale) characterized by short, rather stiff bristles (Geraci 1990, Geraci and St. Aubin 1982, 1985). Petroleum also had little direct effect on isolated baleen from several whale species (St. Aubin et al. 1984). A bowhead probably could filter out the heavier portions of spilled oil, including globules and "tar balls," and would probably swallow the oily material and the dislodged oiled baleen filaments along with its prey.

The Stomach

Broken-off baleen bristles swallowed during feeding can form "tangles" in the stomachs of bowheads (George et al. 1988). Those dislodged bristles could combine in the stomach with weathered oil components (such as tar balls) to form a sticky mass (Albert 1981b).

The stomach of the bowhead whale consists of four chambers, one of which is a narrow channel that connects two other larger chambers (Tarpley 1985; Tarpley et al. 1983, 1987). Blockage, leading to gastric obstruction, could occur in this small, narrow connecting channel, which has small entrance and exit openings, if a bowhead fed in oil-fouled waters (Albert 1981b). Ingested oil would also have toxic effects whose severity would be related to the amount of oil swallowed.

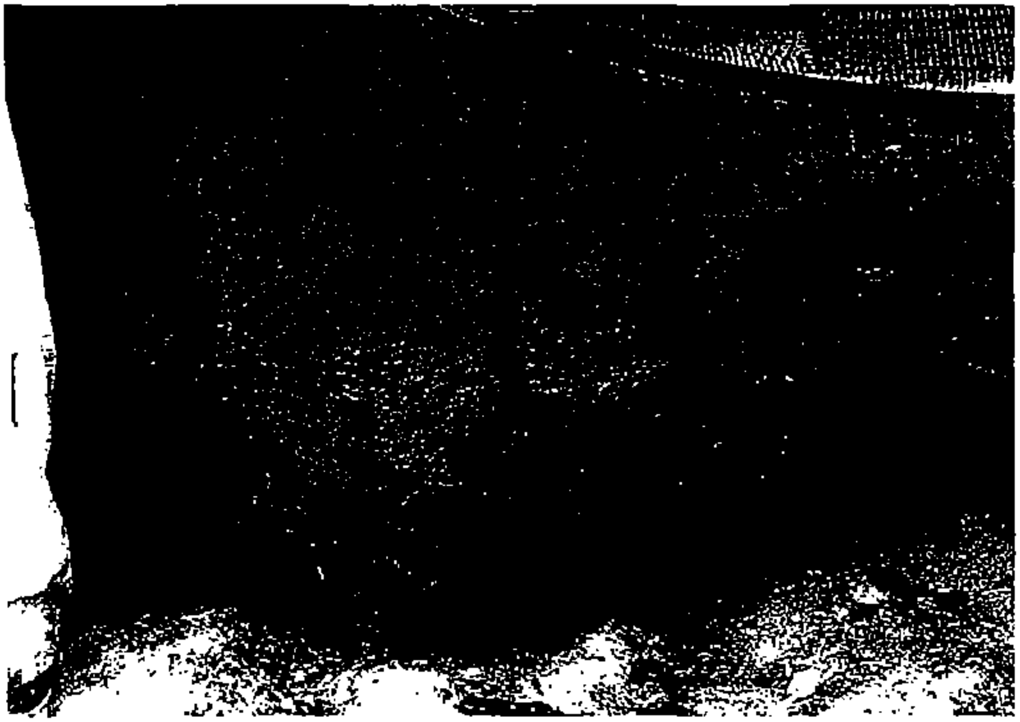

FIGURE 8-1. Subsistence harvested bowhead whale, on the ice at Barrow. This photo shows a portion of the left side of the head. The blowhole area is in contact with ice (near knife). A portion of left row of baleen is visible in the upper right of the photo. Note the large number of lesions (arrows) on the skin surface. These commonly seen eroded areas make the skin surface much rougher than in unaffected areas. A section of skin with lesions (upper right of photo) was removed from the skin of the upper jaw.

Findings

- Noise from exploratory drilling and marine seismic exploration causes fall-migrating bowhead whales to divert around noise sources, including drillship operations and operating
- seismic vessels, at distances of 15-20 km (9-12 mi).
- In view of the large zone of near total avoidance around a single operating seismic vessel, if more than one such vessel is operating in the Alaskan portion of the Beaufort Sea when fall-migrating bowheads are in those waters, the diversion of migrating whales could be much increased.
- Data needed for an improved assessment of the effects of seismic noise was delayed for many years due to overreliance on a study that underestimated such effects, and because of inadequate consideration given to relevant observations by subsistence hunters.
- Available data are inadequate regarding the full effects of industrial noise (seismic noise in particular) on fall-migrating bowhead whales in the Alaskan portion of the Beaufort Sea.
- There are inadequate data regarding the importance of the Alaskan portion of the Beaufort Sea as feeding habitat for the bowhead whale, especially during the fall migration.
- Harm to marine mammals from contact with spilled oil (as in the *Exxon Valdez* experience and other instances) and specific morphological characteristics of the bowhead whale (eroded areas of skin, extent of conjunctival sac, narrowness of stomach-connecting channel) indicate that spilled oil would pose a great potential threat to those organs in bowhead whales.

Recommendations

- Studies should determine the distance from an operating seismic vessel (and received noise at that distance) at which the "average" bowhead whale begins to deflect, begins to change its rate or type of vocalization, reaches the point of greatest deflection, and returns to the normal migration path. Studies also should examine the effects of multiple noise sources in different configurations.
- Studies should determine the extent to which bowhead whales make use of the Alaskan portion of the Beaufort Sea as feeding habitat.
- The use of sound to divert whales from a spill site and prevent them from contacting spilled oil should be investigated.

Seals and Polar Bears

In Alaska, spotted seals, bearded seals, and walrus spend most of their time in the Bering and Chukchi seas and generally use only the westernmost part of the waters off the Alaska North Slope. Ringed seals and polar bears are common in waters off the North Slope where oil and gas exploration and development have occurred. The main areas of concern with regard to effects on those animals from oil and gas activities are the potential for contamination (reviewed by Geraci and St. Aubin 1990) and for disturbance caused by industrial noise in the air and water (reviewed by Richardson et al. 1995).

The effects of industrial activity on marine mammals in the North Slope have been difficult to measure. Clearly, spilled oil can be toxic to marine mammals (Geraci and St. Aubin

1990, Loughlin 1994, NRC 2003), although there have been no major spills in the Beaufort Sea, or in any similar arctic environment, so no field data exist that can be used to evaluate or predict consequences. Observations and studies of responses of marine mammals to noise are difficult to interpret (Richardson et al. 1995); nevertheless, it is clear that noise can cause pronounced behavioral reactions and displacement of some species. However, it has not been possible to predict the type and magnitude of responses to the variety of disturbances caused by oil and gas operations, or, most important, to evaluate the potential effects on populations. Whether there are effects on the biology of the affected marine mammal species, displacement of animals could have important consequences for Alaska Natives seeking to harvest those animals for subsistence.

Hunting and Other Deaths Caused by Humans

Before the Marine Mammal Protection Act (MMPA) became law in 1972, active sport hunting for polar bears off western and northern Alaska reduced that population (Amstrup et al. 1986). Since then, marine mammals may be hunted only for subsistence and handicraft purposes by Alaska Natives, and there are no federally imposed limits on that hunting unless populations are declared depleted. Since 1988, hunting of polar bears from the southern Beaufort Sea stock has been controlled by a conservation agreement between the Inupiat of northern Alaska and Inuvialuit of the western Canadian Arctic who hunt a shared population (Nageak et al. 1991); the number of animals taken each year is well documented. From 1988 to 1995 the average annual take of 58.8 bears was well below the estimated "potential biological removal level" of 73 (FWS 1998) and therefore was considered safe.

Little is known about the number of ringed seals harvested, but they are an important subsistence resource to indigenous people throughout the Arctic (Smith et al. 1991). Alaska Native dependence on, and interest in, hunting marine mammals is influenced by many factors, including cultural involvement, employment, community wealth, logistics, and ice and weather conditions. The number of animals killed by hunters can be expected to vary accordingly. However, current legal restrictions should prevent harm to populations of these animals if they are properly enforced.

Marine mammals also are killed in other ways. At least one ringed seal pup has been killed by a bulldozer that was clearing seismic lines on shore-fast ice of the Beaufort Sea. A polar bear died on the North Slope apparently after eating a container of dye used to mark temporary airstrips (Amstrup et al. 1989). It is not uncommon for residents to shoot polar bears in defense of life and property, both in coastal communities and at industrial facilities. Two polar bears were killed in this manner along the Beaufort Sea coast in 1990 and 1993, one at the Stinson oil exploration site and the other at Oliktok Point (Scott Schliebe, FWS, personal communication). Regulatory agencies and the oil and gas industry have made serious efforts to minimize interactions with polar bears, both to increase human safety and to safeguard the bears (Truett 1993).

Oil

Laboratory experiments in which three polar bears were coated with crude oil showed dramatic effects (Øristland et al. 1981). Oil ingested during grooming caused liver and kidney damage. One bear died 26 days after oiling and another was euthanized. Stirling (1990) detailed numerous behavioral characteristics and ecological considerations that suggest that polar bears are especially susceptible to oil contamination. Laboratory experiments also have been done to determine the effects of oiling on ringed seals (Englehardt et al. 1977). After 24 h in a pen with oil-covered water, ringed seals' blood and tissues showed evidence of hydrocarbons that had been incorporated through inhalation, and kidney and liver damage. In another study (Geraci and Smith 1976), three seals died within 71 minutes after oil was put into their pool, presumably because of a combination of hydrocarbon inhalation and stress. Data presented by St. Aubin (1990a) described the various ways that pinnipeds could be affected by oil, much of it confirmed by studies of effects of the *Exxon Valdez* oil spill on harbor seals (Frost et al. 1994a,b; Lowry et al. 1994; Spraker et al. 1994; NRC 2003). However, as far as is known, neither ringed seals nor polar bears have been affected by oil spilled as a result of North Slope industrial activities.

Noise

Most of the effort to describe the effects of noise and disturbance on marine mammals has been devoted to studies of bowhead whales. However, pinnipeds also react to a variety of disturbances, such as noise from aircraft and ocean vessels (Richardson et al. 1995). Some studies of the potential effects of disturbance on shore-fast ice on pupping ringed seals have been done. Those studies showed that there was probably some displacement of ringed seals from areas close to artificial islands in the central Beaufort Sea (Frost and Lowry 1988), and that there was a higher abandonment rate of seal breathing holes close to seismic survey lines (Kelly et al. 1988). Noise probably affects haulout behavior of pinnipeds but no quantitative data are available. From data collected in the central Beaufort Sea from 1985 to 1987, Frost and colleagues (1988) concluded that there were no broad-scale effects of industrial activity on ringed seals that could be measured by aerial surveys, but they also noted that there was little offshore activity during those years. Subsequent industry-funded monitoring studies for the Northstar and Liberty projects suggested minor effects on ringed seals from ice road construction and seismic exploration (Harris et al. 2001, Richardson and Williams 2000). For most of the year, polar bears are not very sensitive to noise or other human disturbances (Amstrup 1993, Richardson et al. 1995). However, pregnant females and those with newborn cubs in maternity dens both on land and on sea ice are sensitive to noise and vehicular traffic (Amstrup and Gardner 1994). Seismic exploration has disturbed a bear in a maternity den (FWS 1986). Current regulations require industry to avoid polar bear dens as much as possible (FWS 1995b).

Habitat Changes

Human activities in, on, and adjacent to sea ice can cause habitat changes that affect marine mammals. In winter, ringed seals maintain holes in the shore-fast ice, and they give birth to their pups in lairs under the snow in spring (Smith and Stirling 1975). If the thickness of the ice, the amount and distribution of snow cover, or the timing and characteristics of breakup change, seal productivity or survival will be reduced (Furgal et al. 1996, Smith and Harwood 2001). Polar bears can be attracted to artificial structures that create leads in the ice because the leads increase the area bears use to hunt ringed seals. Buildings also offer places for bears to forage for human discards and stimulate their curiosity (Stirling 1988a). Not only does this increase the likelihood that bears will encounter contaminants, but it also increases the chances they will need to be driven away or killed to protect human safety. Ice breaking, especially in areas of shore-fast ice, obviously would result in major changes to habitat, with likely effects on ringed seals and polar bears.

In waters off the North Slope, ringed seals feed principally on arctic cod, euphausiids, and amphipods (Lowry et al. 1980). Those species, along with bowhead whales, copepods, and seabirds, form a relatively simple pelagic trophic system with some obvious potential for competitive interactions (Frost and Lowry 1984). Ringed seals are the primary prey of polar bears (Smith 1980, Stirling 1988b). Changes in population sizes of any of these species, either natural or caused by humans, could affect other components of the ecosystem.

For polar bears, mark-recapture studies in the Beaufort Sea suggest that the population increased considerably between 1967 and 1998 (Amstrup et al. 2001), probably because hunting has been limited (Amstrup et al. 1986). Ringed seals are harder to count. Efforts to develop a program to monitor ringed seals in the Beaufort Sea region began in 1985-1987 and continued in 1996-1999. Analysis of data from 1970 to 1987 (Frost et al. 1988) suggested the density of hauled-out seals fluctuated considerably from a high of 3.5 seals per km^2 (9.1 seals per mi^2) to a low of 1.1 seals per km^2 (2.6 seals per mi^2). Results of more recent surveys are being analyzed (Frost et al. in prep). Neither assessment program is sensitive enough to detect the substantial changes in population size that would be expected to result from oil and gas exploration and development and other human activities. However, because so far the marine waters of the Beaufort Sea have seen only limited and sporadic industrial activity, it is likely that there have been no serious effects or accumulation of effects on ringed seals or polar bears.

Permitting Incidental Take

The Marine Mammal Protection Act prohibits the taking of marine mammals—including polar bears and ringed seals—except in specifically permitted circumstances. The MMPA allows the secretary of commerce to permit industrial operations (including oil and gas exploration and development) to take small numbers of marine mammals, provided that doing so has a negligible effect on the species and will not reduce the availability of the species for subsistence use by Alaska Natives. Regulations governing the permits identify permissible methods, means to minimize harm, and requirements for monitoring and reporting. The permits have been used to minimize the effects of on-ice activities on pupping ringed seals, to require planning and personnel training that minimizes conflicts with polar bears, and to provide buffer zones around known polar bear maternal den sites.

Potential for Accumulation of Effects

No formal projections have been made of how likely effects on ringed seals or polar bears from future oil and gas activities are to accumulate with effects of other human activities, although the U.S. Fish and Wildlife Service (FWS) has produced a useful review of current and future threats to polar bears and their habitats (FWS 1995b). For purposes of making such a projection, the committee's scenario assumes that offshore exploration for oil and gas, and possible extraction, will occur in the Beaufort Sea from Barrow to Flaxman Island, and possibly to the Canadian border. Activity would occur mostly near shore, adjacent to onshore oil reserves, and development would entail methods and structures similar to those currently in use (gravel islands or bottom-founded structures, horizontal drilling, buried pipelines, and an emphasis on working during winter).

Full-scale industrialization of near-shore areas would most likely result in at least partial displacement of ringed seals. The frequency with which polar bears come into contact with people and structures is undoubtedly a function of the amount of activity in their habitats. Even with the best possible mitigation measures in place, it is certain that some bears will be harassed or killed. More human activity along the coast and near shore could reduce the suitability of some areas for use by denning female bears. This effect is likely to be greatest east of the Canning River, especially within the 1002 Area of the Arctic National Wildlife Refuge, where the highest concentration of on-land dens is found (Amstrup 1993, Amstrup and Gardner 1994). Efforts to identify areas where polar bears are most likely to den in the eastern part of the North Slope (Durner et al. 2001), should improve the ability of regulators and industry to reduce disturbance of denned bears.

Contact with spilled oil or other contaminants in the ocean would harm ringed seals and polar bears, and the likelihood of spills would increase with increased exploration and development. Amstrup and colleagues (2000) modeled the spread of a hypothetical 5,900 bbl (939,000 L, 248,000 gal) oil spill from the Liberty prospect[1] as it might affect the seasonal distribution and abundance of polar bears in the Beaufort Sea. The number of bears potentially affected by such a spill ranged from 0 to 25 with summer open-water conditions and 0 to 61 with autumn broken-ice conditions. In its findings permitting the oil and gas industry to take polar bears in Alaska waters, the FWS stated, "We conclude that if an oil spill were to occur during the fall or spring broken-ice periods, a significant impact to polar bears could occur" (Federal Register 65:16833). It seems likely that an oil spill would affect ringed seals the same way the *Exxon Valdez* affected harbor seals (*Phoca vitulina*) (Frost et al. 1994a, Lowry et al. 1994, Spraker et al. 1994), and the number of animals killed would depend largely on the season and the size of the spill. Polar bears could be further affected if they ate oil-contaminated seals (St. Aubin 1990b).

Climate change also will affect marine mammals (Tynan and DeMaster 1997). Sea ice is important in the life of all marine mammals in the arctic and subarctic regions (Fay 1974). Already, there have been dramatic decreases in the extent and thickness of sea ice throughout the northern hemisphere, and those trends are expected to continue through the next century (Vinnikov et al. 1999, Weller 2000). The distribution, abundance, and productivity of Alaskan marine mammal populations will likely be altered by the combined effects of changes in physical habitats, prey populations, and inter-species interactions (Lowry 2000). Warming is likely to

[1] The Liberty prospect is not being developed as of late 2002.

increase the occurrence and residence times of subarctic species (spotted seals, walrus, beluga whales, bowhead whales) in the region.

Negative effects on populations of truly arctic species (polar bears, ringed seals, and bearded seals) are likely to result from climate warming. Polar bears and ringed seals depend on sea ice, and reductions in the extent and persistence of ice in the Beaufort Sea will almost certainly have negative effects on their populations (FWS 1995b). Climate change has already affected polar bears in western Hudson Bay, where bears hunt ringed seals on the sea ice from November to July and spend the open-water season on shore where they feed little. In a long-term study, Stirling and colleagues (1999) documented decreased body condition and reproductive performance in bears that correlated with a trend toward earlier breakup of sea ice in recent years. The earlier breakup gives bears a shorter feeding season. They are leaner when they come ashore, and they must fast longer. Many ringed seals give birth to and care for their pups on stable shore-fast ice, and changes in the extent and stability or the timing of breakup of the ice could reduce productivity (Smith and Harwood 2001). Because of the close predator-prey relationship between polar bears and ringed seals, decreases in ringed seal abundance can be expected to cause declines in polar bear populations (Stirling and Øritsland 1995).

How these independent factors might combine to influence populations cannot be predicted with current knowledge. If climate warming and substantial oil spills did not occur, cumulative effects on ringed seals and polar bears in the next 25 years would likely be minor and not accumulate.

Currently there are no research plans or studies that specifically address potential accumulating effects on polar bears or ringed seals off the North Slope. Unless such studies are designed, funded, and conducted over long periods (decades) it will be impossible to verify whether the effects occur, to measure their magnitude, or to explain their causes.

Findings

- Industrial activity in marine waters of the Beaufort Sea has been limited and sporadic and likely has not caused serious cumulative effects on ringed seals or polar bears.
- Careful mitigation can help to reduce the effects of North Slope oil and gas development and their accumulation, especially if there is no major oil spill. However, the effects of full-scale industrial development of the waters off the North Slope would accumulate through displacement of polar bears and ringed seals from their habitats, increased mortality, and decreased reproductive success.
- A major Beaufort Sea oil spill would have major effects on polar bears and ringed seals.
- Climate warming at predicted rates in the Beaufort Sea region is likely to have serious consequences for ringed seals and polar bears, and those effects will accumulate with the effects of oil and gas activities in the region.
- Unless studies to address potential accumulation of effects on North Slope polar bears or ringed seals are designed, funded, and conducted over long periods, it will be impossible to verify whether such effects occur, to measure them, or to explain their causes.

CARIBOU

Introduction

The effects of North Slope industrial development on barren-ground caribou (*Rangifer tarandus granti*) herds have been contentious. Although much research has been conducted on caribou in the region, researchers have disagreed over the interpretation and relative importance of some data and how serious data gaps are. The disagreements are especially significant because caribou are nutritionally and culturally important to North Slope residents and because caribou are widely recognized as important symbols of the state and well-being of North Slope environments. For these reasons, the committee assembled information on caribou and evaluated conflicting interpretations of the information about how oil and gas development might have affected their population dynamics. The committee's consensus on effects to date, and projections of probable future effects, is the product of this careful analysis and deliberation.

Assessing the effects of oil and gas development on caribou is not straightforward because many factors other than oil and gas activities affect the sizes of North Slope caribou herds—changes in weather vegetation, disease, and predators, for example. Therefore, there is no steady baseline against which to identify and assess disturbance-induced changes. To evaluate the effects of petroleum development on caribou, the committee examined changes in distribution and habitat use, and evaluated the nutritional and reproductive implications of those changes and how they altered population dynamics.

Background

Caribou are ubiquitous on the North Slope. Four separate herds, ranging nearly 20-fold in size, are recognized on the basis of distinctly different calving grounds (Skoog 1968, Figure 8-2). The extent of seasonal migration varies with herd size (Bergerud 1979, Fancy et al. 1989, Skoog 1968). By far the largest is the Western Arctic Herd (WAH), estimated at 460,000 (in 2001). It calves in the Utukok uplands south of Barrow and summers throughout the North Slope and Brooks Range west of the Colville River, including most of the National Petroleum Reserve-Alaska. Wintering areas include both the western North Slope and the southern foothills of the Brooks Range. The annual range of the Teshekpuk Lake Herd (TLH), numbering 27,000 (in 1999), lies within the WAH summer range. Calving and summer ranges are in the coastal zone near Teshekpuk Lake; the winter range typically is confined to the coastal plain and nearby foothills. Estimated at 123,000 (in 2001), the Porcupine Caribou Herd (PCH) calves on the coastal plain and lower uplands in northeastern Alaska within the Arctic National Wildlife Refuge and adjacent Yukon Territory. During the summer, the PCH ranges throughout much of the eastern North Slope and Brooks Range; its wintering areas include the Ogilvie and Richardson mountains in western Canada and the southern Brooks Range in eastern Alaska. At 27,000 (in 2000), the Central Arctic Herd (CAH) is distributed primarily within state lands between the Colville and Canning rivers. CAH calving and summer ranges are on the coastal plain, and the winter range typically extends southward into the northern foothills of the Brooks Range. During the past 27 years, the size of the PCH has been nearly constant; the other three herds have increased substantially (Figure 8-3).

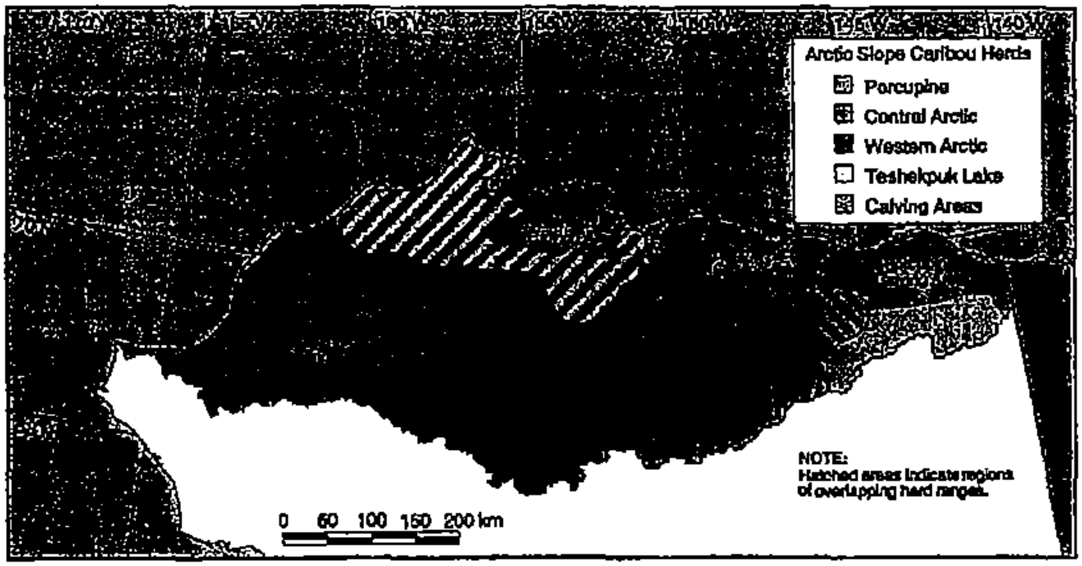

FIGURE 8-2. Arctic Caribou Herds. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

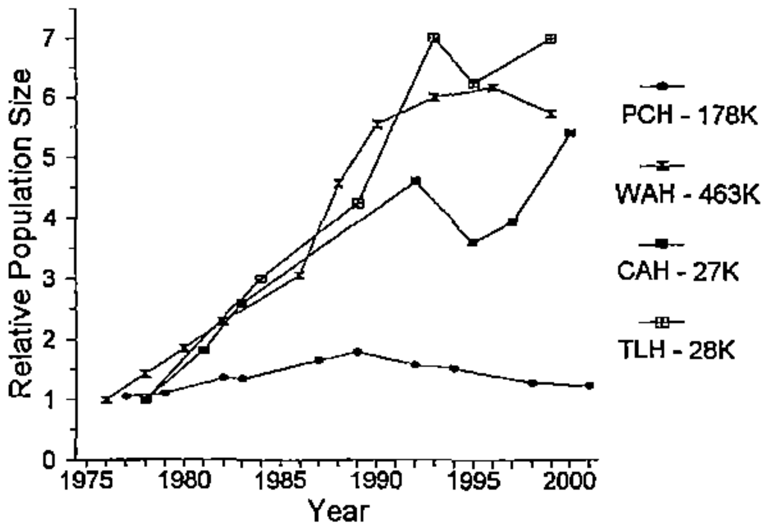

FIGURE 8-3. Relative post-calving herd sizes (minimum observed = 1.0) of the 4 Alaska barren-ground caribou herds (PCH = Porcupine caribou herd; WAH = Western Arctic herd, CAH = Central Arctic herd; TLH = Teshekpuk Lake herd), 1976-2001. Maximum observed population size for each herd is noted in the legend. Source: Griffith et al. 2002.

Central Arctic Herd

For the past 50 or 60 years, all four herds (Figure 8-2) have been exposed to oil and gas exploration activity, but only the CAH has been in regular and direct contact with surface development related to oil production and transport. Its calving ground and summer range lie within the oil-field region near Prudhoe Bay; its autumn, winter, and spring ranges encompass the Dalton Highway (also called the Haul Road) and the area around the Trans-Alaska Pipeline (Cameron and Whitten 1979b). The CAH has increased from around 5,000 animals in the late 1970s to its current (2000) size of 27,000 (Figure 8-3).

Parturient females, along with most nonparturient females and yearlings, arrive on the coastal calving ground in mid-May (Gavin 1978, Smith et al. 1994). The exact timing depends on patterns of snowfall and snowmelt (Cameron et al. 1992, Gavin 1978). Most calving occurs within 50 km (31 mi) of the Beaufort Sea (Whitten and Cameron 1985, Wolfe 2000). Virtually all calves are born between late May and early June (Cameron et al. 1993) within two or three calving concentration areas (Whitten and Cameron 1985, Wolfe 2000). At the landscape level, selection and repeated use of a calving ground is probably related to both the distribution of predators, which are less abundant on the coastal plain (Rausch 1953; Reynolds 1979; Shideler and Hechtel 2000; Stephenson 1979; Young et al. 1992, 2002), and the likelihood of favorable foraging conditions (Griffith et al. 2002). Annual shifts in concentrated calving within the overall calving ground are driven by spatial changes in the quality and quantity of new forage, principally sedges (Bishop and Cameron 1990, Wolfe 2000). An additional advantage of coastal calving is proximity to "insect-relief habitat," which eliminates the need for extensive travel with a young calf.

Bulls and the remaining noncalving females and subadults, which stay inland during the calving period, follow the northward progression of plant growth (Whitten and Cameron 1980), arriving on the coastal plain in late June (Cameron and Whitten 1979, Gavin 1978). The midsummer diet includes a variety of deciduous plants (Roby 1978; Trudell and White 1981; White and Trudell 1979, 1980; White et al. 1975, 1981).

Insects substantially affect nutrient balance by reducing food intake and by increasing energy expenditure. Mosquitoes are present from late June through late July (White et al. 1975, Russell 1976, Dau 1986). On warm, calm days, when mosquitoes are active, caribou move rapidly to cooler, windier areas on or near the coast, returning inland to preferred feeding areas when harassment abates (Cameron and Whitten 1979, Cameron et al. 1995, Child 1973, Dau 1986, Roby 1978, White et al. 1975). These movements appear to optimize foraging opportunity relative to energy expenditure (Russell 1976, Russell et al. 1993, Walsh et al. 1992, White et al. 1975). Oestrid flies (warbles and nose bots) emerge in mid-July and persist through early August (Dau 1986). When oestrids are active, caribou stand head-down or run erratically (Dau 1986, Nixon 1990, Roby 1978). This behavior probably reduces larval infestation, but it increases activity and reduces feeding time at the expense of nutrient balance (Helle and Tarvainen 1984, Murphy and Curatolo 1987, Russell et al. 1993).

By autumn, caribou move inland (Cameron and Whitten 1979a), and breeding occurs from late September through mid-October, while enroute to the winter range. Most of the CAH winters in the foothills and mountainous terrain of the northern Brooks Range, although a few caribou typically remain on the coastal plain year round (Cameron and Whitten 1979b, Cameron et al. 1979, White et al. 1975). Lichens, which are low in protein, predominate in the winter and spring diets (Roby 1978).

Ecological Strategies

During June and July, caribou body energy and nutrient reserves are low (Chan-McLeod et al. 1999, Gerhart et al. 1996), and parturient and maternal females attempt to maximize their intake of high-quality forage (Klein 1970, Kuropat 1984, Kuropat and Bryant 1979, Russell et al. 1993, White et al. 1975). They replenish body protein reserves mobilized during late gestation (Gerhart et al. 1996) and attempt to meet or exceed the metabolic demands of lactation (White et al. 1975, 1981), which are highest during the first 3 weeks postpartum (Chan-McLeod et al. 1999, White and Luick 1984). The benefits of good nutrition include increased growth rates (Allaye-Chan 1991, White 1992) and survival of calves (Haukioja and Salovaara 1978). Good nutrition is enhances summer weight gain of a female and increases the probability that she will conceive in autumn (Adams and Dale 1998; Cameron and Ver Hoef 1994; Cameron et al. 1993, 2000; Dauphiné 1976; Eloranta and Nieminen 1986; Gerhart et al. 1997b; Lenvik et al. 1988; Reimers 1983; Thomas 1982; Thomas and Kiliaan 1998; White 1983).

The intake of high quality forage often is reduced by adverse weather. A late spring snowfall or late snowmelt decreases forage quality and availability, resulting in lower birth weight (Adamczewski et al. 1987, Bergerud 1975, Eloranta and Nieminen 1986, Espmark 1979, Reimers 2002, Rognmo et al. 1983, Skogland 1984, Varo and Varo 1971) and delayed parturition (Cameron et al. 1993; Skogland 1983, 1984), both of which reduce survival of offspring (Adamczewski et al. 1987, Eloranta and Nieminen 1986, Haukioja and Salovaara 1978, Rognmo et al. 1983, Skogland 1984). From late June through early August, repeated and often severe insect harassment reduces the frequency and duration of both suckling (Thomson 1977) and foraging bouts (Helle et al. 1992, Mórschel and Klein 1997, Russell et al. 1993, Toupin et al. 1996). The result is less nursing opportunity, and—because fewer maternal nutrients are allocated to milk—lower rates of milk intake. Factors that individually or collectively reduce a female's ability to raise a calf also reduce her ability to restore her body reserves, to fatten, and to breed (Crête and Huot 1993).

Tradeoffs therefore are inevitable: If maternal protein or fat reserves are not replenished fast enough, calves are weaned prematurely (Russell and White 2000). Calf survival is reduced by early weaning, but parturition and conception rates increase (Davis et al. 1991, Russell and White 2000). Delayed weaning enhances calf survival, but extended lactation precludes breeding that year (Gerhart et al. 1997a,b; Russell and White 2000). By comparison, well-fed cows initiated weaning during the rut, and both calf survival and fecundity are high.

During August and September, when insects are absent, growth of calves and fattening of adults continue relatively unimpeded. Milk production is low (White and Luick 1984), and offspring graze actively (Russell et al 1993) as they approach nutritional independence. Although most forage species have senesced, with a decline in quality, their high biomass permits high rates of food intake (White et al. 1975) and, therefore, body-fat synthesis. Fattening is enhanced in some years by the inclusion of mushrooms in the diet (Allaye-Chan et al. 1990). An unseasonably early, heavy snowfall, however, can disrupt the fattening process, and movement into more mountainous terrain increases exposure to predators. Hunting by humans tends to intensify in early autumn as well.

Females that wean their calves early, together with most that are in good enough condition to wean at normal times, conceive in October (Russell and White 2000). Cows in superior condition are less likely to lose their embryos early (Crête and Huot 1993, Russell et al. 1998), and, hence, are more likely to produce a calf the next spring.

A dietary shift from deciduous vegetation to lichens, begun in autumn, is virtually complete by midwinter. Males and nonpregnant females typically maintain body weight (Steen 1968) even when weather and foraging conditions are unfavorable. In contrast, pregnant females, faced with the increasing metabolic demands of a growing fetus, have difficulty maintaining nitrogen balance. They metabolize muscle tissue and conserve body fat during the last trimester to support early lactation (Chan-McLeod et al. 1994, Tyler 1987). Adequate winter nutrition increases the chances of timely parturition and early postnatal survival (Cameron et al. 1993, Eloranta and Nieminen 1986, Rognmo et al. 1983).

When snow is deep or encrusted, foraging requires more energy because caribou must dig through the snow (Fancy and White 1985a,b; Miller 1976). Far more serious is ground-fast ice. During frequent freeze-thaw cycles, typically in coastal areas during late winter or early spring, vegetation under the snow becomes encased in ice and thus inaccessible (Miller and Gunn 1979, Miller et al. 1982). As during autumn, mortality from predation and hunting can be appreciable.

Effects on Distribution, Movements, and Activity Patterns

Seismic Surveys

Until recently, the location and timing of seismic testing resulted in few conflicts with caribou in arctic Alaska. Surveys on state lands through the 1990s were conducted principally within the area of the CAH summer range, but during winter, when caribou were largely absent. Similarly, long-term programs within the National Petroleum Reserve-Alaska during the 1970s and 1980s occurred mostly within the summer ranges of the TLH and WAH, but again during winter. Seismic exploration crews on the coastal plain of the Arctic National Wildlife Refuge in the 1980s had no contact with caribou of the PCH, which winters south and east of the Brooks Range.

Even when seismic testing was conducted on winter range, the direct effects on caribou were probably temporary and minor. Early two-dimensional (2-D) surveys were of low intensity and, because wintering bands of caribou tend to be small and often widely dispersed, few caribou would have been in simultaneous contact with seismic activities. Moreover, caribou appear least sensitive to human-induced disturbance during winter (Roby 1978).

Recently, however, both the extent and intensity of seismic activities have increased. Active exploration now extends southward into the upper foothills of the central Brooks Range and westward to new lease tracts in the northeastern portion of the National Petroleum Reserve-Alaska. With a seismic line density 10-20 times greater than that for 2-D procedures, expanded application of the new three-dimensional (3-D) technology in those areas will increase the potential for conflicts with the CAH and TLH. Avoidance of seismic lines and the attendant human activity could reduce the animals' ability to avoid areas of deep snow (Dyer et al. 2001). The energy costs of multiple encounters with seismic disturbance could increase winter weight loss and reduce calf production and survival (Bradshaw et al. 1998).

Exploration and Drilling

Most exploration drilling—a site-specific, high-intensity event—is not connected to a permanent road system. As novel features on the landscape, drilling sites that are active in late spring almost certainly would be avoided by calving caribou. During midsummer, effects include localized changes in habitat use, longer approach distances, and altered activity patterns (Roby 1978, Wright and Fancy 1980). Caribou did not approach a drilling site closer than 1,200 m (0.7 mi) and were seen less frequently within 2 km (1.2 mi) of a drilling site than in a control area. Those entering the drilling area spent less time feeding and lying and more time moving than did caribou in a control area (Wright and Fancy 1980). In studies involving a simulated gas compressor station, caribou usually avoided the source of sound by at least 0.2 km (0.12 mi) (McCourt et al. 1974). Sensitivity appears to decline during other seasons, when calves are older.

Isolated Roads and Pipelines

Perhaps as an anti-predator strategy (Bergerud and Page 1987), parturient females and postpartum females with newborn calves distance themselves from potentially threatening stimuli. Aerial survey observations before and after placement of a road system (and later, an aboveground pipeline) through a calving concentration area near Milne Point (Whitten and Cameron 1985), in the Kuparuk Development Area (KDA), illustrate that sensitivity. After construction, the density of maternal females increased with distance from roads; no relationship was apparent before construction (Dau and Cameron 1986). Mean caribou abundance declined by more than two-thirds within 2 km (1.2 mi) of roads and was less than expected, overall, within 4 km (2.5 mi); but abundance nearly doubled at 4-6 km (2.5-3.7 mi) (Cameron et al. 1992), resulting in two separate concentrations (Dau and Cameron 1986, Lawhead 1988, Smith and Cameron 1992). Road traffic was light during the study (Dau and Cameron 1986; Dau and Smith, unpublished data; Lawhead 1988), suggesting that the presence of a road or pipeline alone, without vehicular or human activity, can elicit avoidance.

Concurrent ground observations within the KDA corroborate those findings. Few females and calves were seen from the road system during early June, and correspondingly few were observed crossing roads or pipelines (Smith et al. 1994). This is consistent with a tendency for parturient females to be relatively sedentary during the calving period (Fancy and Whitten 1991, Fancy et al. 1989).

A similar pattern of avoidance of a tourist resort and separate power-line corridor has been reported for semi-domesticated reindeer (*Rangifer tarandus tarandus*) during the calving period. Mean reindeer densities within preferred habitat were 73% and 78% lower in areas less than 4 km (2.5 mi) from the resort and power-line corridor, respectively, than in areas beyond 4 km (2.5 mi). Traffic and human activity were low, again implying a dominant influence of the structures themselves (Vistnes and Nellemann 2001).

From late June through July, sensitivity to disturbance appears to decline as calves mature and are less vulnerable to predation and other sources of mortality. Maternal females are less protective and therefore less reactive to novel stimuli than during the calving period. Also, when insect harassment is high, caribou are less likely to avoid anthropogenic disturbances (Murphy and Lawhead 2000).

Even so, avoidance of transportation corridors can persist through summer. During construction of the Trans-Alaska Pipeline, 1975-1978, calves were increasingly underrepresented among caribou observed from the Dalton Highway; calf percentages, on average, were 69% lower than regional estimates determined by aerial survey. Caribou sightings within, and crossings of, the pipeline corridor in 1976-1978 averaged 30% and 80% less, respectively, than did those in 1975 (Cameron and Whitten 1980, Cameron et al. 1979). Collared males crossed the corridor more frequently than did collared females (Whitten and Cameron 1983). Jakimchuk and colleagues (1987) attributed those observations to sex differences in habitat use, arguing that maternal females avoid riparian habitats to reduce the risk of predation by grizzly bears along the Sagavanirktok River, which is adjacent to the pipeline corridor. A reexamination of the data, however, revealed that bull numbers were high and calf numbers were low only within riparian areas associated with the corridor (Whitten and Cameron 1986). Young and McCabe (1998) reported neither avoidance of riparian habitats by PCH females nor selection of those habitats by bears; they also rejected the antipredator explanation.

Similar avoidance was observed within the KDA, during placement of the smaller Kuparuk pipeline along the Spine Road and during construction of the first processing facility. Calves were underrepresented in groups observed in areas of heavy construction and traffic (Smith et al. 1994).

Within the CAH summer range, crossing success[2] varies with design and juxtaposition of roads and pipelines, as well as with the amount of vehicular traffic. Most early pipelines in the Prudhoe Bay oil-field complex (PBOC) were constructed 1 m or less above ground, posing physical barriers to movement (Shideler 1986). Gravel ramps were placed over some low pipelines to encourage crossings, but anecdotal observations indicated that caribou made limited use of those structures. In the adjacent KDA, however, all pipelines were elevated at least 1.5 m (5 ft), and ramps were built at road intersections. Curatolo and Murphy (1986) reported no selection for particular surface-to-pipe clearances within the range of 1.5-4.3 m (5-14.1 ft), indicating that, under most conditions, the regulatory standard of 1.5 m (5 ft) is sufficient for caribou crossings (Cronin et al. 1994, Curatolo and Murphy 1986). However, crossing success at elevated pipelines close to roads with traffic was lower than for pipelines without associated roads and traffic (Curatolo and Murphy 1986). Large mosquito-harassed groups had particular difficulty negotiating road-pipeline corridors (Child 1974; Curatolo and Murphy 1986; Fancy 1983; Smith and Cameron 1985a,b). Crossing success appears to increase during the oestrid fly season, but it is unclear whether that is attributable to the presence of smaller groups or to different reactions to the two insect pests (Smith and Cameron 1985a). Under some circumstances, ramps enhance pipeline crossings (Child 1973, Cronin et al. 1994, Curatolo and Murphy 1986, Shideler 1986, Smith and Cameron 1985b).

Effects on caribou activity near road-pipeline corridors are most pronounced when there is no insect harassment. During insect-free periods, maternal and nonmaternal groups within 600 m (2,000 ft) of a corridor with traffic spent less time lying and more time moving than did controls. Maternal groups and groups of more than 10 individuals were most reactive to disturbance (Murphy 1988, Murphy and Curatolo 1987).

[2] Curatolo and Murphy (1986) considered a crossing successful when more than half of an observed group crossed a road and/or pipeline (or a hypothetical pipeline in a control site). Success was then expressed as a percentage which was evaluated statistically by comparison with the corresponding "expected" percentage obtained from the control site.

From autumn through early spring, the CAH has considerably less contact with industrial development. By the autumn rut, most of the herd has moved well inland (Cameron and Whitten 1979a). Only those few caribou that winter on the coastal plain are likely to interact with oil fields, and the effects appear to be minor. However, females with calves avoided inland portions of the Trans-Alaska Pipeline corridor during its construction. Calf percentage for caribou near the Dalton Highway was approximately representative of regional percentages in 1975, but diverged during 1976-1978, averaging 32% less than regional estimates. Sighting frequency declined about 60%, relative to the 1975 estimate, but crossing rates were inconsistent (Cameron and Whitten 1980, Cameron et al. 1979). Overall, avoidance of the pipeline corridor by females with calves decreased measurably between summer and autumn, correlated with the advanced age of the calves and distractions of the rut. Habituation to construction activity is also a possibility.

Oil-Field Complexes

Given that calving caribou avoid roads and pipelines (Cameron et al. 1992, Dau and Cameron 1986), their densities should be reduced in areas with corridors closer together than some minimum distance. In fact, the proportion of calving caribou in the densely developed western portion of the KDA declined significantly from 1979 through 1987 (Cameron et al. 1992). Concentrated calving activity shifted inland from the Milne Point area beginning about 1987 (Lawhead et al. 1993, 2002; Murphy and Lawhead 2000; Wolfe 2000), associated with the increasing density of oil-field infrastructure. Caribou did not abandon the area near Milne Point (Lawhead et al. 2002, Nellemann and Cameron 1996), but continued to occupy the KDA in numbers consistent with the amount of undisturbed habitat. Other explanations advanced for the inland shift west of the Sagavanirktok River include expansion of the calving ground with increasing herd size, changing vegetation characteristics, and parasite avoidance (Lawhead et al. 2002). One or more of these factors could have accelerated that process. However, none explains the absence of a similar shift by the undisturbed part of the caribou herd east of the Sagavanirktok River (Wolfe 2000).

During the summer insect season, dense surface development within the PBOC also altered the distribution of caribou, especially females with calves. As early as 1978, mean calf percentage in the core area of the industrial complex was less than half the minimum regional estimate (Smith and Cameron 1983). With continued growth of the complex, changes in caribou distribution became even more pronounced. An analysis of more than 1,200 point locations of 141 radio-collared females (Cameron et al. 1995) suggests that caribou use of the area has declined substantially from that noted by Child (1973), White and colleagues (1975), and Gavin (1978). From 1980 through 1993, abundance within and east-west movements through the area were lower than for other areas along the arctic coast. Conservative calculations yielded an estimated 78% decrease in use and a 90% decrease in lateral movements.

Other researchers (Cronin et al. 1998, Pollard et al. 1996a) concluded that the PBOC infrastructure has had little effect on the midsummer distribution of caribou. However, the studies lack important data needed to support that conclusion. Without spatial controls—undeveloped areas—they lacked the ability to compare the distribution of cows with calves in the field as a whole with that in either the denser central area or in the less-developed areas to the northwest. Many caribou, including some females and calves, do periodically use the

PBOC, particularly the less-developed northwestern areas (Murphy and Lawhead 2000, Ballard et al. 2000). Moreover, data reported by Pollard and colleagues (1996a) indicate that caribou were numerous in the PBOC only during periods of moderate or high insect harassment and that females with calves generally were underrepresented. These latter data and evidence for reduced abundance and movements of females with the complex (Smith and Cameron 1983, Cameron et al. 1995) indicate that patterns of caribou use have been appreciably altered.

Changes in Habitat Use

Ecological theory and data support the premise that animals generally select the best available areas for reproductive activity. For calving CAH caribou, the probable consequence of disturbance-induced changes in distribution is selection of lower-quality habitats. The number of caribou affected is directly related to the area and intensity of disturbance, which could range from the localized avoidance of an isolated road to a regional shift of large calving concentrations away from areas occupied by multiple oil field complexes. With the gradual loss of access to preferred foraging habitats, increasingly more females seek "next best" available areas. As those areas become insufficient to accommodate the population, use declines at a rate proportional to the increase in density of structures (Nellemann and Cameron 1998, UNEP 2001).

The shift in calving activity west of the Sagavanirktok River might have increased predation risk, particularly in recent years. Since at least 1995, the inland calving concentration west of the river has overlapped extensively with relatively high densities of brown bears (R. Shideler, unpublished data). However, estimates of calf survival during 1988-2001 were similar west and east of the river (84% and 88%, respectively; $P = 0.426$) (Table 8-1), implying that any increase in mortality attributable to predation was compensatory (that is, predation on calves predisposed to die from other causes).

Oil-field infrastructure also can delay or prevent access to insect-relief areas and foraging habitats. In the KDA, the lower success of or delays in crossing road-pipeline corridors by large insect-harassed groups of caribou (Curatolo and Murphy 1986, Murphy 1988, Murphy and Curatolo 1987, Smith and Cameron 1985b) apparently encouraged a general shift to peripheral areas of the complex with less surface development and human activity. Routes of movement within and through the KDA are now primarily in the Oliktok Point/CPF-3 area and along the Kuparuk floodplain (Smith et al. 1994). This shift suggests that caribou were impeded in their efforts to move between coastal and inland habitats.

Much of the PBOC poses a behavioral, if not a physical, barrier to movement of adult females at times (Cameron et al. 1995, Whitten and Cameron 1983). Radio-collared females were scarce in the most densely built (and oldest) part of the complex (Figures 8-4 and 8-5), especially when insects were relatively inactive. During periods of moderate to high insect activity, caribou south of the complex often divert eastward, into the prevailing northeasterly winds, to the Sagavanirktok River and move downstream to the coast (Lawhead et al. 1993). Alternatively, caribou might occupy gravel pads for insect relief (Noel et al. 1998, Pollard et al. 1996b, Truett et al. 1994) when other habitats are unavailable (Wolfe 2000).

Table 8-1 Parturition rates of radiocollared female caribou[a] and summer survival of their calves, west and east of the Sagavanirktok River[b], during 1988-1994[c] and 1998-2001[d]. Central Arctic Herd, Alaska.

Years(s)	Parturition rate, %[e] (n) West		Parturition rate, %[e] (n) East		P^g	Calf survival, %[f] (n) West		Calf survival, %[f] (n) East		P^g
1988	72.7	(11)	100.0	(8)		66.7	(6)	100.0	(6)	
1989	53.8	(13)	77.8	(9)		83.3	(6)	60.0	(5)	
1990	83.3	(12)	100.0	(7)		85.7	(7)	60.0	(5)	
1991	45.5	(11)	75.0	(12)						
1992	72.7	(11)	75.0	(12)		87.5	(8)	100.0	(9)	
1993	55.6	(9)	62.5	(8)		100.0	(5)	100.0	(5)	
1994	66.7	(6)	87.5	(8)		75.0	(4)	85.7	(7)	
1988-1994	64.3 ± 5.0		82.5 ± 5.3		0.003	83.0 ± 4.6		84.3 ± 8.0		0.898
1998	92.3	(13)	100.0	(6)		90.9	(11)	100.0	(6)	
1999	100.0	(13)	100.0	(8)		88.8	(9)	100.0	(8)	
2000	83.3	(12)	90.0	(10)		77.8	(9)	77.8	(9)	
2001	90.9	(11)	100.0	(7)		80.0	(10)	100.0	(5)	
1998-2001	91.6 ± 3.4		97.5 ± 2.5		0.062	84.4 ± 3.2		94.4 ± 5.5		0.091
All years	74.3 ± 5.3		88.0 ± 4.1		0.001	83.6 ± 2.9		88.4 ± 5.3		0.426

[a] All sexually-mature.
[b] Individual locations consistently west (oil field development present) or east (no surface development, except for the Badami pipeline and oil field beginning in 1996) during the calving period.
[c] Forty-three females observed for 2-7 years (Cameron 1995; Cameron et al. 2002).
[d] Twenty-nine females observed for 2-4 years (Lenart, ADF&G, unpublished data, 2002).
[e] Based on parturition status determined by fixed-wing aircraft (Cameron et al. 1993).
[f] Percentage of parturient females with calf at heel 2-6 weeks postpartum.
[g] *t*-test, paired comparisons. Mean and standard errors shown.

Changes in distribution and movements during calving and when insects are present reduce the capacity of the range to support CAH caribou. This is due to loss of preferred habitats (Cameron et al. 1995, Wolfe 2000) and through correspondingly greater use of lower-quality habitats (Klein 1973, Nellemann and Cameron 1996, Wolfe 2000).

Nutrition and Reproductive Implications

The reproductive success of arctic female caribou is highly correlated with their nutritional status. Parturition rate varies directly with body weight or fat content during the previous autumn (Cameron and Ver Hoef 1994; Cameron et al. 1993, 2000; Gerhart et al. 1997a), whereas calving date and survival within about 48 h after birth are more closely related to maternal weight at the time of parturition (Cameron et al. 1993).

Those relationships form the link between the disturbance-induced changes in distribution described above and potential changes in reproductive success. Wolfe (2000) studied 96 radiocollared females at 183 calving sites from 1980-1995. Concentrated calving areas west of the Sagavanirktok River (closer to areas of petroleum activity) shifted inland away

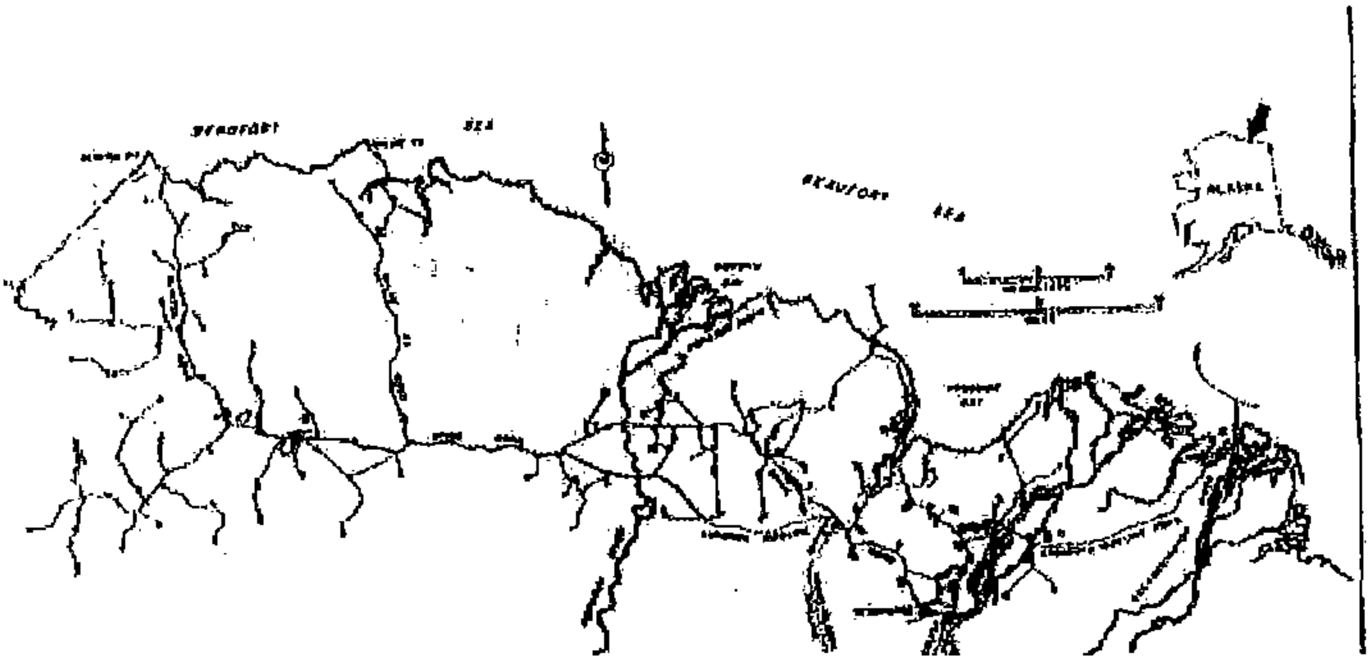

FIGURE 8-4. Roads and pipelines in the Prudhoe Bay region, Alaska, ca. 1990. Note: One or more pipelines (stippled) are adjacent to most roads. Source: Cameron et al. 1995.

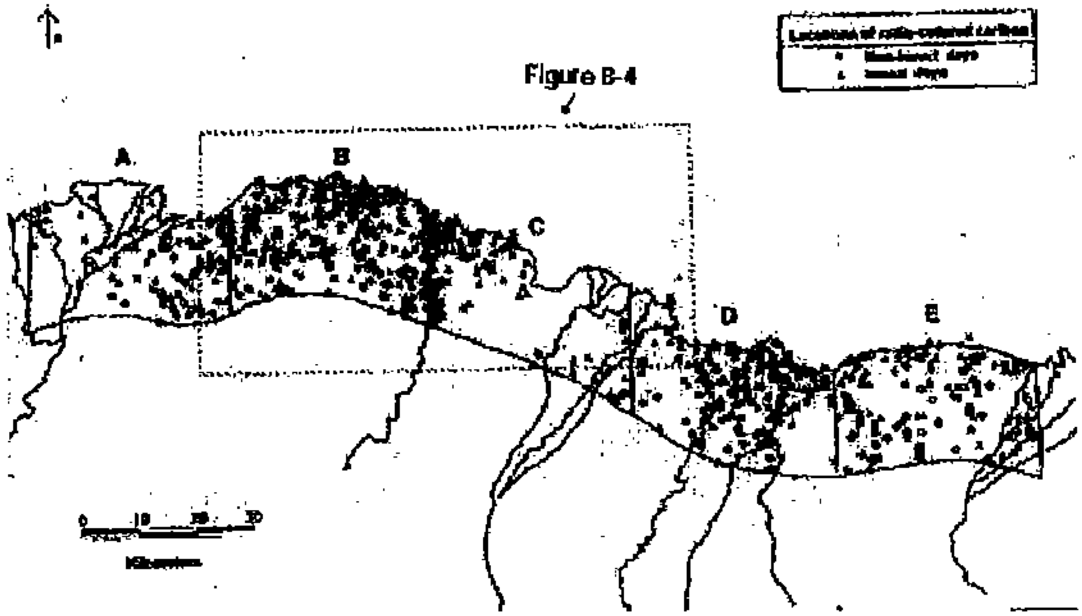

FIGURE 8-5. Locations of radiocollared female caribou within 850-km^2 coastal quadrants in relation to insect activity. Central Arctic Herd, Alaska, summer 1980-1993. Note: Some points represent >1 female in a single group. Source: Cameron et al. 1995.

from development into habitats with lower green-plant biomass.[3] On the east side of the river, an area without development, no such shift in calving was observed: Females selected habitats with above-average green-plant biomass (Wolfe 2000). For the PCH, calf survival through their first few weeks is primarily a function of the relative amount of forage available on the annual calving ground during the peak lactation period (Griffith et al. 2000a, 2002). However, survival estimates (Table 8-1) and Wolfe's (2000) NDVI data do not suggest such a relationship for the CAH, but sample sizes are small.

Impaired movements during the insect season also could decrease energy balance (Murphy and Lawhead 2000, Russell 1976, Russell et al. 1993, Smith 1996, Weladji et al. 2002, White et al. 1975) and hence reduce rates of summer weight gain. However, changed activity patterns of caribou near transportation corridors (Murphy 1988, Murphy and Curatolo 1987) might not reduce weight gain enough to depress parturition rates (Murphy et al. 2000). Nevertheless, individual or collective conflicts that result in nutrient insufficiency can decrease fecundity.

In fact, from 1988-1994, the mean parturition rate for radio-collared females west of the Sagavanirktok River was 64%, compared with 83% for those east of the river ($P = 0.003$). Parturition rates were similar from 1998 through 2001 (92% and 98%, respectively; $P = 0.062$), but differed for the eleven years overall (74% and 88%, respectively; $P = 0.001$) (Table 8-1). Estimated frequencies of reproductive pauses (periodic failure to produce a calf because of poor condition at breeding) (Cameron 1994, Cameron and Ver Hoef 1994) for the combined data were 26% and 12%, or approximately one pause every 4 and 8 years, respectively.

This longitudinal analysis provides a reliable assessment of difference in reproductive success. Because radio-collared females were used, interannual shifts of individual females between areas west and east of the Sagavanirktok River (Cronin et al. 2000; Lawhead and Curatolo 1984, cited in Murphy and Lawhead 2000; Whitten and Cameron 1984) could be detected and samples adjusted accordingly, yielding multiyear histories of females that had consistent use of the two areas.

Lower fecundity of females west of the river could be due to inadequate compensation for milk production (Cameron and White 1992). By reducing rates of forage intake or increasing rates of energy expenditure, conflicts during the calving and insect periods might diminish chances of achieving the weight gain required to support annual reproduction (Cameron and White 1992, Russell et al. 2000). In general agreement are anecdotal reports from Nuiqsut residents that caribou taken recently have been leaner than in years past (Miller 2001, Pedersen et al. in press).

Population Dynamics

Observed changes in the size of the CAH (Figure 8-6) are correlated with estimates of net calf production—the product of parturition rate and calf survival. From 1978 through 1983, when the herd increased, on average, 16% annually, net calf production exceeded 90%. The next census was not done until 1992, so the trajectory in herd size during the intervening period is not known; but the steady decrease in net calf production implies a deceleration of growth though the early 1990s. Between 1992 and 1995, years with consistently low productivity, the

[3] The actual measurement was a Normalized Difference Vegetation Index (NDVI), which measures the amount of land-cover greenness. The NDVI value can vary with species composition and other factors (Jia et al. 2002).

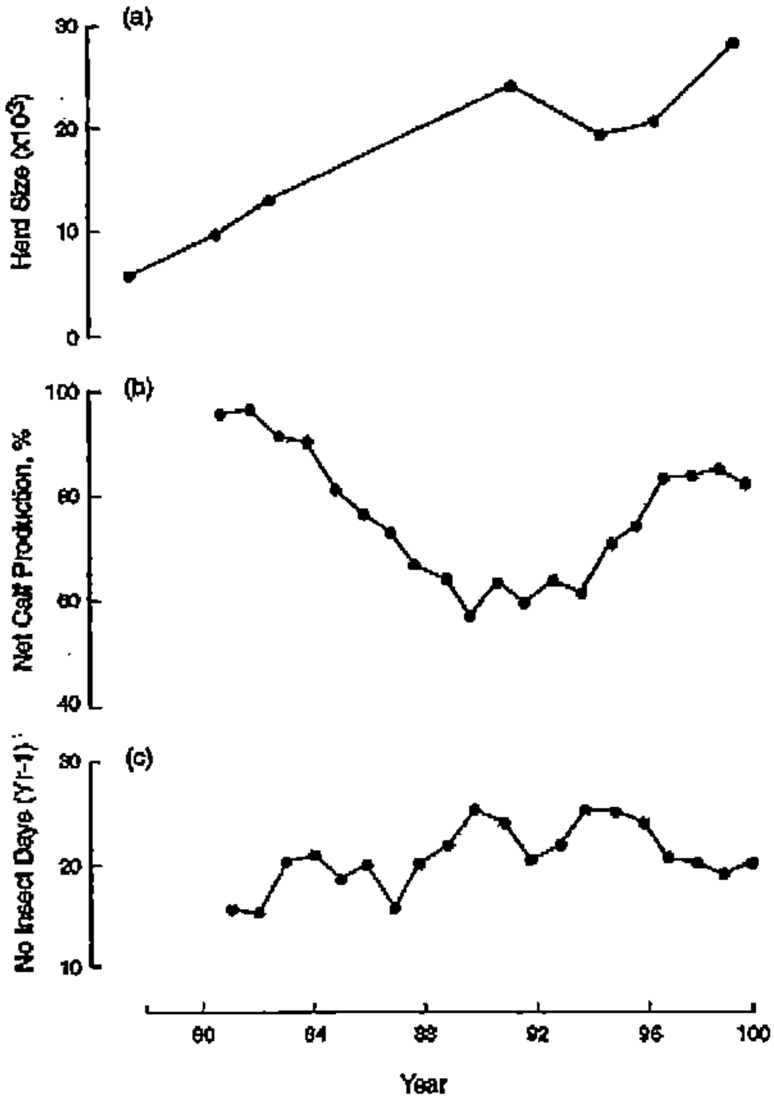

FIGURE 8-6. Central Arctic Herd in Alaska. (a) Herd size, 1978-2000. Point estimates determined by photo-census. (b) Net calf production. Three-year moving averages of radio-collared female caribou, 1981-2000, Lenart 2001, ADF&G files. Percentage of parturient females with a calf at heel ca. 2-8 weeks postpartum; approximate equivalent of the product of parturition rate and over-summer calf survival (see Table 8-1). (c) Number of insect days in July. Three-year moving averages, 1980-1999. Weather data for Deadhorse Airport, Alaska State Climate Center, UAA applied to the predictive models of Russell et al. 1993; criteria for insect days from Cameron et al. 1995.

CAH actually declined by about 8% per year. From 1995 until the census in 2000, the herd increased 14–15% annually, correlated with a sustained increase in net calf production.

Net calf production is affected by factors that influence acquisition and retention of nutrients. An important factor is insect activity. From 1981 through 2000, net calf production was inversely correlated with the number of days of high insect activity in July of the previous year (Figure 8-7) (Spearman's rank, $P = 0.012$). A lower frequency of insect-induced movements and insect avoidance behavior enable caribou to spend more time in high-quality habitats, thereby increasing chances that they will eat enough to produce milk. Maternal females would then experience greater weight gain, superior condition at breeding, and a higher probability of producing a calf the following spring.

Because parturition rate accounts for most of the variability in net calf production (Table 8-1), the committee focused on differences in parturition rate that might be related to level of insect activity. Dividing the 11 paired estimates of parturition rate west and east of the Sagavanirktok River into (previous) years of low and high insect activity yielded significant differences within each category ($P = 0.043$ and $P = 0.004$, respectively; Figure 8-7). When insects were relatively inactive, mean parturition rate of females west of the River was only about 10% lower than for those to the east. Following years of relatively high insect activity, however, the reduction was more than 25%.

Thus, oil-field development, by delaying or deflecting movements of caribou within and between habitats (Murphy and Lawhead 2000, Smith and Cameron 1985, Smith 1994), probably exacerbates the adverse effects of insect harassment. If the ability to forage or escape insects is sufficiently reduced, nutrition and fecundity will decline, with direct consequences for herd growth. Indeed, decreasing herd size in 1992 to 1995 (Figure 8-6) was associated with relatively high insect activity (2 of 3 years, 1992-1994). The subsequent trend of increasing size from 1996 through 2000 occurred during a period of generally low insect activity (3 of 5 years, 1995-1999).

Net growth of the CAH over the past 25 years is not, by itself, sufficient evidence for the absence of any adverse effect of petroleum development on caribou (WMI 1991). We cannot know what the growth trajectory of the herd would have been in the absence of oil-field development. However, multiyear data on the reproductive performance of collared CAH females exposed to oil-field development, relative to an undisturbed control group, indicate that productivity did decline when the attendant disturbance and habitat losses were superimposed on other conditions that adversely affected nutrient balance. Interestingly, these changes occurred during a period in which the growth rate of the CAH decreased relative to that of the similar TLH (Figure 8-3).

Future Effects

The results of the committee's analysis of the consequences of petroleum-related disturbance to CAH caribou provide a basis for assessing the probable future effects on the CAH and other arctic herds of the likely expansion of oil and gas development over the next 25 years eastward on state lands from the Badami unit, southward into the foothills of the central Brooks Range, and westward into the National Petroleum Reserve-Alaska from the Alpine unit. Unless the density of new access roads and new production and support facilities can be substantially reduced relative to infrastructure now in place, conflicts with CAH caribou east of the

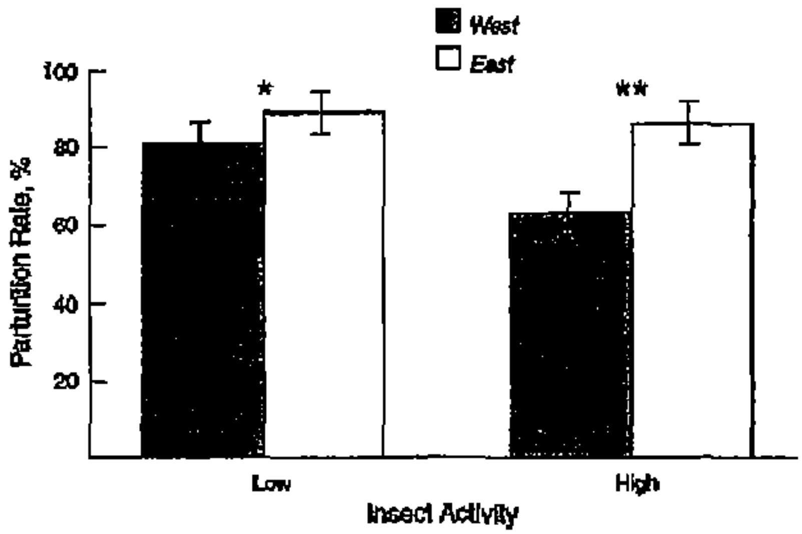

FIGURE 8-7. Parturition rates of 72 radio-collared female caribou of the Central Arctic Herd in Alaska west and east of the Sagavanirktok River, 1988-2001, following years of low and high insect activity. Determined, respectively, as the number of insect days below and above the median of 20.5 days (range, 15-27) for 1987-2000 (see Fig. 8-5 legend). *$P = 0.043$, paired t-test. **$P = 0.004$, paired t-test.

Sagavanirktok River will increase during the calving and insect-harassment periods. Higher insect activity associated with climate warming could counteract benefits of reduced surface development by increasing the frequency with which caribou encounter infrastructure (Klein 1999). With inland expansion, more of the CAH will come into contact with development on this winter range, with unknown consequences. If the calving ground of the TLH continues to be protected, direct conflicts with parturient females of that herd are unlikely, provided that their movements are not impeded. However if inland lease tracts in the northeastern portion of the National Petroleum Reserve-Alaska are developed, effects on midsummer distribution, habitat use, and productivity of TLH caribou are possible. The exact outcome and the degree to which these effects would accumulate depend on a host of unknowns, including characteristics of the oil and gas reservoir and advances in extraction technology. Within the next 25 years, major expansion of industrial activity into the WAH calving ground is unlikely, and inroads to its primary summer range are expected to be modest. If so, effects should be minor and not accumulate significantly.

If a proposed road north of the Red Dog mine to a North Slope site of a coal-fired power plant were constructed, it would cross a major east-west zone of travel, possibly interfering with insect-induced movements. A road would also open the region to further development.

To date, oil and gas activities have had little influence on the Porcupine Herd, but petroleum exploration and subsequent development on the coastal plain (1002 Area) of the Arctic National Wildlife Refuge could lead to development on the calving ground of that herd. To assess the potential effects of such developments on the PCH, Griffith and colleagues (2002) combined pertinent information on the CAH with the extensive data on the PCH. They simulated the effects of progressive development of the 1002 Area by displacing 17 annual calving grounds, between 1985 and 2001, using five scenarios (Clough et al. 1987). The concentrated calving area within each annual calving ground was repositioned 4 km (2.5 mi) from the periphery of industrial infrastructure. June calf survival was then calculated for each annual calving ground observed and for those hypothetically displaced, using a predictive model based on forage biomass during peak lactation and predation risk. A significant ($P < 0.0001$) inverse relationship was obtained between change in calf survival and displacement distance, even though calving still remained primarily on the coastal plain where habitat was good for foraging and predator avoidance. The results of these simulations suggest that an average displacement of approximately 27 km (17 mi) would be sufficient to halt growth of the PCH.

Consequences similar to those reported for the CAH are possible on PCH summer range, depending upon the extent and intensity of surface development. Impaired movements during years of high insect activity could reduce weight gain of lactating females, with comparable effects on fecundity (Figure 8-7). If superimposed on reduced calf survival (Griffith et al. 2002), the additive effects on PCH productivity could be substantial.

The PCH has the lowest growth capacity of the four arctic herds and, consequently, the least capacity to resist natural and anthropogenic stresses (Griffith et al. 2002). That vulnerability is, in part, attributable to the critical importance during calving of free access to the highest quality foraging and predator-avoidance habitats and to a lack of suitable alternative habitats (Griffith et al. 2002).

It is impossible to characterize future development infrastructure and activity in areas that have not been fully explored. Until exploration has occurred, the amount, distribution, and exact nature of any extractable hydrocarbon deposits remain unknown. But the amount, distribution, and type of hydrocarbon deposits profoundly influence the nature and extent of development infrastructure, thus how many roads and pipelines will be needed, and how much activity will occur and when it will occur. Current technology will probably continue to evolve, as discussed elsewhere in this report, but adverse effects on caribou are likely to increase with both the density of infrastructure development and the area over which it is spread.

Findings

- The intensively developed part of the PBOC has altered the distribution of female caribou during the summer insect season. Elsewhere, a network of roads, pipelines, and facilities has interfered with their movements between coastal insect-relief and inland feeding areas. Possible consequences of these disturbances include reduced nutrient acquisition and retention throughout the calving and midsummer periods, poorer condition in autumn, and a lowered probability of producing a calf in the following spring.
- Pregnancy rates and survival of young caribou during their first summer is positively correlated with the availability of food. Insect harassment reduced nutrient-intake rates by females of the CAH as the animals moved to habitats where they could avoid insects but where they foraged less efficiently. Radio-collared female caribou west of the Sagavanirktok River shifted their main calving area from developed areas nearer the coast to undeveloped areas inland. No such shift has occurred for caribou calving east of the Sagavanirktok River where there is no development. The shift by caribou west of the Sagavanirktok River was into an area with lower green-plant biomass than the area previously used. From 1988 to 1994, parturition rates of radio-collared females in regular contact with oil-field infrastructure west of the Sagavanirktok River were lower than those of undisturbed females to the east. Reduction in parturition rates—the variable part of net calf production—for those caribou was exacerbated by intense insect harassment during the period. Thus, it appears that the effects of oil-field development accumulate with effects of insect harassment by impairing movements between coastal and inland habitats.
- As a result of conflicts with industrial activity during calving and an interaction of disturbance with the stress of summer insect harassment, reproductive success of Central Arctic Herd female caribou in contact with oil development from 1988 through 2001 was lower than for undisturbed females, contributing to an overall reduction in herd productivity. The decrease in herd size between 1992 and 1995 may reflect the additive effects of surface development and relatively high insect activity, in contrast to an increase in the herd's size from 1995 through 2000, when insect activity was generally low.
- For the females of the CAH west of the Sagavanirktok River, avoidance of expanding infrastructure in the region triggered changes in distribution, progressing from localized adjustments to major shifts in the use of calving and summer habitats. Expanded loss of preferred habitats, which could accompany the spread of industrial activity across the National Petroleum Reserve-Alaska and into the foothills of the Brooks Range, and climate change that increases insect harassment, are likely to depress nutrient status and, therefore, summer weight gain of lactating females.
- Unless future requirements for infrastructure can be greatly reduced, exploitation of oil and gas reserves within the calving and summer ranges of the CAH, TLH, and PCH will likely have similar consequences.

Recommendations

- Determine the responses of caribou to seismic testing under different snow conditions and estimate the probable consequences in terms of energy intake and nutrient balance and reproductive success.
- Determine the minimum distance between road-pipeline corridors that is compatible with continued use of an area by calving caribou and how design of corridors influences those effective distances.
- Studies are needed to characterize the nutrient-energy tradeoffs associated with insect-induced movements; quantify the conditions of nutrient intake and body condition associated with each of the various weaning decisions (tradeoffs) made by maternal females; and within known levels of exposure to disturbance, determine the over-summer nutritional performance of females and their calves.
- Determine whether winter calf mortality is additive or compensatory, relative to early postnatal mortality; that is, do those that survive unfavorable foraging conditions in spring or summer die during the winter anyhow?

MUSKOXEN

Muskoxen (*Ovibos moschatus*), which were exterminated from Alaska, have been reintroduced and are now found at low densities on the North Slope, mostly in riparian areas. Populations are expanding into other habitats. Helicopters and low-flying aircraft sometimes cause muskoxen to stampede and abandon their calves (Winters and Shideler 1990). Seismic exploration is of concern because muskoxen are present year-round on the North Slope. The response to the noise of seismic exploration appears to differ from herd to herd, perhaps because of each herd's previous experience. Some seem unaffected by seismic activities as close as 300 m (980 ft); others appear disturbed by activity 10 times more distant (Winters and Shideler 1990). Therefore, although no adverse effects have been recorded to date, the expansion of 3-D seismic exploration to primarily unsurveyed areas, particularly in riparian areas, could result in increased disturbance to this species.

Finding

No effects of seismic exploration on muskoxen have been detected to date. However, the expansion of 3-D seismic exploration to new areas, particularly in riparian areas, might increase disturbance to this species.

ARCTIC FOXES

Past and current industrial activities on the North Slope have probably increased the availability of shelter and food for the arctic fox (*Alopex lagopus*). Developed sites within the Prudhoe Bay oil field are used by foxes for foraging on garbage and handouts, and for resting.

Foxes do not avoid human activity—successful litters of pups have been raised within 25 m (80 ft) of heavily traveled roads and within 50 m (160 ft) of operating drill rigs. Foxes use culverts under roads, underground utility corridors in camps, and sections of natural gas pipe as dens (Eberhardt et al. 1982).

In Prudhoe Bay, foxes use developed sites more in winter, when food is more likely to be scarce, than in summer. In December radiotagged foxes spent much of their time on and around developed sites, with large concentrations near dumps and other developed areas (Eberhardt et al. 1983a). During summer, garbage was commonly found at den sites near Prudhoe Bay (Garrott et al. 1983).

The density and rate of occupancy of dens and the sizes of litters, are greater in oil fields than in adjacent areas, so the fox population has grown larger and more stable (Burgess 2000, Eberhardt et al. 1982, 1983b). To reduce the possibility of transmission of diseases, especially rabies, to humans, oil companies have developed employee education programs and have trapped and removed foxes (Burgess 2000). With careful employee education and proper refuse-handling procedures, problems with arctic foxes can be reduced.

Another issue of concern is the foxes' potential to affect populations of nesting birds. Birds are a normal prey (Garrott et al. 1983), and migratory species can provide an especially important food source (Stickney 1991).

Future Effects

In the scenario the committee has used for future development, oil and gas exploration and production would occur on the entire Arctic Coastal Plain outside of the Arctic National Wildlife Refuge. The arctic fox population is likely to increase throughout that region. The current concerns about foxes would then be applied to a more expanded area. A long-term higher density of foxes could result in reduced nesting success and smaller regional populations of some species of birds (Burgess 2000).

Effects of predation can be locally devastating to colonial birds that nest in areas normally inaccessible to foxes (Quinlan and Lehnhausen 1982). Human modifications to habitats such as roads or causeways that connect barrier islands to the mainland could cause serious problems in such circumstances. Such effects would accumulate as more area is developed and as a larger portion of a bird population's nesting habitat is affected by increased fox predation.

Other factors would interact cumulatively with industrial development to influence arctic fox populations on the North Slope over the next 25 years. In particular, habitat characteristics and abundances of prey, competitors, predators, and disease agents could change greatly with climate warming. Although it is likely that there will be more arctic foxes in developed areas in the immediate future, it is not possible to predict long-term patterns of their abundance.

Finding

The increased fox populations due to oil and gas activities could affect regional populations of some bird species.

GRIZZLY BEARS

The infrastructure that supports industrial development in the Arctic substantially increases bear-human interactions. These interactions might have created a population sink associated with industrial infrastructure that could lead to long-term effects on grizzly bear populations on the North Slope.

Development in the central Arctic increased potential hunter access by road and airstrip (Shideler and Hechtel 2000). Defense of life and property (DLP) mortality of grizzlies arises with increases in human residence and anthropogenic food availability. Shideler and Hechtel (2000) found that 21% of oil-field grizzlies supplemented natural forage with anthropogenic foods. When access to garbage and human food was suddenly eliminated, food-conditioned bears suffered DLP mortalities greater than sustainable rates (Shideler and Hechtel 2000; Shideler, personal communication 2002).

Studies of the grizzly bear populations that use Prudhoe Bay oil fields showed that bears that consumed human food resources had higher than average cub survival (possibly because of a scarcity of natural predators such as wolves, wolverines, and adult male bears). This increased cub survival was offset by greater-than-average mortality among post-weaned subadults because their conditioning to human foods made them more vulnerable to hunters along the Dalton Highway and DLP killings (Shideler and Hechtel 2000).

Bears are often drawn into human camps by simple curiosity or cooking odors; however, once there they often remain because of deliberate feeding—which is now relatively unusual—or by improperly stored food and garbage, which can lead to additional grizzly bear mortalities. Although efforts have been made to reduce food available to bears, they have been only partly successful because some individuals have become expert at defeating them. In the Prudhoe Bay oil fields, the mortality rates of all adults and subadults that fed on anthropogenic foods was significantly higher than for bears that fed on natural foods (Shideler and Hechtel 2000). Of 12 offspring weaned by 4 food-conditioned females, 7 were killed, the status of 2 was unknown, and only 3 are known to have survived (Shideler and Hechtel 2000). During the summer of 2001, 5 food-conditioned bears were killed in the Prudhoe Bay oil fields (Shideler, personal communication 2002). These DLP kills are an example of the risks facing grizzly bears following industrial development in wilderness habitat. Of 9 known grizzly bear deaths associated with oil-field development, all were within the support service enclaves outside the immediate control of the oil companies (Shideler, personal communication 2002). On the basis of this experience, support areas appear likely to be a source of human-bear interactions.

Western arctic grizzly populations are low, and they are vulnerable to increasing harvest rates. Northern and northwestern areas of the western Arctic are marginal grizzly bear habitat (Shideler, personal communication 2002), but grizzlies can be lured out of the foothills to food sources on coastal plain habitats (Johnson et al. 1992). Seismic exploration, particularly new three-dimensional techniques, could disrupt denning (Shideler, personal communication 2002).

Future Effects

Expanded oil and gas exploration and production on the North Slope does not appear likely to have a large effect on bear populations, especially if the attention to the issue of bears and garbage continues. If some bears continue to be food-conditioned, some of them probably will be killed when their food source is removed. Also, bear predation on other species such as caribou could increase (Shideler and Hechtel 2000).

Even with the best possible mitigation programs, there will always be interactions with humans who live and work in grizzly bear habitat, and some bears will be killed in defense of life and property or by accident. Also, increased access opportunities (roads and airstrips) and changes in village lifestyles or economies could result in more bears being killed for sport or subsistence.

Construction of industrial facilities results in alteration or destruction of grizzly bear habitat, and as the amount of developed area expands so will the effect on bear habitat. Issues of potential concern are the effects of disturbance from roads and from seismic exploration on denning habitat and on bears in dens and habitat alterations that influence food availability (R. Shideler, personal communication). Those effects will be greater when development expands into the foothills because grizzly bear densities are higher there than on the coastal plain (Carroll 1995, Stephenson 1995).

It is also very likely that in the next 25 years the nature of habitats available to grizzly bears on the North Slope will be affected by climate warming. How the effects on grizzly bears of development-related killing of bears, hunting, alterations of habitat, and climate warming will accumulate cannot be predicted.

Finding

Oil and gas activities on Alaska's North Slope have changed the demographics of the grizzly bear population primarily because of the availability of anthropogenic food sources.

BIRDS

To assess the accumulation of effects of oil and gas activities on birds it is necessary to understand factors that limit avian populations in areas influenced by the petroleum industry. This task is complicated because migratory species can be affected by factors away from the oil fields. The limiting factors generally involve habitat, but there are associated variables, such as the availability of food in wintering and migration areas and of the food birds need for maintenance and production of eggs or tissue on the breeding area. Hunting, primarily of waterfowl, also is of concern, as is predation on eggs, young, and adults. Habitat change in wintering or migration areas can reduce populations that breed in oil development areas independent of local effects, or can keep breeding populations below local carrying capacity. Reduced winter habitat could hamper first-year or adult survival or reduce the proportion of breeding adults by altering their ability to store nutrients required for migration and reproduction (Ankney 1982, Ens et al. 1990). Also, large molting concentrations of pintails (*Anas acuta*), long-tailed ducks (*Clangula hyemalis*), king eiders (*Somateria spectabilis*), and black Brant (*Branta bernicla nigricans*)use Alaska's North Slope and adjacent lagoons for postbreeding molting and migration. Declines in breeding populations away from the North Slope could cause declines in northern Alaska independent of local industrial activities. Such cross-seasonal effects are difficult to measure and will be considered only in the context of evaluating local effects in developed areas on Alaska's North Slope.

Dynamics of Habitat

Habitat for breeding and molting birds has been directly affected by placement of gravel fill (Gilders and Cronin 2000, Walker et al. 1987a) and by thermokarst (Walker and Everett 1987). There have been several indirect effects: Dust shadows on the leeward side of roads and gravel pads can accelerate snow melt and alter the condition of plant communities (Walker and Walker 1991). Drifted snow on the windward sides of roads can delay snowmelt and the damming effects of roads can create impoundments (Kertell and Howard 1997, Walker 1996). Almost 3% of the area of current oil fields is covered by gravel, although newer developments require only about one-tenth the amount of gravel fill that was required for the earliest oil fields (Gilders and Cronin 2000). The area affected by thermokarst and impoundment associated with gravel fill is approximately double the area covered by gravel.

Because raptor densities are concentrated inland from existing oil fields especially along the Colville River, which has one of the highest densities of nesting raptors anywhere on Earth. Past development has probably not measurably affected those populations. Rough-legged hawks (*Buteo lagopus*) and ravens (*Corvus corax*) might have benefited slightly from development because they use anthropogenic structures for nest platforms (Day 1998, Ritchie 1991).

The power lines that are ubiquitous in older oil fields cause minor mortality of migrating birds in other regions (e.g., Faanes 1987). One study detected 4 collisions and reported 31 dead birds over 2 years (Anderson and Murphy 1988). Correcting for detection bias, (dead birds scavenged before being found), Anderson and Murphy (1988) estimated 1 collision for every 1,000-7,000 flights across the power line, which was at the low end of reports from other studies of bird collisions with powerlines. Nonetheless, if rare species or pre-breeding adults are among the colliders, these could be effects of importance for those particular species. Individuals from fifteen avian species were identified; no species was represented by more than three individuals (B. Anderson, ABR Inc., unpublished data). Five of the carcasses were identifiable only as waterfowl. Potentially sensitive species represented in the sample of carcasses included long-tailed ducks (three individuals), and an unidentified eider. Given the small numbers representing any individual species, power line collisions are unlikely to represent an important source of mortality in the oil fields. This source of mortality is likely to remain confined to the core areas of the Prudhoe Bay and Kuparuk oil fields if new fields continue the recent trend of placing power lines on pipeline supports or burying them in roads.

Tundra Ponds

Spills that contaminate tundra ponds could cause significant damage to the ponds and to birds that use them. If oil becomes trapped in sediments, preventing weathering, the effects on organisms can persist as fresh oil emerges. Miller and colleagues (1978) studied tundra ponds affected by natural oil seeps and experimental spills. Zooplankton was virtually eliminated, although phytoplankton productivity that was reduced initially returned to normal. Recovery can take several years, however. Data from experimental spills suggest that recovery could be enhanced by the addition of nutrients to stimulate the growth of oil-degrading organisms (Bergstein and Vestal 1978, Horowitz et al. 1978).

Predators

Birds and their nests in the oil fields have a suite of predators, the most important of which are arctic foxes, glaucous gulls (*Larus hyperboreus*), grizzly bears, and ravens. The populations of all of those predators have increased in the oil fields (Burgess 2000, Burgess et al. 1993, Eberhardt et al. 1982, Truett et al. 1997), most likely because of the increase in garbage. Gull populations are on the rise throughout the Arctic (Bowman et al. 1997, Kadlec and Drury 1968, Mallek and King 2000, Vermeer 1992), however, so it is not clear whether the increases in the oil fields are part of a global pattern or associated with local changes caused by oil development (Day 1998). Day (1998), however, cites numerous accounts of heavy use on the North Slope of landfills, including those in the oil fields, for foraging by glaucous gulls.

Bird Species of Special Concern

Loons

Pacific loons (*Gavia pacifica*) sometimes nest on the shores of impoundments (Kertell 2000), so increases in impounded water in developed areas could be beneficial to this population if productivity on impoundments is similar to that in natural wetlands. Kertell and Howard (1997) were unable to detect important limnological differences between natural wetlands and impoundments, and Kertell (1996) found little difference in adult foraging behavior or provisioning of chicks for loons that fed on natural ponds or impoundments. Nest success on a study site in the Kuparuk oil field averaged 60% ($n = 19$) (Moiteret et al. 1996), and nest success in the Prudhoe Bay field was 41% and 33%, respectively, for natural ponds and impoundments (Kertell 1996). Nest success of Pacific loons on the Yukon-Kuskokwim delta in southwestern Alaska was 32% (Petersen 1979), slightly lower than that in the oil fields. Overall productivity (fledged young per nesting attempt) of Pacific loons was comparable at Prudhoe Bay to that of arctic loons in Scandinavia (Gotmark et al. 1989, Kertell 2000). Neither loon density nor trend estimates exist for the oil fields, however, making it impossible to determine whether changes in habitat have influenced the Pacific loon population within the oil fields.

Much less is know about yellow-billed loons (G. *adamsii*) but Alaska's North Slope, particularly the National Petroleum Reserve-Alaska, is a major breeding area for this species, which is being considered for listing under the Endangered Species Act.

Shorebirds

Semipalmated sandpipers (*Calidris upsilla*), pectoral sandpipers (*C. melanotos*), and red-necked phalaropes (*Phalaropus lobatus*) are the most widespread and abundant breeding shorebirds across the North Slope, with densities exceeding 10 nests per km^2 (26 nests per mi^2) in the National Petroleum Reserve-Alaska (Cotter and Andres 2000). The North Slope is a relatively important breeding area for red phalaropes (*P. fulicaria*) (Cotter and Andres 2000, FWS 1986), bar-tailed godwits (*Limosa lapponica*), stilt sandpipers (*C. himantopus*), and long-billed dowitchers (*Limnodromus scolopaceus*) (Cotter and Andres 2000). Dunlins (*Calidris alpina*) are locally important and were intensively studied during the 1960s near Barrow (Pitelka et al. 1974). Buff-breasted sandpipers (*Tryngites subruficollis*) are not abundant, but about half of the world's population nests on the North Slope, entirely within the area of known or probable oil and gas resources (Audubon Alaska 2001, Gottthardt and Lanctot 2002, Lanctot and Laredo 1994). This species is also being considered for listing under the Endangered Species Act.

Shorebird populations appear to be stable in the oil fields, except for dunlins, which have declined there (Troy 2000) and elsewhere on Alaska's North Slope (Norton in Troy 2000). It is possible that the population losses are the result of factors outside the oil fields. Habitat declines on wintering and staging areas in Asia (Hanawa 1985, Melville 1997, Tobai 1997) could be the cause of the Alaskan declines (Troy 2000).

Two mechanisms have been examined: habitat alteration, which causes direct or indirect effects, and reduced nest success associated with predation. Direct alteration of habitat displaces individuals from locations where they might otherwise nest. Secondary effects, including changes in drainage patterns, thermokarst, deposition of dust, and disturbance associated with activity on roads, can displace additional individuals. Shorebird densities are lower near roads and gravel pads than in more distant areas (Connors and Risebrough 1979, TERA 1993a, Troy and Carpenter 1990), but densities are higher on the leeward sides of roads than elsewhere, suggesting that dust shadows could create conditions attractive to shorebirds (TERA 1993a). Both Meehan (1986) and TERA (1993a) estimated that 5% of shorebirds were displaced from preferred nesting areas by the direct or secondary effects of oil-field facilities. The impact of such displacement on population dynamics is unknown, however, because potential limiting effects of nesting habitat are poorly understood on Alaska's North Slope. Attempts to assess tertiary effects, such as habitat fragmentation, have produced contradictory results (Meehan 1986, TERA 1993a).

Troy (1996) reported that semipalmated sandpiper abundance was correlated with nesting success two years before, suggesting that recruitment might play an important role in regulating this population in the oil fields. Few estimates of nest success for other sites in Alaska are available for comparison. There is evidence that nesting success for other ground-nesting birds is unusually low in the oil fields (Anderson et al. 2000, Sedinger and Stickney 2000), and that, combined with Troy's (1996) results, suggests that increased predation in the oil fields is affecting local shorebird populations.

Shorebird populations have probably been affected by the loss in food supply caused by contamination of wetlands by reserve pits (West and Snyder-Conn 1987). West and Snyder-Conn (1987) demonstrated that invertebrate diversity and abundance were reduced in wetlands within 25 m (80 ft) of reserve pits. However, because reserve pits are no longer used for disposal of drilling waste and because existing reserve pits are being emptied, the outlook is improved.

Tundra Swan

Tundra swan (*Cygnus buccinator)* populations have increased in Alaska (Conant et al. 2000) after their over-harvesting in the early part of the twentieth century (Banko and McKay 1964). The rate of increase in the Kuparuk oil field between 1988 and 1997 (Ritchie and King

2000) exceeded that in other parts of Alaska (Conant and Groves 1997). There are caveats, however. Alaska's North Slope tundra swans, including those that inhabit the oil fields, winter on the east coast of the United States; those that breed in southwestern Alaska winter west of the Rocky Mountains (Bellrose 1980). Thus, tundra swans in the two regions experience different winter conditions. Additionally, climate warming has been pronounced on the North Slope, producing longer frost-free periods during the breeding season (Lachenbruch and Marshall 1986), which might have disproportionately benefited swans there. Thus, if there have been negative effects of oil-field development on tundra swans, they have been insufficient to prevent the rapid growth of the population during the past decade.

As with other species of birds, loss of habitat could reduce swan densities in the oil fields. Given the large territories (Ritchie and King 2000) and resulting low densities of breeding swans throughout their range, however, it is unlikely that the loss of less than 5% of potential breeding habitat has substantially affected breeding swans in the oil fields. Disturbance associated with facilities might be more important than habitat loss, because swans are sensitive to human disturbance at considerable distances (greater than 500 m [1600 ft]) (Monda 1991). Tundra swan broods have been reported to avoid some areas within 100-200 m (330-660 ft) of roads, although habitat use outside the breeding season did not appear to be affected by roads (Murphy and Anderson 1993). Ritchie and King (2000) concluded that oil-field facilities had little influence on distribution of tundra swan nests because the mean minimal distances from swan nests to structures were less than the mean minimal distances between nests (Stickney et al. 1994), so territorial spacing is more important to breeding distribution than is proximity to artificial structures.

Predation does not seem to have influenced nest success in the oil fields (83%) (Murphy and Anderson 1993), which was comparable to that for tundra swans nesting in Arctic National Wildlife Refuge (76%) (Monda et al. 1994).

Black Brant

Nest success of black brant in the oil fields has been chronically low, ranging from 44% to 55% (Sedinger and Stickney 2000), in contrast to that in other colonies where nest success is typically near 80% (Barry 1967, R. Sedinger, unpublished material). Low nest success is associated with high predator populations in the oil fields. Modeling of this population suggests that oil-field populations are not sustainable at such inadequate nest success and could represent a sink population (Sedinger and Stickney 2000). Thus, high predator populations associated with human activity in the oil fields likely represent the greatest harm to nesting brant in the region.

Black brant nesting in the oil fields are a relatively small proportion (less than 2%) of the entire breeding population for this subspecies (Sedinger et al. 1994, Sedinger and Stickney 2000), although many brant broods from the Colville River Delta use the oil fields after hatching. Brant breeding in the oil fields and in the delta increased several-fold between 1982 and 1992 (Sedinger and Stickney 2000), supporting the view that the growth has been sustained by immigration from other areas.

Brant nest colonially or semi-colonially (Sedinger et al. 1993) and are therefore, less likely to be displaced by oil-field structures unless the facilities are placed on or immediately adjacent to nesting concentrations. Facilities do not seem to have displaced nesting brant (Murphy and Anderson 1993, Stickney and Ritchie 1996). The largest nesting concentrations in the oil fields occur on Howe and Duck islands, 5 km (3 mi) and a few hundred meters, respectively, from the Endicott causeway. Similarly, large numbers of brant broods use the salt marsh within 0.5 m (1.6 ft) of the Oliktok long-range radar site (Sedinger and Stickney 2000). During nesting and brood rearing at these sites, brant responded to humans at distances of less than a few hundred meters (Murphy and Anderson 1993). Brant also responded to 12% of vehicles that passed within 300 m (980 ft), although those responses lasted less than 5 min (Murphy and Anderson 1993) and likely had little effect on their nutritional status. Observations of color marked and radiotagged brant broods provided no evidence that roads or other oil-field facilities impeded movement from nests to brood-rearing areas (Stickney 1996). Brant goslings in the oil fields were actually larger than those from the Yukon-Kuskokwim delta at the same age, implying greater abundance of food in the oil fields (Sedinger et al. 2001).

A long-term color-marking and monitoring program has allowed estimates of annual survival for adult and juvenile brant from the oil fields. The estimates show that adults from the oil fields have similar if not slightly higher survival rates than those from the delta in southwestern Alaska (Sedinger et al. 2001). Juvenile brant from the oil fields survived the first stage of fall migration at higher rates than did those from the Yukon-Kuskokwim delta, probably because of their superior growth conditions (D.H. Ward, U.S. Geological Survey, personal communication).

The North Slope is particularly important as a molting are for black brant. About one-third of the world's population of Pacific black brant assemble in the lakes and tundra north and east of Teshekpuk Lake to molt. During that time they are sensitive to disturbance by aircraft, especially helicopters (Berksen et al. 1992, Tensen 1980, Ward and Stehn 1989). If industrial activity expands into this region in the form of satellite fields without permanent road links, increased air traffic is inevitable. The fact that brant fly long distances to molt in this area strongly suggests it is unusually favorable as a place to molt. This assumption is supported by analyses of the tundra vegetation in this area.

Eiders

Spectacled (*Somateria fischeri*) and Steller's (*Polysticta stelleri*) eiders are currently listed as threatened under the Endangered Species Act, mainly because of their decline in excess of 90% since the 1970s on the Yukon-Kuskokwim delta in southwestern Alaska (Stehn et al. 1993). Threatened status has heightened interest in the North Slope populations, but the historical record is short, and there are no data with which to compare pre- and postdevelopment populations. Spectacled eiders nest at relatively low densities on the North Slope (Ducks Unlimited 1998, Mallek and King 2000), so it is difficult to acquire sufficient censuses to make inferences.

Nesting spectacled eiders do not appear to avoid oil-field structures, although nests appear to be farther from facilities than are those of prebreeding spectacled eiders (Anderson et al. 2000). Nest attendance patterns in the oil fields (Anderson et al. 2000) are comparable to those in the delta (Flint and Grand 1999), indicating that disturbance of incubating females does not reduce nest attendance in the oil fields. Nest success in the oil fields (42%) (Anderson et al. 2000), however, is substantially lower than in the delta (48%, Grand and Flint 1997; 70%, Moran 2000). Low nest success in the oil field is primarily associated with predation (Anderson et al. 2000). Despite the low nest success, the population in the oil fields was stable over 8 years of monitoring (1993-2000) (Anderson et al. 2000), although the relatively short study period and the small numbers recorded (typically fewer than 10 nests) each year make it difficult to discern actual trends. Low nest success is cause for concern, however, and the local population might not be sustainable without regular immigration.

Because common eiders (*Somateria mollissima*) nest predominantly on barrier islands in the Beaufort Sea they have not been close to most oil field activities. One exception was intensive operations in 1983 near Thetis Island, north of the Colville River Delta (Johnson 2000). Nest success on Thetis Island in 1983 (81%) was higher than in other years or at other locations on Alaska's North Slope (less than 45%), possibly associated with removal of arctic foxes from Thetis Island that year (Johnson 2000). Numbers of common eider nests on barrier islands north of the oil fields have generally increased since 1970, possibly as a result of placement of anthropogenic debris on the islands, which eiders use as nesting cover (Johnson 2000). Glaucous gulls are important predators of eider ducklings but there are no data to evaluate the potential effects of increased glaucous gull populations in the oil fields on survival of common eider ducklings in coastal lagoons immediately north of the oil fields (Johnson 2000).

King eiders (*S. spectabilis*) have been studied for a shorter period, but there are no apparent trends in their populations within the oil fields (Anderson et al. 2001). They do not appear to avoid oil field structures (Anderson et al. 2001). Nest success in the Kuparuk oil field averaged 32% from 1993-2000 (Anderson et al. 2001), similar to that of other waterfowl in the oil fields, and consistent with the hypothesis that nest success rates are low in the oil fields.

Lesser Snow Goose

Like black brant, lesser snow geese (*Chen caerulescens caerulescens*), nest on Howe Island and Duck Island near the Endicott Causeway (Johnson 2000). As with other birds nesting in the oil fields, predation appears to be the principal negative effect of oil development. Oil-field-nesting snow geese are less than 1% of the North American winter population (Bellrose 1980, Johnson 2000), but the oil-field population has increased 10-fold since monitoring began in 1980 (Johnson 1980). Snow geese typically rear broods in salt marshes east of the Endicott Causeway and in freshwater and salt marshes west of the causeway. Broods are reared much closer to the nesting area than is normal for most other snow geese, which often move 70 km (40 mi) for brood rearing. The broods did not change their use of brood-rearing areas after construction of the causeway (Johnson 2000). Nest success was generally lower than for snow geese nesting at La Perouse Bay (mean 92%, Cooke et al. 1995) and no eggs hatched in 1991 or 1992, when arctic foxes were present on the island during the normal nest initiation period. Nest success has been low from 1991 through 2001, with complete failure some years (Alaska Audubon 2001). Thus, the population on Howe Island appears to be a sink.

The North Slope of the Arctic National Wildlife Refuge supports more than 60% of the Pacific population of lesser snow geese during fall premigratory staging (Robertson et al. 1997), so significant effects would accumulate if industrial development were to spread to that area, accompanied by increased aircraft traffic.

Conclusions and Projections of Future Effects

Because of higher predator densities, increased predation on nests is the most apparent effect of oil development on birds that nest in the oil fields. Reduced nest success is sufficient in some cases to cause population declines, so the apparent stability of some oil-field populations is presumably the result of immigration. As industrial activity spreads into new areas, the amount of sink habitat will increase. Placement of oil-field facilities does not appear to have reduced overall densities in the oil fields, although some shorebirds do exhibit local displacement away from facilities and roads. Of course, the direct loss of habitat caused by placement of gravel fill could have reduced numbers, but the small areas actually covered, combined with the low densities of breeding birds, make it impossible to measure that effect.

Similar changes are to be anticipated in newly developed areas, and it appears that controlling anthropogenic food sources that could enhance predator populations will be essential to minimizing effects of predation on birds. One important unknown is how the expanded use of 3-D seismic exploration will affect birds: To the degree that this activity affects vegetation, it might affect breeding birds in areas of new development.

An important consideration is that new development in the foothills of the Brooks Range could impinge on raptor species' nesting and hunting habitats. Assessment of the effects of human activities on breeding raptors has produced mixed information (Andersen et al. 1990, England et al. 1995, Schueck and Marzluff 1995, Schueck et al. 2001, Grubb and Bowerman 1997). Andersen et al. (1990) detected shifts in home ranges of less than 1 km in response to military training activity in southern Colorado. Schueck and colleagues (2001), however, detected little effect on the number, distribution, or behavior of raptors in the Snake River Birds of Prey National Conservation Area in response to military training activity, although they noted that raptors responded to firing of live ammunition. When effects of weather were removed from the analysis, effects of military activity on raptor distribution were further reduced (Schueck and Marzluff 1995). England and colleagues (1995) documented reduced fledging success for Swainson's hawks (*Buteo swainsoni*) in urban relative to rural areas of the Central Valley of California. That research group attributed reduced fledging success of urban nests to the distance the birds had to travel to foraging areas rather than to disturbance around nest sites. Grubb and Bowerman (1997) reported that fixed-winged aircraft elicited a response from nesting bald eagles less than 30% of the time at distances greater than 500 m (1,600 ft). Bald eagles flew less than 5% of the time in response to those disturbances. Helicopters less than 500 m (1,600 ft) from nests, in contrast, elicited flight responses about 10% of the time (Grubb and Bowerman 1997). It is difficult to evaluate is the potential effect of 3-D seismic exploration on prey for raptors, such as ptarmigan (*Lagopus lagopus*) and arctic ground squirrels. Direct effects on these populations are unlikely, but any changes in vegetation and soils over large areas could reduce habitat quality for prey, thereby reducing their populations. Given the relatively small effects of large disturbances and the location of raptor nests on cliffs and steep lakeshores and river banks, it should be possible to conduct oil development in the foothills of the Brooks Range with small effects on nesting raptors, especially if aircraft and other human activities near nests are regulated.

Future industrial development will likely occur in a warming climate that would probably affect timing and success of reproduction of many bird species. Tundra vegetation also is likely to change. Shrubs are likely to increase at the expense of herbs, favoring some species over others. Not enough information is available at present to evaluate how likely such effects are to occur and how they will accumulate with the effects of oil and gas activity.

Findings

- Shifts in nesting distribution of shorebirds have occurred in response to oil-field facilities but because of insufficient information the committee cannot determine whether the displacement has affected oil-field populations.
- Inadequate disposal of garbage has resulted in artificially high densities of gulls, ravens, and mammalian predators in the oil fields. The resulting increased predation of birds' nests and young has likely made some oil-field populations dependent on immigration from more productive populations elsewhere. That is, nesting areas that might have been source habitats have become sink habitats. However, population studies alone cannot reveal such effects.
- Future development in the foothills of the Brooks Range could affect nesting raptors.
- If development moves into the Teshekpuk Lake area of the National Petroleum Reserve-Alaska, molting waterfowl could be adversely affected, especially brant.
- A major oil spill associated with shoreline or offshore oil development would endanger molting flocks of waterfowl in nearshore lagoons.

FISH

The life cycles of freshwater and diadromous fishes on the North Slope are adapted to the region's long winters and low productivity (Craig 1984, 1989; Power 1997). After break-up, fish move quickly during the brief summer into many habitats, often at great distances from the wintering area. For example, arctic cisco (*Coregonus autumnalis*) from the Colville River can return to spawning areas more than 600 km (370 mi) from the wintering area (Gallaway and Fechhelm 2000). Locating a suitable wintering area at the end of the summer is critical to survival. Craig (1989) estimated that substantially less than 5% of stream habitat remains available to fish by late winter. These widespread movements and the greatly restricted area of habitat available to fish in winter make many of these species highly vulnerable to the effects of oil and gas exploration and development.

Nearly 40 species of fish are routinely caught during studies in freshwater and nearshore habitats of the North Slope (Bendock 1979, Cannon et al. 1987, Craig and Haldorson 1981, Fechhelm et al. 1984, LGL Alaska Res. Assoc. 1990-1996, Moulton et al. 1986, NSB 2001). Others are caught occasionally, but they tend to be rarer or associated with offshore marine areas.

Seventeen of the frequently occurring species commonly enter the subsistence harvest. Arctic cisco and broad whitefish (*Coregonus nasus*) have the highest subsistence value. An average of 18,500 kg (40,800 lb) of arctic cisco was harvested annually from the Colville River delta each fall from 1985 to 1998, with an additional 3,200-4,000 kg (7,100-8,800 lb) taken near Kaktovik (Craig 1987, Fuller and George 1997). The broad whitefish harvest by North Slope villages is estimated to be more than 28,000 kg (62,000 lb) annually (Fuller and George 1997, Hepa et al. 1997).

Fishes along the North Slope have three principal life histories: freshwater, diadromous, or marine. Diadromous fishes move between fresh water and the sea during their lives. The term includes *anadromous* species, which spawn in fresh water and grow in the sea; *catadromous* species, which do the reverse; and those species that can spend substantial amounts of time in either environment, but not necessarily mainly to reproduce or mainly to grow. The term *diadromous* is applied to ciscoes, whitefishes, and Dolly Varden char (*Salvelinus malma*) that migrate each year between freshwater and coastal habitats (Gallaway and Fechhelm 2000). Most freshwater species spend their entire lives in rivers and lakes of the North Slope and generally avoid saline waters, although some, such as arctic grayling (*Thymallus arcticus*) and round whitefish (*Prosopium cylindraceum*) move down river to enter low-salinity estuarine waters during early summer.

Diadromous species, such as Dolly Varden char, arctic cisco, broad whitefish, and least cisco (*Coregonus sardinella)* migrate each summer between upriver overwintering areas and feeding grounds in coastal waters. That group is more abundant along the Beaufort Sea coast than along the northeastern Chukchi coast, possibly because of a lack of large rivers and because of the Chukchi's less-productive coastal region (Fechhelm et al. 1984).

Most marine species inhabit deeper offshore waters and are rarely reported in the North Slope coastal zone. Notable exceptions along the Beaufort Sea coast are arctic cod, fourhorn sculpin (*Myoxocephalus quadricornis*), and arctic flounder (*Pleuronectes glacialis*), which specifically migrate into shallow, low-salinity coastal waters and estuaries during summer. Those species, along with capelin (*Mallotus villosus*) and Pacific herring (*Clupea harengus pallasi*), also dominate the fish biota along the Chukchi Sea coast (Fechhelm et al. 1984).

Diadromous and Freshwater Fishes

Diadromous fishes in the Beaufort Sea exist in two major population centers: the Mackenzie River system of Canada in the east and the Colville River and Arctic Coastal Plain systems of Alaska in the west (Craig 1984). Most of the major river systems along the 600 km (370 mi) coastline between the Mackenzie and Colville rivers originate in the Brooks Range (Craig and McCart 1975). The rivers are shallow and provide little over-wintering habitat except for that associated with warm-water perennial springs (Craig 1989). Dolly Varden char and arctic grayling are the two principal species that inhabit those mountain streams, although lakes associated with the drainages can contain lake trout (*Salvelinus namaycush*), arctic char (*Salvelinus alpinus*), and arctic grayling. Ninespine sticklebacks (*Pungitius pungitius*) also are prevalent in drainages within the western mountain streams. Small runs of pink salmon (*Oncorhynchus gorbuscha*) occur in the Sagavanirktok and Colville rivers, and spawning populations of chum salmon (*O. keta*) inhabit the Colville and Mackenzie rivers (Craig and Haldorson 1986, Moulton 2001). The remaining salmon species consist of individuals from southern populations (Bering Sea) that are incidental visitors to the Beaufort Sea (Craig and Haldorson 1986). Three species—arctic cisco, broad whitefish, and arctic grayling—are examined here in detail. These three use the complete range of habitats affected by the North Slope oil and gas development, and at their various life stages they are vulnerable to the consequences of development. The few diadromous species found along coastal region of the northeast Chukchi Sea likely originate from large river systems in the southeast Chukchi Sea or along the Beaufort Sea (Fechhelm et al. 1984).

Arctic Cisco

Arctic cisco in the Alaskan Beaufort Sea originate from spawning grounds in the Mackenzie River system of Canada (Gallaway et al. 1983, 1989). Fry emerge by spring ice break-up in late May to early June and are swept downstream to coastal waters, where they begin feeding in the brackish waters near the Mackenzie delta. Young-of-the-year are transported away from the Mackenzie region by wind-generated currents. In years with predominant easterly winds, some young-of-the-year are transported westward to Alaska by wind-driven coastal currents (Colonell and Gallaway 1997, Fechhelm and Fissel 1988, Fechhelm and Griffiths 1990, Gallaway et al. 1983, Moulton 1989, Schmidt et al. 1991, Underwood et al. 1995). They arrive in the Prudhoe Bay area from mid-August to mid-September. In summers with strong and persistent east winds, enhanced westward transport can carry the fish to Alaska's Colville River where they take up winter residence. After entering the Colville River, they return to the river every fall for wintering until the onset of sexual maturity at about age 7, at which point they migrate back to the Mackenzie River to spawn (Gallaway et al. 1983). Juvenile arctic cisco are abundant enough to support a commercial fishery in the Colville River and a subsistence fishery at Nuiqsut (George and Kovalsky 1986, George and Nageak 1986, Moulton 1997, Brower and Hepa 1998).

Possible Accumulation of Effects and Likeliness of Occurrence

Recruitment of young arctic cisco into the Alaskan Beaufort Sea is a function of wind-generated coastal currents, so facilities that interrupt the movement of fish along the coast could lead to reduced recruitment. The presence of multiple similar structures would cause effects to accumulate. To affect recruitment, a structure would modify the coastal habitat in such a way as to hinder young arctic cisco from reaching the Colville River, the most suitable wintering area. The hindrance could result from modifying the coastal environment so that westward movement is delayed enough that they fail to reach the Colville River in the recruitment year. The available data indicate that arctic cisco recruitment has not been affected by existing causeways (NSB/SAC 1997).

In an environment where heat is at a premium, the warm coastal waters are important to diadromous fishes (Craig and Haldorson 1981). Facilities that disrupt this narrow coastal band could disrupt the coastal movements of arctic cisco and other diadromous species (Hachmeister et al. 1991, Hale et al. 1989). Any future operations that discharge warm water could serve as attractants that would prevent fish from moving to wintering areas at the proper time. The potential for effects to accumulate arises when multiple facilities affect the same populations of fish.

Broad Whitefish

Broad whitefish are common in lakes and streams of the Arctic Coastal Plain, most abundantly in large rivers, such as the Colville, Ikpikpuk, and Chipp rivers, that have deep, low-velocity channels and a multitude of connected lakes. They are also in the Sagavanirktok River, but its steeper channel gradient and low number of connected lakes limit the population. During summer, some broad whitefish enter small tundra streams.

The fish use a variety of habitats through their life cycle. Spawning is in deep portions of large rivers in the fall. In the Mackenzie River in Canada, broad whitefish spawn in the lower river just upstream of the marine influence. Similarly, the anadromous population in the Colville River spawns in the main river upstream of the delta. Bendock and Burr (1986) identified a prespawning migration in August. During the spring flood, age-0 and juvenile broad whitefish enter a variety of available habitats, including seasonally flooded lakes, lakes connected to stream systems, river channels, and coastal areas. Fish that use perched lakes remain in the lakes until they reach maturity, then return to the river in the spring of the year in which they will spawn. Broad whitefish that do not enter perched lakes either enter the coastal region and adjacent small drainages to feed or remain within the river system to feed in low-velocity channels, tapped lakes, or drainage lakes. In fall, they move out of the shallow feeding areas and return to the deep wintering areas in the main river or lakes. Fish from the Sagavanirktok River population move through the Prudhoe Bay coastal region and enter lakes attached to small drainage systems (Morris 2000).

During summer, broad whitefish are distributed throughout the drainages and coastal plain water bodies. The highest abundance in coastal marine waters is near river deltas (Furniss 1975, Griffiths et al. 1983, Moulton and Fawcett 1984, Moulton et al. 1986, Schmidt et al. 1983), although large fish move at least between the Colville River and Prudhoe Bay region. When they are in coastal waters, broad whitefish show a strong preference for nearshore habitats, appearing only rarely offshore or near barrier islands (Craig and Haldorson 1981, Moulton et al. 1986).

The main overwintering areas in the Colville River are upstream from the Itkillik River. Most broad whitefish leave the delta after ice forms and move upstream beyond the influence of salt water. In the Sagavanirktok River, wintering areas have been identified in both the east and west channels within 20 km (12 mi) of the river mouth (Morris 2000).

Possible Accumulation of Effects and Likeliness of Occurrence

Because of the wide range of habitats used by broad whitefish populations in the Sagavanirktok and Colville rivers, the potential for effects to accumulate is high. They use nearly all stream systems between Barrow and the Sagavanirktok River, they enter a large number of lakes associated with the streams, and they move widely along the coast, ranging as far east as the Canning River. As a result, they are vulnerable to facilities that change the distribution of fresh water and the coastal nearshore band. Because many rear in lakes, they are vulnerable to excessive water withdrawal and the introduction of contaminants.

Arctic Grayling

Arctic grayling is the second-most-widespread freshwater fish on the North Slope, after ninespine stickleback. It occurs in most stream systems and in many lakes (Moulton and George 2000). Grayling typically overwinter in deep areas within larger rivers—the Colville, Kuparuk, Sagavanirktok, and Canning. Wintering areas are limited or nonexistent in smaller tundra streams (Hemming 1993). During or after ice break-up, adult grayling move into tributary streams for spawning. Streams with sand or gravel substrates seem to be most heavily used.

After spawning, adults disperse to summer feeding areas, moving downstream in the tributary to feed on drift insects, moving into lakes, or returning to the main river. Grayling embryos hatch after about three weeks. Young-of-the-year (age-0) grayling feed in tributary streams until late summer, then move into the main river for wintering. Juveniles, which do not participate in spawning migrations, move in spring from wintering areas into small streams, lakes, or shallow areas within the main river to find suitable feeding areas.

As with most arctic freshwater fish, arctic grayling are strongly limited in abundance by the availability of wintering habitat. Many streams across the Arctic Coastal Plain are devoid of grayling or contain only a few juveniles because they are far from suitable wintering areas and lack dispersal routes that allow free passage during both spring and late summer.

Possible Accumulation of Effects

Disruptions to flow patterns that affect arctic grayling movements can affect survival, and the proliferation of roads and culverts across wetlands and streams creates the potential for effects to accumulate. Delays in the upstream spawning migration were common in the early stages of oilfield development, when culverts were too small to handle break-up flows. Road-crossing and culvert designs now include fish passages, so effects should be less than in the early years of development.

The distribution of arctic grayling has expanded because of habitat alterations in the oil-field region. Some of the large, deep gravel pits excavated for oil-field construction material filled with water after abandonment to form large artificial lakes that provide abundant wintering habitat. Hemming (1988) reported that a mine site connected to the Sagavanirktok River contained 88 times more water than the largest wintering areas reported within the river itself. Two of the deep gravel pits were connected to small tundra streams that appeared to contain suitable spawning and rearing habitat but lacked wintering areas. Arctic grayling of various ages were introduced over several years and eventually developed reproducing populations (Hemming 1995). The cumulative effect of these large gravel pits is to increase the available freshwater wintering area. It is not known whether the amount of habitat added by the gravel pits outweighs possible loss of habitat attributable to hampered migration caused by roads and pads, but with the recently increased attention to structural design it is likely that most of the migration problems have been solved.

There is a reasonable amount of information on fish-passage problems and ways to mitigate them (Ott 1993). The rehabilitation and success of habitat restoration in many of the North Slope gravel pits are well documented (Hemming 1988, 1993, 1995, Hemming et al. 1989).

Effects in Freshwater Systems

Effects in streams and lakes can accumulate through disruption of drainage patterns combined with water withdrawal and contamination. Hershey and colleagues (1999) demonstrated that the landscape controls biological interactions in lakes through facilitating or limiting fish dispersal. Activities that affect dispersal through alterations to drainage patterns can ultimately affect the assemblage of fishes in different habitats. Water withdrawals affect the amount of water present during winter, which can affect fish survival.

Drainage Patterns

Drainage patterns are altered by the construction of roads or pads in or across wetlands or drainage areas. To date, 2,338 ha (5,777 acres) of gravel pads, including more than 875 km (544 mi) of roadways, have been constructed in association with oil-field development on the North Slope (Chapter 4). Much of the gravel fill has been in wetlands where cross-pad drainage has been blocked by road construction. During spring ice break-up, there is substantial flow across expansive wetlands into lakes and streams. When long stretches of gravel road interrupt flow, the difference in water surface elevation from one side of the pad to the other can produce high-velocity water flow in the cross-pad drainage structures, usually culverts, that can inhibit upstream fish movements and delay migration to various summer habitats. The delays are particularly problematic for arctic grayling, which spawn shortly after break-up and often undertake long, rapid migrations from wintering areas to spawning sites.

An opposite effect can occur in mid- to late summer when stream flow is low. Fish that disperse during or after break-up must leave small drainages and shallow lakes to reach wintering areas before those waters freeze because there are often limited or no opportunities for overwintering within the habitats used for summer feeding. Fish that cannot leave will freeze. An inadequate number or improper placing of culverts or modifications to the stream bed can cause flow to go below the surface or to be spread too shallow to allow downstream movement when flow levels are reduced in late summer.

Large quantities of gravel have been used to construct the oil-field infrastructure. In the early period of development and pipeline construction, much of the gravel was obtained from gravel deposits within floodplains. But concerns arising from this practice prompted the FWS to study the effects of floodplain gravel mining on the floodplains physical and biotic processes (Woodward-Clyde Consultants 1980). The study identified numerous examples of habitat modification, including increased channel braiding, loss of wintering areas, spreading of flow, and restriction of fish movements, including mortality caused by stranding. The study also set forth guidelines for gravel mining that minimize floodplain damage (Joyce et al. 1980). In response to agency concerns, and results of the FWS study, new gravel mines were primarily in upland sites during the 1980s. Some of these were flooded when mining ceased and used as reservations, with the long-term goal of establishing aquatic habitat. Recently, some new mines have been in floodplains, again following established guidelines.

Water Withdrawal

Use of fresh water has increased in recent years because of expanded oil-field development and increased exploration. In the early years of exploration, water was obtained from any source, including rivers during winter. Bendock (1977, as cited in Winters et al. 1988) documented water withdrawals from the Sagavanirktok River that depleted water in wintering areas and increased mortality to fish in the area. Much of the water needed in the established oil fields is now obtained from reservoirs that are replenished with runoff during spring ice break-up; most of the water used in exploration is from lakes.

Ice thickness has a great influence on the distribution of fish in lakes across the Arctic Coastal Plain. Most lakes in the existing development area between the Colville and Sagavanirktok rivers are less than 2 m (6.5 ft) deep, few fish are present and effects have been minimal. As development spreads into regions with deeper lakes, such as the Colville delta and the eastern part the National Petroleum Reserve-Alaska there is greater potential for having fish populations within lakes. Under current Alaska Department of Fish and Game (ADF&G) policy, water withdrawals from fish-bearing lakes are limited to 15% of the estimated minimum winter water volume. This policy was adopted to allow some water use while preserving most of the water for wintering fish, and the criterion was set arbitrarily because there were no data to support a different use. Fish populations in lakes subjected to this maximum allowable withdrawal appear to be unaffected, but data on consequences are limited, and there has been no research to determine the effects of withdrawals on populations of invertebrates in the lakes or on vertebrate food supplies.

The current practice for ice road construction is to permit withdrawals from a large number of lakes along a desired route, then to allow the ice road contractor to draw from the nearest suitable lake. This allows for maximum construction flexibility, but it complicates the tracking of withdrawal volumes: Much more water is permitted for withdrawal than is used. Between 1998 and 2001, for example, Phillips Alaska obtained annual permits for withdrawals of more than 8.3 billion L (2.2 billion gal), but used less than 908 million L (240 million gal) in any given year (Table 8-2).

Table 8-2 Phillips Alaska Water Permits

Winter Year	Lakes Permitted	Withdrawal Limit (million L)	Total Used (million L)	Percentage Used
1998-1999	26	8,477.4	771.1	9.1
1999-2000	41	8,468.7	886.2	10.5
2000-2001	24	8,944.1	344.5	3.9

Source: Phillips Alaska, Inc., data files submitted to Alaska Department of Natural Resources.

For lakes that do not support wintering fish, there is essentially no current regulation of winter water withdrawals, and the amount estimated to be present during summer is typically set as the withdrawal limit. Because ice thickness grows to 1.2-1.5 m (4-5 ft) by the time withdrawals are needed in January through March, there is substantially less water available than the permitted amount, thus the full amount is not really available for use and the actual withdrawal is considerably less than that permitted. This practice essentially allows withdrawal of all remaining unfrozen water in the lake at the time of withdrawal. The effects of such withdrawals on lake flora and fauna have not been analyzed. Effects on invertebrates are not likely to be significant because during winter most invertebrates inhabiting shallow lakes are in freeze-tolerant resting stages. The potential effects of reduced water levels on vegetation and waterfowl nesting or feeding have not been evaluated.

An additional issue associated with water withdrawals from fish-bearing lakes is the potential to remove fish during pumping. In recent years, as construction of ice roads has increased in the vicinity of Nuiqsut, residents have reported finding fish frozen into the roads. Contracts issued for ice road construction specify that water is to be screened to avoid removing fish, but contractors sometimes fail to install screens. In some cases, sampling to identify the presence of fish before water withdrawal used gear that was not appropriate for detecting smaller species, such as ninespine stickleback and Alaska blackfish (*Dallia pectoralis*). The problem can be aggravated when lighted shacks are placed over the hole from which water is withdrawn.

Ninespine stickleback, in particular, are drawn to the light, then are sucked up with the water and spread on the road. Procedures have been adopted recently to prevent taking fish with water for road construction.

Seismic Effects

When seismic exploration was conducted with explosives, there was a great potential for harming fish that were exposed to large, rapid changes in ambient pressure. The advent of vibrating equipment has reduced concern, because the energy it generates is much less than that generated by explosives. The ADF&G blasting standards require that the instantaneous change in pressure resulting from any explosion must remain below 0.02 megapascals (MPa, 2.7 psi). Results of a recent field test involving vibrators on ice, over water indicate that peak pressure changes below a vibrator (under 1.2 m [4 ft] of ice) can be as low as 0.01 MPa (1.57 psi). In addition, the energy velocity appears to be many times slower than velocities known to harm fish. Peak sound pressure levels associated with vibroseis exploration, calculated at 7.3 m (24 ft) from the source, appear to be about 12 dB lower than sound pressure levels associated with airguns. When converted to energy, the vibroseis machines transfer many times less energy to the water than do airgun arrays (W. Morris, ADF&G, personal communication, 2002). The effects of summertime seismic exploration with airguns on coastal and marine fish in the Beaufort Sea have not been investigated.

Coastal Development

Coastal development that poses the greatest risk of causing effects that accumulate in nearshore habitats includes facilities that change physical conditions that are important to nearshore biota. Such structures include causeways that modify water temperature and salinity.

Two major causeways have been built into the nearshore region to support oil-field activities (Table 8-3). The Prudhoe Bay West Dock was built in the winter of 1974-1975 primarily to support off-loading of large modules used to develop the field; it was modified in 1981 to support the intake structure for the Prudhoe Bay waterflood facility to supply water needed for injection into the oil reservoirs. The causeway runs from the east end of Simpson Lagoon to the west entrance to Prudhoe Bay. The second major causeway, in the middle of the Sagavanirktok River delta, was built to support facilities for the Endicott oilfield.

Accumulation of effects is a concern when multiple causeways affect the same fish population. The migratory stocks found along the Beaufort Sea coast are likely to encounter multiple causeways during their annual summer feeding movements. From the late 1970s to late 1980s, there was substantial concern over the potential effects of the two long causeways to migrating fishes, especially for the integrity of the nearshore band of relatively warm, low salinity coastal water that is used by migrating fish Craig (1984). Causeways built perpendicular to shore disrupt the east-west flow of the coastal currents, and that can alter fish movements within the band. Permits issued by the U.S. Army Corps of Engineers and the North Slope Borough for causeway construction included stipulations for monitoring the effects of the causeway on fish movements and habitat, among other issues. Initial monitoring studied the West Dock Causeway between 1981 and 1984 and then the West Dock and Endicott causeways between 1985 and 1987. In 1988, the U.S. Army Corps of Engineers concluded that significant harm to habitat had been demonstrated and that further monitoring for effects on fish populations was not required (Hachmeister et al. 2001). Those effects, as summarized Ross (1988), included degradation of habitat quality in the nearshore region, alteration to fish movements and fish use of the Prudhoe Bay area, and changes to fish community structure.

Table 8-3 Causeway Construction, Nearshore Beaufort Sea

Facility	Year	Length of Fill (m)	Notes
East dock	pre-1974	350	
West dock			
Initial dock	1974-1975	1,340	
Emergency extension	1975-1976	1,524	
Waterflood extension	1981	1,125	-18 m breach
Breach Retrofit	1996	-200	at 1,520-1,720 m
Endicott			
Initial causeway	1985	8,000	
Breaches (2)	1986	-60, -150	
Breach retrofit	1994	-200	

Source: U.S. Army Corps of Engineers permitting documents and causeway monitoring reports.

The North Slope Borough, with the advice of its Scientific Advisory Committee, determined that the findings were not supported by the existing data, however, and decided to continue the causeway-monitoring program under its permitting authority. The effects described by Ross (1988) were used to frame a set of hypotheses that were then used to design the monitoring investigations. The North Slope Borough monitoring program focused its investigations on four main issues:

- effects of causeway-induced changes in circulation and hydrography on the migration of young-of-the-year arctic cisco from Canada to the Colville River,
- effects of causeway-induced changes in circulation and hydrography on the nearshore migration corridor used by most species of diadromous fish,
- changes to temperature and salinity of the nearshore habitat and ramifications of those changes to the population of broad whitefish inhabiting the Sagavanirktok River, and
- effects of causeway-induced changes to fish and fish habitat on the fisheries that harvest arctic and least cisco in the Colville River.

The North Slope Borough's program showed that the causeways, particularly the West Dock Causeway, interfere most notably with the eastward movement of juvenile least ciscoes and humpback whitefish moving from the Colville River into the Prudhoe Bay area during early summer (Fechhelm 1999, Fechhelm et al. 1989, Gallaway and Fechhelm 2000, Moulton et al. 1986). Juvenile Dolly Varden char also might be affected (Hachmeister et al. 1991). The movement of young-of-the-year arctic cisco from the Mackenzie River into the Alaskan Beaufort Sea region did not appear to be affected by the causeways (NSB/SAC 1997). Retrofitting of breaches in both causeways in 1994 and 1996 appears to have reduced the effect of the interference to least cisco and humpback whitefish (*Coregonus pidschian*) migrations (Fechhelm 1999).

The causeway studies revealed that, when wind is from the east, a wake eddy forms on the west side of the causeways that allows cold, high-salinity water to reach the surface (Colonell and Niedoroda 1990, Gallaway and Fechhelm 2000). That cell of cold water on the west side of West Dock is the mechanism that most likely impedes fish movements. Because the wake eddy on the west side of Endicott Causeway is offshore of the Sagavanirktok delta, its effects on fish movements are less pronounced. Various researchers have noted that the density of epibenthic fauna (mysids and amphipods), which constitute the main foods of diadromous fish and sea ducks, was particularly high along the west side of West Dock (Feder and McGee 1982, Moulton et al. 1986, Robertson 1991), perhaps as a result of the wake-eddy effect in the lee of the causeway under east winds.

Gallaway and Fechhelm (2000) concluded that fish populations in the region appear to be fluctuating in response to naturally occurring physical phenomena. Effects of the existing causeways have been at least partially mitigated with retrofitted breaches.

In addition to the causeways, large intake pipes are used to withdraw water from the nearshore region. The Prudhoe Bay waterflood facility, constructed in 1981, can supply 350 million L (92.4 million gal) of seawater per day (4.07 m^3/s [5.32 yd^3/s]), with an estimated 2.55 km^3 (0.61 mi^3) to be used over 20 years (USACE 1980). There are also seawater intakes at Endicott (44 million L [11.6 million gal] per day), and Kuparuk (95 million L [25.2 million gal] per day). Monitoring of the intakes and marine bypass systems was conducted after start-up for the Prudhoe Bay and Kuparuk waterflood facilities from 1984 to 1987 to assess entrainment and impingement (Dames and Moore 1985-1987). Fish were rarely observed during the monitoring studies and most of those that entered the system passed successfully. However, approximately 1.5 million fish larvae of 9 species were estimated to have been entrained in the Prudhoe Bay facility in 1985. The intakes were judged to performing as designed and predicted, and monitoring was discontinued after 1987.

Beaufort Sea causeways are among the most intensively studied anywhere. From 1978 to 1997, the West Dock and Endicott causeways were monitored for changes to physical oceanography, coastal processes, sedimentation patterns, fish populations and movements, fish growth, subsistence landings, fish-species diversity, benthic invertebrate populations, epifaunal populations, river hydrology, vegetation, and bird habitat use. Annual reports of the monitoring efforts were produced that summarized the results of the annual investigations. A decade of investigations on oceanographic changes related to the two major causeways was summarized by Colonell and Niedoroda (1990), by Hachmeister and colleagues (1991), Hale and colleagues (1989), and by Niedoroda and Colonell (1990).

The spatial extent of the causeways is relatively limited; the two receiving most of the attention are on either side of Prudhoe Bay. Some of the fish that encounter the causeways, including arctic cisco, however, move between the Colville and Mackenzie rivers at least twice during their lifespan. Some of the least cisco, humpback whitefish, and broad whitefish move between the Colville and Canning rivers for the summer feeding (Fechhelm et al. 2000, Griffiths et al. 2002). The effects of causeways in this region on those fish population could accumulate if the breach retrofits have not completely eliminated movement and habitat changes. Any impacts resulting from the causeways will exist until the structures are removed, or are made porous enough that fish movements are unaffected.

Future Scenario

The potential effects on freshwater systems have become clear during the development of the existing oil fields, so it is likely those effects will be addressed during the design and permitting of new fields and field expansions. The probability for serious effects is low, assuming due diligence by the responsible resource agencies. There will be new challenges, however, as exploration and development practices change. For example, exploration to the east and south will be hampered by the reduced availability of water during winter. In addition, because those areas have more hills and valleys the grades for roads will be more extreme. The current technology based on ice road access is not likely to be feasible in those areas. Similarly, current field development depends on a ready supply of gravel for pad construction. Development of fields in the National Petroleum Reserve-Alaska, where gravel is scarce, will need to rely on other materials for pad construction, and the consequences associated with alternative materials will need to be examined.

Future coastal developments could include more docks and causeways to transport structures or oil on shore. Given the adversarial history of causeway impact assessment, construction of new causeways will be approached carefully with substantial scrutiny by regulatory agencies. Each potential causeway site along the Beaufort Sea coast is unique with respect to currents and the ways that fish use the region. Therefore, the design constraints on each proposed causeway will be site-specific. Nonetheless, long solid-fill causeways are likely to be problematic and therefore are unlikely to be permitted. New docks are likely to be relatively small bulkhead structures near water deep enough to allow barges to approach the shore, so as to minimize the offshore reach of the docks. Where shallow water requires a longer reach, docks will likely have numerous large bridged beaches that allow freer flow of water and minimize the impediments to fish movements.

Findings

- During the early years of development gravel mining for roads and pads often interrupted both ice sheet flow and stream flows, and hence fish movement. The permitting process and the regulatory environment for protecting fish have improved over time and are generally effective. Proper construction and placement of bridges and culverts have greatly reduced effects but have not eliminated them.
- Guidelines for gravel mining and subsequent habitat rehabilitation or enhancement in and near active floodplains have been developed. Since 1989, arctic grayling have been introduced to several of the deep gravel pits that now provide productive fish habitat. One effect of these large gravel pits is to increase the available freshwater wintering area; it is likely that the tradeoff is positive and the negative effects are less than would have occurred if the gravel had been taken from active floodplains.
- The energy produced by vibration equipment used to acquire seismic data is not an issue because the vibrations are below threshold known to affect fish in streams and lakes crossed during the seismic investigations. The potential effects of airguns on Beaufort Sea fish have not been studied.
- Because of a lack of information it is not possible to determine whether biota associated with North Slope lakes are protected by regulations that cap water withdrawal from lakes.

- Existing causeways near Prudhoe Bay do not affect the westward recruitment of arctic cisco into the Colville River and associated rearing areas. Blockage of young least cisco and whitefishes moving eastward from Colville to Prudhoe Bay was demonstrated under certain wind conditions in some years at the West Dock causeway. This blockage has been reduced by the breach retrofit installed in 1996.
- The effectiveness of breach design for existing or new causeways has not been resolved. Breaches are effective, but there is more to be learned about the best or most appropriate design and placement of them. The North Slope Borough's Scientific Advisory Committee recommends that breaches be required in any causeway that extends across the nearshore zone, which seems to be appropriate.
- Seawater intakes have been designed to prevent entrainment and impingement of fishes.
- Large-scale industrial development could harm widely distributed fish, such as grayling, arctic cisco, broad whitefish, and other species in other areas, by interfering with their migration patterns or their overwintering habitat.

Recommendations

- Monitoring of rehabilitated deep gravel pits should continue to evaluate the long-term viability of these sites as aquatic habitat.
- The current baseline of 15% of minimum winter water volume that is allowed to be removed from fish-bearing lakes should be evaluated to determine the degree to which that criterion prevents loss of fish and invertebrates.
- An initial study of the effects of withdrawing water from lakes that have no fish should assess the degree to which current water use affects other biota associated with these water bodies.

OTHER MARINE ORGANISMS

Coastal developments that pose the greatest risk of accumulation of effects to nearshore habitats include industrial structures that change the physical conditions that are important to nearshore biota, especially causeways that alter water temperature and salinity.

Effects of Oil on Marine Plankton and Benthic Organisms

The degree to which surface oil spills affect benthic communities depends on many factors, including the weather at the time of the spill, the biotic composition of the communities and their sensitivity to oil, and how deep they are (NRC 2003). Oils produced on the North Slope rise to the surface, and do not sink to the sea floor. Although surface slicks undergo some natural dispersion, the amount of oil reaching benthic organisms is less than one part per million (McAuliffe et al. 1981, Humphrey et al. 1987). Shallow benthic communities are vulnerable if oil strands on shorelines and is mobilized into the nearshore subtidal zone. Sometimes cleanup actually mobilizes oil to cause fairly high concentrations in nearshore subtidal areas. If there is a high load of suspended sediments in nearshore waters, oil can be adsorbed onto particles and be deposited in the nearshore subtidal area where it affects epibenthic organisms. Subsurface spills from pipelines released over extended periods could affect benthic communities close to the release.

Epibenthos and infauna are usually not abundant in very nearshore waters in the Beaufort Sea. Boulder patch communities are in deeper water and are only likely to be affected if a subsurface spill occurs in the immediate vicinity. If chemical dispersants are used, short-term exposure to fairly high concentrations of dispersed oil is possible. Short-term exposure to dispersed oil (from a single surface spill) is not likely to cause mortalities of the benthos. Mortalities could be caused from a prolonged surface leak repeatedly treated. Recovery of benthic epifauna is likely to be more rapid than is recovery of infauna. Recovery of boulder patch communities would probably take several years (Martin 1986).

Oil spills on or under spring ice would diminish primary production either as a result of toxic effects or because the oil would block light that passes though the ice sheet (Schell et al. 1982).

Some species of phytoplankton are more sensitive to oil than are others (NRC 2003). They can be affected by a surface oil slick or if dispersants are used and more oil enters the water column. The affected standing stock and primary production return to pre-spill conditions rapidly through natural transport of organisms from surrounding areas and rapid reproduction of these populations (Trudel 1986c). Fish larvae and eggs can be harmed by spilled oil, and oil can be ingested by higher trophic-level organisms with prey or as a result of prey contamination (NRC 2003). Thus, the effects of spills on phytoplankton communities generally are localized and short lived enough so that recovery occurs before effects accumulate.

Many zooplankton species, especially as larvae, are sensitive to oil. Studies of zooplankton have followed several oil spills, and localized, short-lived effects have been detected. There are seldom changes in biomass, however, because of high reproduction rates and rapid recrüitment from other areas (Trudel 1986d).

Effects on Biological Processes and Marine Communities

Studies of the Boulder Patch indicate that development of its kelp-community depends on four factors: There must be a hard substrate for attachment of algae and associated invertebrate fauna. There must be free (unfrozen) water under the winter ice canopy and protection from extensive ice-gouging and reworking at the bottom. There must be an erosional rather than depositional sedimentary environment (Dunton et al. 1982; Coastal Frontiers Corporation and LGL Ecological Research Associates, Inc. 1998). Those factors can exist in the vicinity of both natural and anthropogenic hard substrates.

As part of the Endicott environmental monitoring program, studies were conducted to measure long-term colonization of bare boulders placed at sites in the Stefansson Sound Boulder Patch. Colonization initially was slow, being negligible (Martin et al. 1988) or sparse after 3 years (Dunton et al. 1982). Five to six years were required before full colonization was achieved (Martin and Gallaway 1994). The slow appearance of colonizing organisms and the presence of uncommon species led Martin and Gallaway (1994) to suggest that Boulder Patch species disperse as relatively long-lived, slow-growing larvae. Species that fail to colonize could have a nonmotile dispersal stage or otherwise be limited in ability to disperse.

After 2 years in Stefansson Sound at drill island BF-37 red algae, particularly *Phyllophora truncata* and *Phycodrys rubens*, and one animal, a small hydroid had colonized gravel-filled bags (Toimil and Dunton 1983). No organisms were observed on the loose gravel at the base of BF-37. During inspections in 1994 and 1996 of gravel-filled bags and concrete mats placed as protective armor on Tern and Northstar exploratory drill islands, divers reported algae, worms, and soft coral (Craig Leidersdorf, Coastal Frontiers Corporation, personal communication cited in Wilson 2001). A 1998 survey reported algae about 2 m (6.5 ft) long, consisting of two distinct blades, probably representing 2 years growth, attached to coarse gravel (3-5 cm [1.2-2 in.]) lying near the toe at 6 m (20 ft) on Tern Island's western slope (C. Leidersdorf, Coastal Frontiers Corporation, personal communication cited in Wilson 2001). In the Stefansson Sound area, algae of this size likely would have been kelp, and those with distinct blades likely would have been *Laminaria*. Leidersdorf believed the plants colonized the gravel at the base of the island (Wilson 2001).

Laminaria solidungula and *L. saccharina* attached to coarse gravel have been collected along the eastern shore of the Endicott causeway after heavy easterly storms. Those plants with attached gravel were presumably moved westward along the bottom by surge and wave action created by storm winds and deposited along the causeway shoreline (Busdosh et al. 1985). It is possible that the kelp at the base of Tern Island were moved along the seabed by westerly storm conditions and deposited there.

Findings

- Other than those caused by permitted discharges and physical alterations or addition of structures, there have been few measurable effects on marine invertebrate communities from oil exploration and production operations on the North Slope.
- Hard substrates added to the marine environment in the form of causeways and artificial islands have been colonized slowly by benthic invertebrates.
- The Boulder Patch community has not been affected by oil operations.
- Monitoring is frequently required as a condition of discharge permits to ensure that discharges do not exceed water quality standards, are not toxic to marine organisms, and do not degrade water quality or pose a threat to human health. Most of the records of the monitoring programs are retained by the principal permitting agency, the U.S. Environmental Protection Agency, and are not readily available. Records also are kept by individual operators, but they are not summarized, and few annual reports are available.
- Oil operations have not had measurable population effects on epibenthic invertebrates, the sessile invertebrates of the Boulder Patch communities. The epontic communities under the ice have not been specifically studied, but it is unlikely that operations have affected them.
- Hard substrates added to the environment in the form of causeways and artificial islands have been slowly colonized by benthic invertebrates such as those found in the Boulder Patch.
- The committee found no data showing that discharges to the Beaufort Sea have had effects on biota. The trend is toward using disposal wells instead of discharging wastes directly to the ocean.

9

Effects on the Human Environment

> There is no turning back. We were introduced to the cash economy and now we can't do without it. How do we balance these? I don't know. We are learning it as we go. I don't know where is the middle place and I don't know what the future holds.
>
> Bernice Keigelak

> The land can tell us everything we want to know. The only problem is that it doesn't have a voice. But the spirit of the land is always there—talking to us. We must listen.
>
> Arctic Elder

Some effects on the human environment of oil and gas activities are analogous to effects on physical and biotic environments in that they are related in space and time to physical changes in the environment. But others differ in major ways because an effect on humans can occur without a physical change in the environment. Information—the announcement of a leasing decision, or knowledge about an event that occurred far away, for example—can profoundly affect people individually and collectively. These effects can occur before any local biotic or physical changes. Similarly, effects on people can occur by changing people's perception of risk or reward, and hence their behavior. Also, people can adapt faster and to a greater degree than many other organisms. As result of those differences, social and economic assessments on Alaska's North Slope must include an analysis of prior and distant effects. There is no analogy between the analysis of those effects and the analysis of any physical or biotic effect.

In addition, the harvesting of the wildlife resources that live or migrate through the region is of major cultural, nutritional, and economic value to North Slope residents. Although peoples in other rural areas traditionally hunt and fish for local wildlife, those activities are generally a supplement to other forms of subsistence activities such as gardening and timber harvest (Field and Burch 1991). There is no agriculture or forestry on the North Slope, so the Native cultural heritage there is based to a much greater degree on subsistence hunting and fishing than are subsistence cultures elsewhere.

Energy-resource development on Alaska's North Slope differs from the boomtown experience in the continental United States (Kruse et al. 1983). The isolation of rural communities on the North Slope, particularly because of their lack of connection to a highway network, meant they did not become staging areas for development. Instead, virtually independent infrastructures developed, centered on the terminus of the haul road that was built to support the Trans-Alaska Pipeline. The people hired to support the industrial development of the North Slope were not local or permanent, and in that they are similar to the populations that support offshore petroleum development elsewhere (Gramling 1989, 1996).

Because of these differences, the two research traditions that have guided much social and economic impact assessment are not entirely satisfactory. The first research approach flows from the National Environmental Policy Act (NEPA) of 1969, which requires that federal or federally funded agencies assess and mitigate the environmental effects of their actions.

The NEPA led to the birth of a variety of assessment techniques, summarized by Burdge (1994) and condensed into guidelines by the Interorganizational Committee on Guidelines and Principles for Social Impact Assessment (1994). The focus is to predict and evaluate social and economic effects *before* activities occur. It is necessary to describe baseline conditions (how the basic social and economic environment functions beforehand), identify the full range of probable social effects based on discussions with the affected parties, and project responses to the most likely effects. The approach identifies alternatives to the action proposed, and it establishes procedures for monitoring and mitigation.

The second tradition, which assesses the effects of development activities *after* it happens, has a long history, particularly in rural sociology (Field and Birch 1988; see Landis 1938). The focus sharpened in the early 1970s with research on the effects of the construction of coal-fired power plants in the rural western United States. The driving force of this "boomtown" model is population growth, which leads to a host of associated, frequently undesirable, societal effects. They include overcrowding; degradation of various municipal services, with a subsequent loss of informal control of deviance and community support of its disadvantaged members (Freudenburg 1986); and increases in substance abuse, divorce, homicide, and suicide (Albrecht 1978, Bates 1978, Cortese and Jones 1977, Gilmore 1976, Gramling and Brabant 1986).

To allow assessment of social and economic consequences related to oil and gas development on the North Slope, the committee used the typology developed by Gramling and Freudenburg (1992a, Freudenburg and Gramling 1992) in its analyses. In this typology, effects are separated into opportunity and threat effects, which can occur before any physical or biotic change; developmental effects, which occur during and soon after development activities occur; and adaptation and post-developmental effects, which generally occur after development is complete. Because developmental effects—those attributable to oil and gas exploration, development, and production—have been far greater on the North Slope than opportunity and threat or adaptation and post-developmental effects, they are discussed in the most detail.

OPPORTUNITY AND THREAT

In the human environment, real, measurable effects—*opportunity and threat effects*—begin with changes in social conditions and so can start with a rumor or announcement about a proposed activity (Krannich and Albrecht 1995). They result from the efforts of interested parties to define, and to respond to, the anticipated effects of development, either as an opportunity (for those who see the effects as positive) or as a threat (for those who see them as negative). Many effects on the human environment of the North Slope began with the announcement in 1968 of the discovery of oil reserves in Prudhoe Bay, and they were accomplished facts—or well on the way to becoming so—even before Congress approved construction of the Trans Alaska Pipeline in 1973.

Two types of information have resulted in the accumulation of opportunity and threat effects for the residents of the North Slope Borough: information concerning the initial find and information concerning various development scenarios.

Discovery

In January 1968, Atlantic-Richfield (ARCO) and Humble (now Exxon/Mobil) announced that they had found significant quantities of oil and natural gas at Prudhoe Bay. In July, ARCO estimated the find as 9.6 billion barrels (Berry 1975). The announcement of the discovery, the largest in the western hemisphere, was a catalyst for changes that affected the human environment of the North Slope and that increasingly moved North Slope residents into the mainstream economy. With the discovery, North Slope lands and waters that were the traditional Inupiaq hunting and fishing grounds suddenly had new meaning and value to the industrialized world to the south.

Although the concept of a pipeline to move oil from the North Slope to Valdez dates back to at least 1946 (Thomas 1946), the 1968 discoveries led engineers from British Petroleum, Humble, and ARCO to undertake more extensive studies. In 1969, those companies announced plans for a 1300 km (800 mi) long pipeline, at an estimated cost of $900 million. New companies joined the venture: Mobil, Phillips, Union of California, Amerada-Hess, and Home Oil. On June 6, 1969, they applied to the U.S. Department of the Interior for permission to build the pipeline across public land in Alaska.

In addition to opposition by environmental and commercial fishery groups there were two key legal impediments to the pipeline: long-standing native claims to the land across which the pipeline would traverse and the then-new NEPA. The importance of the land rights issue encouraged the multinational oil companies to support settlement of Native claims. Once that support was forthcoming Congress acted fairly quickly to pass the Alaska Native Claims Settlement Act (ANCSA) in 1971, which can be seen as the first major social and economic effect of petroleum activities on the North Slope. The ANSCA fundamentally changed the relationship between North Slope Alaska Natives and the environment they had occupied for thousands of years. The effects of that change accumulate to the present.

Congress chose a corporate model to address the issue of common "ownership" of native lands. The ANCSA created 13 regional corporations, 12 in Alaska and 1 to represent Alaska Natives living outside the state. Alaska Natives who enrolled were made shareholders. Approximately 200 village corporations also were created. Alaska Natives who enrolled in their village corporations received shares of that corporation. In general, Alaska Natives were allowed to enroll either in the region and village where they grew up and which they considered home, or in the region where they were living at the time the act was passed.

The act also provided for the distribution of $962 million in compensation to the regional and village corporations, essentially on a per capita basis. Of the funds, $462 million came from the federal government and $500 million came from state royalties on petroleum over a period of 11 years. Thus, approximately half of the original funds to establish the regional and village corporations did not come directly from North Slope petroleum activities.

One ANCSA provision requires that regional corporations share 70% of their resource revenues (those derived from timber or subsurface mineral rights acquired as a result of the ANCSA) with the other regional corporations. However, the Arctic Slope Regional Corporation (ASRC) would not be required to share resource revenues from its subsurface inholdings in the Arctic National Wildlife Refuge, because those lands were obtained in a land exchange (GAO 1989). This provision was designed to ensure that resource-rich corporations shared with those that were resource-poor simply by accident of location. This provision has had major and continuing effects.

Finally, under the ANCSA, 18 million ha (44 million acres) of land was conveyed to the regional and village corporations. Of that, 9 million ha (22 million acres) of surface estate went to village corporations, using a population-based formula. This land was generally located around villages and consisted of prime subsistence areas. The subsurface rights to this land, some 6.5 million ha (16 million acres), went to the regional corporations. However, under ANCSA, regional corporation selections for subsurface lands could not be made within existing national wildlife refuges. About 810,000 ha (2 million acres) was conveyed for specific uses, such as cemeteries, historical sites, and villages with fewer than 25 people, and another 1.6 million ha (4 million acres) went to reserves where the villages took land instead of land and money. The ANCSA also specified that if the secretary of the interior wanted to set aside a pipeline transportation and utility corridor, neither the State of Alaska nor Alaska Native groups could select lands within it. The ANCSA has been both praised and criticized, but its role in bringing permanent and still accumulating change to the lives of Alaska Natives on the North Slope and elsewhere cannot be denied.

The second major legal impediment to the pipeline, the NEPA, led to a bitter fight in Congress, primarily over a proposed alternative route through Canada and alternate sources of energy for the nation. The fight over the Trans Alaska Pipeline concerned loss of wilderness, marine oil spills at Valdez, earthquakes, and other issues (Coates 1991). The battle was finally settled, not by discussion or the NEPA process, but by the October 1973 oil embargo staged by the Arab members of OPEC. Shortly after the embargo began, opposition to the pipeline in Congress declined: the Trans-Alaskan Pipeline Authorization Act was passed November 12, 1973; and signed by President Nixon on November 16. The act barred further review on the basis of the NEPA, and it restricted further legal action only to questions concerning the act's constitutionality (Gramling and Freudenburg 1992b).

A third impediment in 1970 through 1973 was a technical review process that indicated the pipeline, as designed (to be buried), was vulnerable to failure by thawing permafrost and to destruction by plausible earthquakes. It mandated redesign according to specific technical stipulations (DOI 1972). The redesign, in which about half the pipeline is elevated, was completed during those three years. The estimated project cost rose from the original $900 million to $8 billion.

The haul road was completed in September 1974, and pipeline construction took the next three years. (For a concise description of the pipeline and associated facilities, see Coates 1991.) Oil first reached the Valdez terminal on July 31, 1977.

On the North Slope, the initial discovery started a chain of effects. The Arctic Slope Regional Corporation (ASRC) was created to serve as the North Slope's regional corporation; it is one of the major players on the North Slope. The North Slope Borough (NSB) was incorporated July 2, 1972. The North Slope Borough almost would certainly not exist except for

North Slope petroleum, but if it did exist it would certainly not be the dominant social, economic, and political force that it is today.

The initial discovery at Prudhoe Bay, the subsequent enactment of the ANSCA, establishment of the ASRC and the village corporations, and the founding of the NSB have been the primary factors in the growth, concentration, and development of the communities and populations on the North Slope. Without petroleum development on the North Slope, those communities and populations, and the conditions under which they live would be vastly different. The initial announcement of the discovery at Prudhoe Bay resulted in the restructuring of the social, economic, and political life on the North Slope in a way that allowed large amounts (by North Slope standards) of capital to flow into the region. That capital resulted in major changes in North Slope communities.

Specific Development Scenarios

Information about two specific development scenarios has led to significant opportunity and threat effects: offshore development and development in the 1002 Area of the Arctic National Wildlife Refuge.

Offshore Development

The 1983 observation of Kruse and colleagues, that Native Alaskans' "fears that offshore development will inevitably harm subsistence resources are both intense and widespread and themselves constitute an impact of development," is still true. The committee was repeatedly told that this is *the* issue for the Inupiat.

The concerns fall into three categories, all involving the bowhead whale. The first is that the Inupiat do not believe anyone has demonstrated the ability to clean up oil spilled in a frozen sea or in broken ice. In fact, many have voiced the belief that large marine spills cannot be cleaned up in any situation, citing as evidence the *Exxon Valdez* spill and the failure of any large marine spill to be contained and cleaned up (see also ADEC 2000). The *Exxon Valdez* oil spill was a sensitizing event on the North Slope, as it was around the world, in reinforcing the perceived consequence of a large marine spill. Along the coast, the first concern is that a spill during the migration of the bowhead and will injure or kill significant numbers of whales. The Inupiat believe this would be especially critical during the spring migration when both spilled oil and whales would be concentrated in leads (cracks in the ice cover).

The second concern is that a spill would cause the International Whaling Commission to judge the bowhead to be under greater threat than is currently perceived, causing that group to curtail or reduce quotas for the striking of whales. The final concern is that the noise associated with offshore exploration and production would alter the migration routes of the bowhead. This concern is based both on observations by Inupiat hunters and on recent scientific data that bowheads will avoid seismic activity, moving as much as 20-30 km (13-19 mi) away from their normal migration routes (Richardson 1997, 1998, 1999). When whales move farther from shore, the hunters must follow in their small boats to unpredictable seas, and tow killed animals farther, as well. Hunters are exposed to greater danger and the amount of the harvest is reduced because of spoilage.

It would be difficult to overstate the importance of bowhead hunting to the Inupiat. The subsistence harvest dates back several thousand years, but outside influences have brought about social changes, and so whale hunting has become a rallying point for the maintenance of Inupiaq cultural continuity in at least four important ways. First, the organization of whaling crews and the preparation for the hunt is a continuous activity that creates and reinforces social and cultural bonds. Second, the hunt itself is an intensive experience that involves crews camping out on the ice, near a lead, for up to a month. Third, the preparation and preservation of a successfully taken whale involves the entire community. Luton (1986) estimated that 70% of the entire population of Wainwright was directly involved after the successful taking of a bowhead. Finally, sharing the whale is an integral part of Inupiaq culture that reinforces cultural continuity and that goes beyond social action to the way Inupiat are intertwined with the world. For the Inupiat, the only way humans can take an animal as powerful as a bowhead whale is if the whale gives itself to the hunters. Whales will do this only if they are treated with respect. Sharing the whale is one way of showing respect, as are activities such as cleaning the ice cellar, the final resting place of the whale. Whales are shared in three ways. First, whales are shared by whaling crews according to a community formula (Luton 1986). Second, as with other subsistence commodities, once a crew member has received his share, various portions of the whale are shared with relatives, friends, and elderly members of the community and others who cannot participate directly in the hunt. Finally, a large part of the successful captain's share of the whale goes to the Nalukataq, a festival and important community gathering that includes a blanket toss, dancing, and the sharing of food.

Each successful captain holds a Nalukataq (usually the last two weeks in June), and friends, relatives, and former community members travel to the community to visit and catch up on what has happened over the past year. No other shared pursuit involves as many members of the community, for as much time, and as intensively as the activities that surround hunting the bowhead. In Barrow, hundreds of thousands of person-hours are spent in those activities (Harcharek, unpublished material, 2001). The same is true in other North Slope whaling communities.

Finally, the size of bowheads makes them an extremely important food source. It is doubtful that any of the North Slope communities could survive in their present form without the harvest. Of the 74% of NSB households that responded to a 1998 survey, 68.7% of Inupiaq households and 36.4% of non-Inupiaq households reported that at least one-half of their annual food came from subsistence activities.

Hunting the bowhead has been the Inupiaq cultural anchor as change has come to the North Slope. The ongoing, accumulating effects posed by offshore development, in the form of perceived threats, would be diminished only by clear evidence that the technology exists to mitigate large oil spills in broken ice. There is no evidence to date that such cleanups are possible. Current mechanical means of collecting spilled oil are not likely to be successful in the Beaufort and Chukchi seas (ADEC 2000). Alternative methods, such as in-situ burning and chemical dispersion, still must be developed for use in ice-filled waters, incorporated into response plans and practiced, and approved by regulatory agencies.

Engaging in subsistence activities is not simply a matter of choice. Isolation from major transportation routes and the area's inability to produce agricultural products mean that the prices of goods and the cost of transporting them to the North Slope are considerably higher than in the rest of Alaska or in the continental United States. In 1998, the cost of a "typical market basket" in Anchorage was $122.19; in Barrow it was $218.03 (NSB 1999); it is substantially higher in outlying North Slope villages. Costs for vehicles, construction materials, fuel, appliances, and tools are similarly inflated in the North Slope. This does not mean that Barrow residents spend 178% of what residents in Anchorage spend; indeed they cannot. Because North Slope residents do not have greater per capita incomes than some of their counterparts in Alaska or in the United States in general, they must have a lower standard of living, rely to a greater extent on subsistence harvest, or both. Accordingly, examination of any potential effects on subsistence resources is critical to the assessment of the accumulation of effects of energy development on the human environment.

Development in the 1002 Area

The Gwich'in Indians are a traditionally nomadic people who follow the migration of the Porcupine Caribou Herd (Mishler 1995, Time-Life Books 1998). For thousands of years, their ancestors have relied on caribou to meet their nutritional, cultural, and spiritual needs (Gwich'in Niintsyaa 1988). The Gwich'in Nation consists of 15 villages in northeastern Alaska and northwestern Canada (Arctic Village, Christian, Venetie, Beaver, Birch Creek, Fort Yukon, Stevens Village, Circle, Eagle Village, Chalkyitsik, Old Crow, Fort McPherson, Arctic Red River, Aklavik, and Inuvik), all of which are outside the North Slope. However, the coastal plain of the North Slope, primarily the 1002 Area of the Arctic National Wildlife Refuge, is the traditional calving ground for the Porcupine Caribou Herd. The Gwich'in believe that oil- and gas-related activities there would affect the reproductive potential and migration patterns of the Porcupine Caribou Herd and as a result threaten their way of life. As with the Inupiaq concerns about offshore development, the beliefs are intense and widespread and themselves constitute a continuing effect that is exacerbated by the past and current political debate over development in the Arctic National Wildlife Refuge.

As an indication of the strength of their concerns, in 1988, in response to initial attempts to open the refuge, the Gwich'in Nation met in Arctic Village to draft a resolution petitioning the Congress and president to preserve the right of the Gwich'in people to their life-style by prohibiting development in the calving ground of the Porcupine Caribou Herd and to designate the 1002 Area of the Arctic National Wildlife Refuge as wilderness.

The residents of Kaktovik, who live on Barter Island at the northern edge of the Arctic National Wildlife Refuge coastal plain, are generally in favor of environmentally sensitive development there, which could bring significant economic resources to them.

EFFECTS OF DEVELOPMENT

Most research on effects on the human environment has focused on development effects—those associated with the actual development, construction, and operation of a project or with the onset of a particular activity or process. Development activities also can alter physical systems in ways that affect humans, and they can alter cultural, social, political, economic, and psychological systems. Development effects have been studied the most and are the best understood of all socioeconomic consequences. A variety of effects can be observed on the North Slope, including those attributable to noise and disturbance, availability of money, and alterations to the physical environment, with indirect effects on people.

Noise, Bowhead Whales, and Subsistence Hunting

Inupiaq hunters in the coastal villages first expressed their concerns about seismic noise affecting fall-migrating bowheads in the 1980s (Ahmaogak 1985, 1986, 1989). The hunters' contention was that seismic disturbances were forcing the bowhead off shore, making access to the whales more difficult and time making the whales more wary and therefore more difficult to hunt.

However, early scientific studies concluded that the bowheads did not react strongly to an approaching seismic vessel until it was within 7.5 km (4 mi) (Ljungblad et al. 1985, 1986, 1988). Native hunters strongly disagreed with this assessment, and eventually two apparent problems with its methods were identified. First, the whales were approached by the boat, rather than the whales approaching the boat. Thus, what was measured was how close a seismic vessel needed to approach to force whales to move out of an area they were already in, rather than to what extent migrating whales would alter their paths to avoid a seismic vessel. Second, in three of the four experimental situations in the study there was already another seismic boat "booming" in the distance before the test boat began. This compromised the controls. Those problems led scientists to conduct more carefully controlled studies in the late 1990s. Data from three years showed that nearly all fall-migrating bowheads stayed 20 km (12 mi) away from an operating seismic vessel, a finding that supported native observations (Richardson 1997, 1998, 1999). In addition to avoiding active seismic vessels, whales change their rate of calling as they approach seismic sources. Data from seismic monitoring in 1996 and 1997 show that call rates changed at least 45 km (27 mi) from an active seismic vessel (Richardson 1998), probably indicating detection of seismic activity. (Details of the effects of noise on whales and other marine mammals are in Chapter 8.)

In recent years, the Alaska Eskimo Whaling Commission (AEWC) and seismic-exploration operators have reached an agreement that reduces the effects of seismic noise. The "oil-whaler agreement" restricts seismic vessel operations to the west of the Nuiqsut and Kaktovik hunting areas until the subsistence hunt has been completed. The agreement must be renegotiated annually because the areas of seismic operation vary each year. The National Marine Fisheries Service (NMFS) established the program and continues to require operators to cooperate with the AEWC. Although the agreement is helpful, substantial expense of time and resources is required for AEWC negotiations each year in full consultation with its members in the affected villages.

Petroleum activities on the North Slope have affected, and have the potential to affect, subsistence activities in several ways. Direct effects have been documented in three areas. First, traditional hunting areas within active oil fields are now closed to hunting. Second, offshore activity alters bowhead migration routes. Third, as noted in Chapter 8, calving caribou tend to avoid intensive oilfield activity, shifting to less disturbed areas. As activities expand on the North Slope those effects could expand as well.

In addition to the effects noted above, Alaska Native residents told the committee that there are subtle changes in species harvested by subsistence hunters, who have identified changes in the color, texture, and taste of the flesh and skin of several species.

Alterations to the Land

Alterations to the North Slope physical environment have had aesthetic, cultural, and spiritual effects on human populations. They come primarily from construction of roads, pipelines, buildings, and powerlines, and from offroad travel.

Structures and Roads

Before the completion of the haul road in September 1974, the only regular, mechanized access to the North Slope was by air, or by water during the late summer and early fall. Increases in settlement, agriculture, and forestry generally accompany road building in temperate and tropical areas, but for the North Slope the most relevant effect is the increased hunting pressure that accompanies roads (Box 9-1). Currently, roads of the industrial development stretching from Kuparuk to Endicott are closed to public traffic, but should any of them be opened to public use, effects would increase. The Alaska Department of Transportation is considering a new all-season road to connect the National Petroleum Reserve-Alaska with the Dalton Highway (Petroleum News Alaska 2002).

Box 9-1 Recreational Fishing and Hunting

Fish, mammals, and birds on the North Slope are taken by subsistence, commercial, and recreational users. Here we consider the effects of recreational fishing and hunting.

Fishing

Recreational fishing is mostly for Dolly Varden char and arctic grayling, although lake trout, burbot, pink salmon, chum salmon, and whitefish are also taken (as reported in the Alaska Department of Fish and Game [ADF&G] annual catch surveys, such as that by Howe and colleagues [2001]). From 1977 to 1981, the annual fishing effort averaged 2,030 angler days (range: 1,422-2,601), but since then it has averaged more than 5,000 angler days (range: 2,541-8,344). Effort as measured by the number of angler-days increased after completion of the Dalton Highway but appeared to stabilize after 1981. Reported catch rates of Dolly Varden char and arctic grayling declined from peaks in the early and mid-1980s to about 1990 and have fluctuated with no significant trend since then. However, before 1990 only fish taken were reported. After 1990, the estimates also include fish caught and released, reflecting that increasingly common practice (Howe et al. 2001). Thus, it is possible, and perhaps likely, that the change in reporting has masked a decline in catch rates.

The catch-per-unit-effort (CPUE), a measure of how many fish are caught for a given fishing effort, has declined substantially since the mid-1980s. CPUE is related to fish abundance and to other factors, such as the fish learning to avoid capture, which substantially affects CPUE for catch-and-release fishing. It is difficult to accurately estimate the number of fish caught and released by recreational anglers. Catch-and-release fishing usually has little effect on the populations of targeted fishes (Policansky 2002), so it is difficult to evaluate how the effects of recreational fishing accumulate with other effects on the target populations.

Box 9-1 (continued)

Hunting

Records of recreational hunting kills in Game Management Unit 26 (the North Slope) start in 1977 for sheep and moose, in 1960 for brown bears, in 1981 for caribou, and in 1984 for wolves. The latest information available is for 2001: records for caribou were not available between 1983 and 1997. Because the Dalton Highway was completed in 1974, the records do not permit any evaluation of its effect on hunting other than for bears, but observation and anecdote indicate that hunting increased after the road was completed.

Recreational caribou hunting varies widely from one year to another. For example, in 2000, 979 animals were taken; only 74 were reported killed in 2001, although the information for that year appears incomplete. All other years for which there are records, more than 360 caribou were taken. The recorded take of sheep was around 200 in most years, with a few years recording slightly more than 300. The number of bears ranges from 1 in 1960 and 1962, to 51 in 1990, and 62 in 1991. No clear trend is apparent except that relatively few bears were taken before 1963 and more were taken in the early 1990s than at other times. In most years between 1979 and 1995, 100-200 moose were taken; 48 were taken in 1977 and 81 were taken in 1978. Since 1995, the annual take has declined markedly, ranging now from 5 to 17 animals per year. The annual take of wolves was a low of 2 in 1984 to a high of 91 in 1993, but other than an increase after 1987 and a peak in the early 1990s, no clear trend is apparent.

The available information makes it clear that hunting is a source of mortality for the target species that likely has increased as a result of the opening of the Dalton Highway. However, no obvious population effects have been documented, so the committee was unable to assess how the effects of recreational hunting accumulate with other effects on the target populations.

Access by Nuiqsut caribou hunters to oilfield complexes has been reduced because hunting is prohibited within some, but not all, such areas. Physical barriers to use of all-terrain vehicles, and snowmachines are posed by pipelines, and many hunters are reluctant to enter the oilfields for personal or aesthetic reasons. The committee heard repeatedly from North Slope Inupiat residents that the imposition of a huge industrial complex on the Arctic landscape was offensive to the people and an affront to the spirit of the land.

The roads and gravel pads are not likely to be removed because exploration and development leases do not generally require rehabilitation. Rather: "[A]t the option of the state, all improvements such as roads, pads, and wells must either be abandoned and the sites rehabilitated by the lessee *to the satisfaction of the state*, or be left intact and the lessee absolved of all further responsibility as to their maintenance, repair, and eventual abandonment and rehabilitation" (Alaska Division of Oil and Gas 2002, emphasis added). It was the State of Alaska, not the oil companies, that pushed for public access to the Dalton Highway. Thus, the extent of permissible access to the infrastructure associated with current and future petroleum production on the North Slope ultimately rests with the state government.

Off-Road Travel

The primary effects of off-road tundra travel are imprints on the land that persist for varying amounts of time. Off-road travel does physical damage to the land and vegetation, and the tracks laid down by various types of vehicles are aesthetically unpleasing. The recognition that imprints of human activity make a qualitative difference in a landscape can be seen in the wording of the Wilderness Act of 1964 (PL 88-577): "[A] wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammeled by man..." As with most questions of aesthetics, different people—perhaps even entire cultures—are affected differently by seeing, or just knowing about, changes to the environment caused by human activity. That the landscape is altered, however, is undeniable.

Seismic exploration leaves an imprint on the landscape, particularly the more recent 3-D (three-dimensional) methods that require receptor lines to be much closer together than earlier methods. Of the activities associated with seismic surveys, the camp trains (pulled by D-7 Caterpillar bulldozers) appear to leave the most visible scars. It is not known how long the tracks left by seismic activity will remain on the tundra; however, some of the tracks left in the 1984-1985 seismic surveys in the Arctic National Wildlife Refuge are still visible.

Human-Health Effects

During the committee's four meetings in Alaska, residents offered individual perspectives on many subjects, and we heard testimony about both positive and negative effects from oil and gas development. Alaska Natives recognize that oil production in the region has given them money to spend on community facilities, schools, modern water and sewer systems, village clinics, child emergency shelters, and behavioral outpatient and residential programs that provide mental health care and counseling for substance abuse and domestic violence. North Slope residents reported that money has increased the quality and quantity of health care for elders, especially for those who need assisted-living services. Each individual receives a permanent fund dividend every year that is funded by investment of state money. Barrow residents already enjoy low-cost natural gas heating for their homes, and other communities are expected to receive it soon. Some residents believe that the access to the Internet increasingly will provide people with education without the cost of travel or absence from the village.

North Slope residents also reported that traditional subsistence hunting areas have been reduced, the behavior and migratory patterns of key subsistence species have changed, and that there is increased incidence of cancer and diabetes and disruption of traditional social systems. They also see vastly increased time, effort, and funding necessary to respond politically and administratively to the ever-multiplying number of projects proposed in their own back yards.

Alaska Natives told the committee that anxiety over increasing offshore and onshore oil and gas activity is widespread in North Slope communities. Hunters worry about not being able to provide for their families or about the added risk and expense of doing so if game is more difficult to find. Elders who can no longer provide for themselves worry about the challenges facing younger hunters who will go to great lengths to provide them with essential and traditional foods. Families worry about the safety of hunters who must travel farther and more often if game is not easily accessible. Many adult residents already lead dual lives as wage earners and subsistence providers for their families. They also are faced with the need to attend industry-related meetings and hearings, and review documents, because they believe that decisions will be made that can significantly affect their daily lives and those of generations to come. They worry about contamination of the food they consume and know that their health will suffer if they are unable to eat as their ancestors did.

In addition to stress contributing to adverse health effects, oil development has increased the smog and haze near some villages, which residents believe is causing an increase in asthma. The stress of integrating a new way of life with generations of traditional teachings has increased alcoholism, drug abuse, and child abuse. Higher consumption of nonsubsistence food, such as shortening, lard, butter, and bacon, and reduced consumption of traditional foods, such as fish and marine mammal products, have increased the incidence of diabetes (Ebbesson et al. 1999).

The NSB bears the costs of those social stresses. Villages now provide substance abuse treatment, counseling, public assistance, crisis lines and shelters, and other social service programs. The borough provides the search and rescue services that respond when hunters put themselves at risk in the pursuit of less accessible game. The revenue from oil development has funded a police force, which must respond to the situations that arise when people and their communities are subjected to long-term and persistent stress. The borough supports biologists, planners, and other specialists who review and offer recommendations on the volume of lease sale, exploration, and development project documents that are produced each year. It must also cover the ever-increasing expense of travel to Fairbanks, Anchorage, and Juneau, Alaska; Seattle, Washington and Washington, D.C., where agencies with authority over oil and gas leasing, exploration, and development, and the subsistence resources they depend on, conduct most of their work and make most of their decisions. Although many public services would not have been possible without the revenue from oil development, many of those public services would not have been necessary if oil had not been found and extracted from the North Slope.

Wilderness and Wildlands

The only legally designated wilderness areas under study by the committee is a portion of the 3.2 million hectare (8 million acre) Mollie Beattie Wilderness that lies north of the Brooks Range within the Arctic National Wildlife Refuge and a small segment of Gates of the Arctic National Park north of Chandler Lake (Box 9-2) (NWPS 2002). The Wilderness Act expressly prohibits the construction of roads and structures and the use of motor vehicles, motorized equipment, and motorboats, or aircraft and other mechanical transport, in formally designated wilderness [Sec. 4(c)]. However, the Alaska National Interest Lands Conservation Act (ANILCA) of 1980 subsequently authorized the use of motorized boats and snowmobiles, subsistence hunting and fishing, the construction of temporary structures, and the landing of airplanes and other activities in Alaska wilderness areas.[1]

In addition to formally designated wilderness, more than 300,000 ha (750,000 acres) of federal land in the 5.2 million ha (12.8 million acre) area between the Arctic National Wildlife Refuge and the National Petroleum Reserve-Alaska has been collectively managed by the Bureau of Land Management (BLM) as a wilderness study area (R. Delaney, BLM, personal

[1] Sections 811,1110, 1316 of ANILCA and 50 CFR Sec. 36.12. See 66 F.R. 3716 et seq. for a discussion of ANILCA exceptions to wilderness study area (WSA) prohibitions.

communication, 5/17/01 and 1/30/02).[2] BLM is required to maintain the wilderness character of this area. Although the amount of formally designated wilderness on the North Slope is small, a substantial portion of the slope outside the oil fields retains the characteristics of wildlands and is de facto wilderness (TAPS Reapplication EIS).

Box 9-2 The Arctic National Wildlife Refuge

Wilderness was perhaps the most prominent of the values the Arctic National Wildlife Refuge was established to protect. Refuge founders Olaus and Margaret Murie, George Collins, Lowell Sumner, and U.S. Supreme Court Justice William O. Douglas focused their work to establish the refuge on the theme of "America's Last Great Wilderness," and their writings are replete with references to the wildland values of the area and to its status as one of the last large, wild systems remaining in the United States (FWS no date). Additional purposes of the refuge were to preserve unique wildlife and recreational values, including the Porcupine caribou herd, polar bears, grizzly bears, and other mammals and birds, and Arctic char and grayling; to fulfill international fish and wildlife treaty obligations, to provide for continued subsistence use by local residents, and to ensure water quality and quantity (FWS no date).

In 1960, the 3.6 million ha (9 million acre) Arctic National Wildlife Range was established by the secretary of the interior. In 1980, the ANILCA more than doubled the size of the range and renamed it the Arctic National Wildlife Refuge. Some 3.2 million ha (8 million acres)—or about 40% of the refuge—is legally designated wilderness. The 1002 Area is not part of the designated wilderness. The U.S. Fish and Wildlife Service seeks to preserve the same level of naturalness on both designated and de facto wilderness within the refuge (Kaye 2000).

Wilderness

The term "wilderness" carries many connotations, depending in part on the cultural and historical perspectives of the beholder. The definition provided by the Wilderness Act of 1964 is viewed with profound skepticism and resentment by many Alaska Natives, who have lived for generations in "wilderness" areas on Alaska's North Slope:

> None of this country is wilderness, nor has it ever been. It has been continuously used and occupied by us and by our ancestors for millennia. Since wilderness is defined as a place without people, we are deeply insulted by those who proclaim any of this country wilderness, as if we were not considered to be real people (From *In This Place* [Anonymous, unpublished, 2001]).

Although reconciling the various views is a task well beyond the committee's charge, some commonalities are worth noting. Some ideas embodied in the legislative vision of wilderness are also seen by Alaska Natives of the North Slope as essential elements of their history and culture:

[2] Due to transfers of some of this land to the state and native corporations, this number is now less than 750,000. BLM does not have an accurate accounting of the current area managed as WSA in this area.

We told these [visitors] we liked the mountains and we liked the sea. We liked to spend as much time in these places as we could, the frozen sea, the snowy mountains, the summer sea, this gorgeous, ever changing, breath-taking country which is our homeland. Nowhere else is all of this possible, a sea full of great whales and seals and fish and polar bear and foxes and birds of every kind, from nearly every land, with mountains just nearby full of white sheep and wolves and wolverine and with great plains in between the mountains and the sea with muskoxen and caribou and river and lake fish and many more birds and a thousand other things, all intermingled with the spirits and memories and stories and legends and graves and old houses of our people. This is the perfect place, the perfect place for us, which is why God probably put us here, these few of us, and made us tough enough to stay (From *In This Place* [Anonymous, unpublished, 2001]).

The nature and intensity of human use, along with the persistence of evidence of such use, determine the extent to which an area retains its wild, "untrammeled" character. Land use by indigenous peoples on the North Slope has been for the most part nonintensive, leaving few traces on the landscape outside of established villages. In contrast, oil development has altered the landscape in ways that will persist long after oil and gas extraction ceases. Testimony provided to the committee in various communities on the North Slope repeatedly cited "scars on the land" that result from industrial development and that have altered both the physical and the spiritual elements of the landscape, and thus the very basis of Alaska Native culture on the North Slope. Many Alaska Natives argued, however, that a wilderness designation can unfairly exclude them from their own ancestral land. However, the Gwich'in people support wilderness designation of the 1002 Area as the appropriate legal tool to protect their subsistence way of life.

Although acknowledging the existence of divergent views, the committee evaluated the effects of oil development on wilderness as the term is defined in the Wilderness Act. To avoid confusion, we use the word "wildlands" rather than wilderness except when discussing legally designated wilderness. A typology of wildland values is presented in Figure 9-1.

Effects of Development on Wildlands

Before oil development began in 1968, the area north of the Yukon River, including the North Slope, was considered the largest intact wildland area in the United States (DOI 1972, FWS 1987). Since that time, a large segment of this region has been transformed. The perimeter of the oil fields now extends over some 2,600 km^2 (1,000 mi^2) of the North Slope, an area roughly equivalent to the land area of Rhode Island. The oil fields constitute one of the world's largest industrial complexes, and they have substantially affected many of the wildland qualities of the region. The associated roads, pads, pipelines, seismic vehicle tracks, transmission lines, air, ground and vessel traffic, drilling activities, landfills, housing, processing facilities, and other industrial infrastructure have reduced opportunities for solitude; displaced animals; altered ecological processes; compromised scenic values; and resulted in noise and air emissions. Because the landscape is open, the changed nature of the landscape—the roads, pads, pipelines, other structures, alterations of the tundra from seismic activities—is visible at a distance, particularly from the air. Similarly, changes in noise and air quality are perceptible far beyond points of emission. All of these effects have resulted in the erosion of wildland values over an area that is far larger than the area of direct effects.

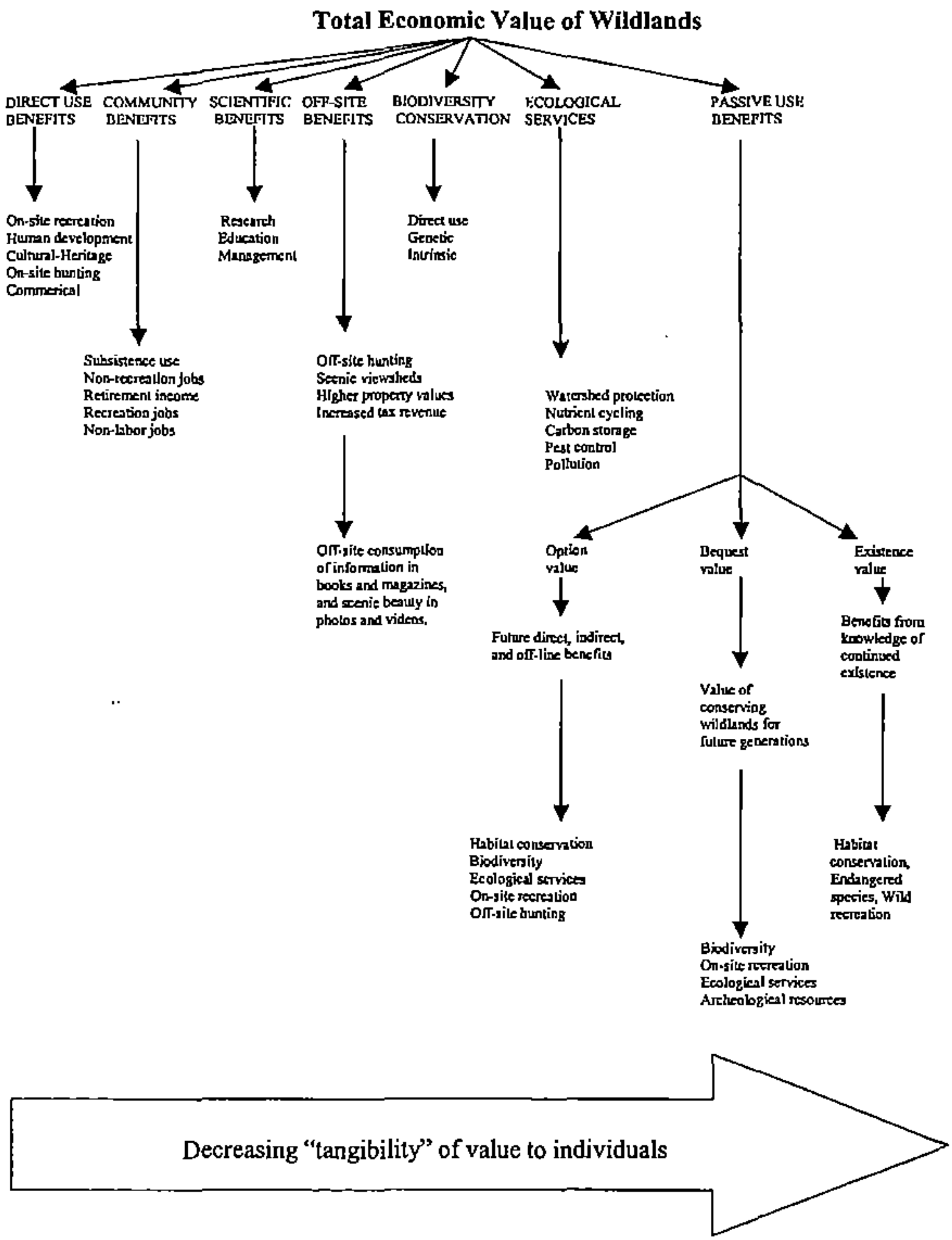

Figure 9-1. Total Economic Value of Wildlands. Source: Morton 1999.

Most analyses of effects on the wilderness and wildlands of the North Slope have been conducted in the context of environmental impact statements. And the analyses generally are cursory and often out of date. None has used new techniques for measuring wilderness values; none has attempted to coordinate wilderness planning or assessment among different jurisdictions.

The National Petroleum Reserve-Alaska Production Act of 1976, for example, required BLM to examine all resource values, including wilderness values, in the National Petroleum Reserve-Alaska. This analysis (known as the 105(c) study) was completed in 1978, almost a quarter of a century ago. It is the only comprehensive wilderness evaluation that has been done for the entire National Petroleum Reserve-Alaska. In connection with the 1996 decision to open up the northeast portion of the reserve to leasing, BLM prepared an integrated activity plan/environmental impact statement (IAP/EIS). At the time, BLM was barred from recommending wilderness designation (which would require an act of Congress) for any portion of the area under consideration under a directive issued in 1981 by then Interior Secretary James Watt. As a result, although the IAP/EIS for the northeast lease sale area contains scattered references to the wildland values of the area (principally focused on recreation), there is little meaningful analysis of the consequences of development for the range of wildland values.

Economic Benefits

The cash economy of the North Slope Borough largely would not exist without oil and gas production. To supplement their subsistence activities, some residents would have earned income from U.S. government transfers such as social security, medical and veterans' payments, or Bureau of Indian Affairs payments. Sport hunting, fishing and other recreational activities would have generated some income. And although the ASRC has generated some earnings recently, without North Slope oil that corporation would not exist.

Table 9-2 is a summary of total personal income data for residents in the NSB. After oil production began in the late 1970s there was a dramatic increase of total personal income. The NSB was established in 1972. Per capita income in 1999 was about $27,000. For comparison, per-capita income in Arctic Village, not part of the NSB, was $10,761 in 2000.

Table 9-2 Total Aggregate Personal Income for the Alaskan North Slope, 1970-1999

	Year	Total Personal Income (millions $)
Barrow-North Slope Division	1970	12.4
	1975	42.4
North Slope Borough	1980	82.1
	1985	133.6
	1990	145.6
	1995	200.6
	1999	205.8

Source: BEA 2002

Personal income is not necessarily the best measure of effects, especially over the long term. Another, longer-term accumulating effect is the progressive exhaustion of oil and gas resources, because current and past cash income has been purchased at the cost of denying income to others in the future.

An informative way to illuminate the accumulated beneficial aspect of oil and gas development is to measure net assets on the North Slope. Assets are a measure of the private and public wealth of an economy that, by their nature, represent the accumulation of value over time. In contrast, income represents value earned for a relatively brief period, such as a year.

Table 9-3 summarizes the private and public assets on the North Slope as of 2000. More than 90% of the private property value on the North Slope, including oil deposits, is directly attributable to the oil sector. Most private property is taxed, and that revenue supports public services in the borough. A region that has a substantial tax base, such as private petroleum assets, can collect corporate taxes to provide generous social services or to reduce its private citizens' tax liabilities.

Over time, the NSB has used its income to create net public assets that stood at $1.8 billion in 2000. The public and private net assets that year amounted to $13.4 billion—more than $1.77 million per capita. It is hard to compare such figures with those for counties or for other small towns, because public assets generally are not recorded. Instead, a comparison is made with private assets. A sample of a dozen small towns in Washington state (population 5,000-10,000) reveals a private per capita taxable asset value owned by individuals, corporations, and other taxable sources averaging about $74,000; on the North Slope it is about $1.53 million.

Table 9-3 Net Assets: North Slope Borough and Private Assets, 2000

	Assets/Liabilities ($ millions)	
Private Assets		11,607
Petroleum	10,528	
Other Private	334	
Exemptions	745[a]	
North Slope Borough Assets		2,937
Cash and investments	903	
Profits	713	
Physical improvement	372	
Other	949	
Borough liabilities[b]		1,152
Net Assets		13,392

[a]Tax exempt value for 2001

[b]Personal communication, Dennis Packer, Office of the Mayor, North Slope Borough, February 27, 2002.

Source: Comprehensive Annual financial Report of the North Slope Borough, Alaska, 2000. pp. 29, 31, 33, 104-105, 108.

North Slope Borough

The North Slope Borough is the dominant economic force in North Slope communities. Petroleum activities have been and continue to be the primary source of income on the North

Slope. In addition to property tax revenue from petroleum installations, income flows into NSB communities from royalties paid to the State of Alaska, which are returned to the NSB; through direct oil-field employment of NSB residents; and through the activities of the regional and village corporations.

The property taxes underpin the current NSB economy. In the 1999-2000 fiscal year, revenues for the NSB were $240,105,567, of which $201,223,579 (83.8%) came from property taxes. Of that amount, $192,524,702 (95.4%) was paid by five petroleum companies. Fifty-two percent of all jobs reported in the NSB 1998 survey are funded by the borough. Thus, petroleum activities have had massive developmental effects on the economy of the NSB and on the lives of its residents (Table 9-4).

Table 9-4 North Slope Borough Revenue, 1991-2000 ($ Thousands)

Fiscal Year	General Property	General Sales/ Economic Impact Assistance	Inter-government	Charge for Services	Miscellaneous	Total
1991	221,630	4,408	36,796	7,786	45,345	315,965
1993	235,928	5,009	30,209	8,663	51,337	331,146
1995	227,292	5,000	32,664	10,497	37,714	313,167
1997	223,923	4,900	32,240	11,643	43,018	315,724
1999	211,512	4,700	33,900	13,935	27,770	291,817
2000	201,224	4,600	37,088	9,493	30,213	282,618

Arctic Slope Regional Corporation

The Arctic Slope Regional Corporation currently receives annual revenues of approximately $1 billion. Throughout its existence, it has distributed approximately $123 million in dividends to its shareholders, and it currently employs more than 500 of those shareholders (ASRC 2001). In 2000, the ASRC distributed $8,841,000 through shareholder dividends, through distributions from its permanent fund, and through its Elders' Settlement Trust investment fund program. The ASRC subsidiaries were heavily involved in the construction and drilling of the Alpine field, which recently came on line, and the ASRC owns, with the state, the subsurface mineral rights to the Alpine field. The ASRC and the village corporations have been and continue to be dominant economic forces on the North Slope. ASRC subsidiaries employ the overwhelming majority of North Slope residents who work in the oil and gas sector on the North Slope (Alaska Petroleum Contractors Inc. and Houston Contracting Co-Ak Lt. employed 50 of the 64 employees noted by Alaska Department of Labor and Workforce Development in 2001). The ASRC owns the mineral rights to approximately 2 million ha (5 million acres) of land on the North Slope, much of which has proven reserves of, or holds promise for, oil, gas, coal, and base metal sulfides. The ASRC and its subsidiaries constituted the largest local property tax payers on the North Slope in fiscal year 1999-2000 (NSB 2000).

State Royalties Returned

Another useful economic measure of the accumulation of effects is the Alaska Permanent Fund. Royalties from oil sales, which have accumulated in this fund, amounted to more than $28 billion in 2000. Its size ranks in the top 100 funds in the world (Everest Consulting Association 2001). Annual payments to every resident of Alaska, including children, have grown steadily from a few hundred dollars per year in the early 1980s to about $1,900 in 2000 and 2001 (Table 9-5). North Slope oil is not the only source of fund revenue, but it constituted more than 95% of Alaska's oil production in 1999 and has been a major source of the fund's revenue since inception. Thus, assuming the population of the North Slope is 7,500 this year, the Permanent Fund Dividend program will produce approximately $13.5 million for the North Slope economy, much of that initially generated by past oil royalties.

Table 9-5 Permanent Fund Dividends, 1982-2001

Year	Amount
2001	$1,850.28
2000	$1,963.86
1998	$1,540.88
1996	$1,130.68
1994	$983.90
1992	$915.84
1990	$952.63
1988	$826.93
1986	$556.26
1984	$331.29
1983	$386.15
1982	$1,000.00

Source: Alaska Permanent Fund 2001

Economic Costs

There have been no economic valuation studies of effects on the physical, biotic, or human environment on the North Slope. That is, no research has translated positive and negative effects measured in physical units into how people value them in monetary terms. From the rich array of potential economic effects of oil and gas activities a few can be used to illustrate methods and types of data needed for economic evaluations: air pollution; altered spatial distributions of caribou and bowhead whales; and effects of long-lasting structures, roads, and trails on landscapes.

Air Pollution

A sample of time series emission data coupled with a diffusion model would help to establish where and how much air pollution North Slope residents are exposed to. These data can then be related to observed rates of morbidity and mortality. The economic value of lost days of work and medical expenses can then be tied to the rates of morbidity specific to the identified pollution loads. Estimated rates of mortality can be combined with estimated value(s) of a life (Freeman 1993, Viscusi 1992, EPA 1997). This cannot be done for the North Slope because records of emission are incomplete.

Subsistence Hunting

Oil exploration and development can alter the spatial distribution of caribou and the migration paths of bowhead whales. No studies, to our knowledge, demonstrate quantitatively whether spatial redistributions alter the sustainable equilibrium harvest or change the time it takes to harvest caribou or bowhead whales. The lack of data precludes estimating the dollar value of increased harvest time or of changed size of sustainable harvest. Other possible losses, such as the lowered quality of whale meat, are even more difficult to measure because of the lack of market prices. Finally, this method does not capture the economic cost of the reported greater risk involved in hunting when bowhead whales move farther from shore in response to seismic activity.

Passive Use Values

Some values cannot readily be directly or indirectly tied to market prices. For example, the benefits of wildlands include (Morton 2000) the scientific (protection of structure, composition and functioning of natural communities and entire landscapes as well as archeological and paleontological resources), the recreational, and the scenic. They also include protection of reservoirs of biological diversity, provision of ecological services, and spiritual (connection with "something beyond our modern society and its creations, something more timeless and universal"[66 FR 3729]), psychological (solitude; respite from machines, steel and concrete, crowding) and cultural and historical benefits, and "passive use values," as enumerated here (see also Figure 9-1):

- **option value**, maintaining for oneself or one's children the option of visiting wildland,
- **existence value**, the value of knowing a place exists independent of ever going there,
- **bequest value,** the value associated with bequeathing wilderness to future generations ("the hope of an undiminished future [66 FR 3730].")

The value of those benefits tends to increase as large, relatively undisturbed landscapes become scarcer. In the absence of markets for the goods and services illustrated above, people are studied using carefully designed surveys with methods developed by cognitive psychologists and market research specialist to elicit monetary values for quantitative changes in the qualitative features of an ecosystem (Cummings et. al. 1986, Diamond and Hausman 1994, Hanemann 1994, Hausman 1993, Mitchell and Carson 1989, Portney 1994). Many elements and values of wildlands can be roughly quantified, allowing those areas to be mapped according to the quantitative values they retain.

Of these different types of costs, the direct measurable costs associated with environmental effects are the easiest to quantify and are the best understood. In contrast, the committee could find no evidence of attempts to quantify the long-term future costs, passive-use values, or indirect costs of environmental effects. The information essential to assessing such effects is not even being collected. As a result, the full cost of oil development on Alaska's North Slope has not been assessed, quantified, or incorporated into decisions that affect use of public land. The section below illustrates a method for valuing passive-use values indirectly.

Incorporating Economic Costs of Environmental Effects into Decision Making

Incorporation of indirect, long-term, and passive use costs into an overall economic assessment of development would alter projections of economically recoverable oil and gas on public land on the North Slope. For example, the U.S. Geological Survey (USGS) periodically estimates the amount of recoverable oil in various areas of federally owned land on the North Slope. In doing so, the USGS generally projects the amount of oil that is economically recoverable from these lands given a particular price of oil and given a set of costs associated with development and transportation. By not fully accounting for indirect, future, and passive-use costs in its projections, the USGS underestimates the cost of development, which in turn inflates the amount of oil considered economically recoverable at a given market price.

This problem is most acute in light of uncertain, but plausible, effects that are likely to be irreversible and the traditional economic prescription: "Invest when expected benefits exceed expected costs" does not hold. The following example illustrates this fact. For the necessary geographic specificity, and because data are available, the Arctic National Wildlife Refuge is used as an example. The analysis can be applied to any undeveloped area. Development can include the construction of roads, pads, and other long-lived changes to the landscape. Before that, exploration creates seismic trails, of which about 15% are visible from the air after 15 years. Figure 7-7a captures the footprint of seismic lines laid down in 1985, more than 15 years ago. Many would regard seismic trails as having a negative effect on landscapes that accumulates as more trails are created. Given that about 4,000 km (2,500 mi) of lines or trails were surveyed during 1984-1985 in the Arctic National Wildlife Refuge, the appropriate setting is the value of further visual effects on the 600,000 ha (1.5 million acre) Arctic Coastal Plain.

The USGS has estimated that Arctic National Wildlife Refuge oil development would not be feasible if the price of North Slope oil is $15 per barrel ($0.36 per gal) or lower (because costs could not be covered by revenues). But this estimated minimum does not include any environmental costs associated with development or decommissioning (K. Bird, USGS, personal communication, 2001). At one point during the time this report was being prepared, the price of North Slope oil was around $17.50 per barrel ($0.42 per gallon) (*Wall Street Journal*, Jan. 24, 2002), and prices have fluctuated considerably before and since. Figure J-2 (Appendix J) illustrates a time series of crude oil prices whose level and fluctuations approximate North Slope oil prices.

Suppose, however, the expected price warranted development now, but that, in the future, the actual or expected price does not warrant further development and would not have justified the up-front exploration and development costs in the first place. Nevertheless, the environmental damage effects of seismic trails associated with the original exploration, together with the effects of roads and pads, persist.

Appendix J works out empirically the (stochastic dynamic programming) method (Arrow and Fisher 1974) used to analyze investment options under uncertainty with irreversibility.

Oil development might not be warranted from a social perspective, even if privately profitable; that is, if the private net benefits of development are positive. From a social perspective, expected private net benefits from oil development must be reduced by the accumulated environmental effects, including the loss of nonmarket values described in the section on wildland values in this chapter. The expected private value of oil development in the Arctic National Wildlife Refuge for alternative futures is calculated in Appendix J. A particular "future" is the chance that the price of oil will be a specific price above the break-even private cost of oil development. For any given future, there is an expected private net value of oil development. The important public-policy issue is whether the private net value for any given scenario is greater or less than the expected accumulated environmental costs of exploration and development. Because environmental costs have not been estimated in money terms, the analysis is done in terms of hurdles or thresholds. How large must the accumulated environmental costs be to offset the positive expected net private benefits of oil development? Equivalently, from a national perspective, if oil development in the Arctic National Wildlife Refuge (or elsewhere) should go forward, what is the highest value of accumulated environmental opportunities forgone that would *not* thwart this decision economically?

Employment

A main effect of the expansion of services and the capital improvement program by the NSB was the creation of borough jobs—in the expanded educational system, in construction for the capital improvement program, and in businesses that emerged—of the growing economy.

Two patterns characterize employment in the NSB (Table 9-6). First, the NSB has a disproportionate concentration of employment in government and government-funded activities. The borough government, school district, and capital improvement projects; Ilisagvik College; and the city, state, and federal governments together employ 61% of the workforce. A second pattern is the disproportionately low number of Inupiaq people employed in the oil and gas industry (although that is partly attributable to the larger percentages of Inupiaq young people: approximately 50% of North Slope Inupiat are under 20).

Table 9-6 North Slope Borough Residents' Employment by Sector and Ethnicity,* 1998

Employer	Inupiat	White	Other Minority	Total
NSB Government	509	217	151	877
NSB School district	134	108	47	289
Village Corporation	225	33	17	275
ASRC or subsidiary	90	26	16	132
NSB capital improvement	82	23	7	112
Service	28	36	19	83
Ilisagvik College	21	36	12	69
Private construction	44	14	8	66
City government	43	8	6	57
Transportation	14	17	12	43
Federal government	17	11	11	39
State government	9	19	7	35
Trade	14	9	12	35
Oil industry	10	4	2	16
Communications		4	1	5
Finance and insurance		1		1
Other	171	68	45	284
Total	1,411	634	373	2,418

*Includes only the 74% of the borough who responded to a survey (NSB 1999).

That few who live in the North Slope Borough are directly employed by the oil and gas industry has been noted for almost two decades (Kruse et al. 1983) and is supported by findings of both the NSB survey (NSB 1999) and the Alaska Department of Labor (Alaska Department of Labor and Workforce Development 2001). The NSB survey recorded only 16 local people of the 2,418 people surveyed who worked for petroleum companies. The Alaska Department of Labor reported that, for companies that collected and reported residency, of the 7,432 people who reported working on the North Slope in 1999 in the oil and gas sector, only 64 lived in the state's Northern Region—the Nome, North Slope, and Northwest Arctic boroughs (Alaska Department of Labor and Workforce Development 2001). Most of that group (50) were employed by two companies that are subsidiaries of the ASRC. Kruse et al. (1983) reported a variety of factors that affected both male Inupiaq willingness to work in the oil fields and the desire of companies in Prudhoe Bay to hire them.

An important factor is a desire to participate both in the cash economy and in the subsistence harvest. Borough jobs are preferable to oil industry jobs in part because they offer more flexibility, allowing time off for hunting. Those jobs also pay as well as the oil industry jobs do, and they are available locally instead of requiring extended periods of time away from home. In addition, Inupiat at Prudhoe Bay find they area small minority in a primarily white workforce that can sometimes express hostility toward Alaska Natives. The jobs available to the Inupiat often are seen by them as menial or as token jobs. And employment by the oil companies can threaten participation in the activity that provides the most status, hunting the bowhead whale. Another barrier is the lack of formal training and certification for skilled jobs.

Industry employees need specific skills from employees and often are unwilling to train workers unless there is some certainty that trainees are committed to remaining employed. Frequently, hiring takes place not on the North Slope at all, but in Fairbanks, Anchorage, or at company headquarters in the continental United States. Acknowledging that racism is difficult to document, Kruse et al. (1983, p. 138) recognized antagonism toward Inupiat among North Slope oil industry workers. Anecdotally, the committee heard from industry representatives that they hire Iñupiat only to have them not come to work reliably, and from Inupiat that they experienced discrimination in hiring and promotion. Whatever the causes, a main vehicles for funneling cash generated on the North Slope to residents of the NSB is functioning only marginally. Several programs have attempted to address this issue, but with limited success.

Because employment in the oil industry has been minimal, adaptation effects on North Slope residents are slight. However, if North Slope residents were to move increasingly into oil-field jobs there will be consequences (primarily on families) attributable to concentrated work scheduling (7 days on, 7 days off) (Forsyth and Gauthier 1991; Gramling 1989, 1996; Gramling and Forsyth 1987). Although the desire to participate in subsistence hunting is perceived as a barrier to employment on the North Slope, in the Gulf of Mexico the same work schedule allows employees extended periods to engage in traditional activities, such as fishing and shrimping (Gramling 1989).

ADAPTATION EFFECTS

Human systems are adaptable, even in extreme situations (Bettelheim 1943). The issue is not whether people will adapt—to externally generated perturbations or to internally negotiated threats and opportunities—but rather what consequences will accrue. As the various components of the human environment adapt to a development activity, new skills, knowledge, tools, and resources become available to support traditional activities. Two potentially problematic results also can occur.

First, the old patterns of behavior, economic activity, skills, and capital improvements, might be lost (sometimes quickly, sometimes across generations) because they are no longer relevant. The losses occur as Alaska Natives are entrained into a cash economy and increasingly need to use English as their primary language for communication about political, economic, and social changes. As they strive to become full partners in discussions about these changes, including those related to oil and gas development, it is difficult for them not to lose fluency in their traditional language, with its embedded knowledge of adaptation to the physical environment and of traditional relationships with the biota. Cable television, common in North Slope households, accelerates the cultural changes. Many North Slope residents reported to the committee their concerns about losing their traditional knowledge and practices and their way of life, despite their general reluctance to forgo the economic advantages they enjoyed.

Second, human and financial capital and nonrenewable resources can be, and usually are, actively committed to and consumed by the new development. If the new activity is not sustainable, when it declines or ceases communities or regions can be left less able to survive in their environment than they were before the new development came along. Freudenburg and Gramling (1992) call this *overadaptation.*

Oil and gas development has provided significant tax revenue to NSB residents. But the tax base is now declining, raising the question of whether the NSB can maintain its budget and its capital improvement program if oil and gas development diminish. Even in the short run—as newer, more efficient types of development are adapted and as older methods are phased out—the tax base for the NSB could decline more, leading to less support for the existing infrastructure and fewer borough jobs. Declines in borough revenue would require residents to pursue some mix of seeking oil industry jobs more aggressively, finding alternative sources of economic activity, relying more heavily on subsistence, migrating off the North Slope, or accepting a lower standard of living.

Another effect could precede actual declines in production. Increasingly, petroleum production on the North Slope is using new technologies, such as directional drilling, that occupy much smaller surface areas. This brings obvious environmental benefits, but also benefits the companies. Producing oil from a smaller space is cheaper because less gravel is mined and moved for pads and roads. Fewer shutdowns are needed to move the rigs and support equipment; there are fewer locations to deliver supplies to; fewer facilities to be built, heated, and maintained during production; and if rehabilitation is required, much smaller areas to be rehabilitated. Highly concentrated sites, however, can have lower assessed values, relative to the size of the subsurface structure they exploit, than huge surface complexes like Prudhoe Bay. So as big facilities are shut down and new, smaller facilities such as Alpine open, property tax revenues could decline significantly even as production increases.

The construction of a gas pipeline could forestall, at least for a time, the decline in tax revenue for the NSB. Commercial gas production would require the construction of new, taxable processing and transportation infrastructure, which presumably could remain operational in older fields even after they are no longer producing commercially feasible quantities of oil.

At some point, North Slope oil and gas will no longer be economically viable to recover. The potential for overadaptation by the communities now dependent on funds generated by this resource is a real one. The current standard of living—an economic benefit of oil and gas activity—could be impossible to maintain once petroleum activities cease.

The same trend toward smaller facilities and more environmentally friendly petroleum development is also likely to affect the ASRC, which is heavily invested in the oil-field-service industry. Smaller facilities will require less support during drilling and production, reducing the need for equipment and services. As with the NSB, there also is the potential for building infrastructure—private as opposed to publicly funded—that will be difficult to maintain once petroleum activity ceases in the region. The ASRC's primary assets appear to be its heavy investments in the energy services sector and its potentially mineral rich lands. Natchiq is a family of more than 20 diverse and strategically aligned companies and subsistence that operates in Alaska, Canada, the U.S. Gulf Coast and the rest of the continental states, and Russia to support the oil and gas industry. It offers exploration to development, construction to production, and maintenance services, and the Natchiq companies employ nearly 4,000 people (ASRC 2001, p. 14). As Freudenburg and Gramling (1998) have noted, however, in examining the petroleum support sector in the Gulf of Mexico, a support sector that has fiscal linkages primarily to one sector (petroleum extraction and production) is likely to mirror the performance of that sector, both as it rises and as it falls.

FINDINGS

- Without the North Slope petroleum discoveries and development, the North Slope Borough, the Alaska Native Claims Settlement Act, and the Arctic Slope Regional Corporation would not exist. The emergence of those structures has caused major, significant, and probably unalterable changes to the way of life in North Slope communities. The primary vehicle of change is revenue that has flowed into communities from NSB property taxes on petroleum infrastructure. Oil development has resulted in assets for North Slope residents that exceed $1 million per capita. Asset value per capita, excluding petroleum structures, exceeds $100,000. Many North Slope residents view the changes positively. However, social and cultural changes of this magnitude are not without costs in terms of social and individual pathology.
- Offshore exploration and development and the announcement of offshore sales have resulted in perceived risks to Inupiaq culture that are widespread, intense, and themselves are accumulating effects. The people of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale, and most view offshore industrial activity as a threat to bowheads and thereby to their cultural survival. They have generally supported onshore development, however, subject to adequate environmental controls.
- Proposals to explore and develop oil resources in the Arctic National Wildlife Refuge have resulted in perceived risks to Gwich'in culture in Alaska and the Yukon Territory that are widespread, intense, and themselves are accumulating effects. The Gwich'in have a centuries-old nutritional and cultural relationship with the Porcupine Caribou herd and oppose new onshore petroleum development that they believe threatens the caribou.
- The current standard of living for North Slope residents will be impossible to maintain unless significant external sources of local revenue are found.
- There has been little direct employment of North Slope residents by the petroleum industry. Several programs have addressed this issue, but their success has been limited.
- Many activities associated with petroleum have changed the landscape in ways that have had aesthetic, cultural, and spiritual consequences and those consequences will increase as the use of these facilities and infrastructure declines.

- Wildland values over more than 2,600 km^2 (1,000 mi^2) of the North Slope have been compromised by oil development. The potential for further loss is at least as great as what has already occurred as development expands over the next 20-50 years, although the nature and degree will vary. Some effects will dissipate when oil activities end, but many structures now on the North Slope are likely to remain long after industrial activities cease, rendering their effects on wildlands essentially permanent.
- There is no integrated, North Slope-wide framework for wildland evaluation, mapping, ranking, planning, and analysis of effects. There has been a steady erosion of wildland values over a vast area through a series of individual, project-by-project decisions by different state and federal government agencies.
- Environmental impact statements do not in general evaluate the individual or the accumulation of effects of development proposals on wildland values in a meaningful way.
- The common practice of describing the effects of particular projects in terms of the area directly disturbed by roads, pads, pipelines, and other facilities ignores the spreading character of oil development on the North Slope and the consequences of this to wildland values. All of these effects result in the erosion of wildland values over an area far exceeding the area directly affected. The loss of wildland values has not been assessed in terms of the total area affected.
- Although there are rigorous means of evaluating wilderness values, academic and agency researchers have paid insufficient attention to developing meaningful, qualitative, and quantitative metrics for evaluating wildlands and incorporating findings into the decision-making process. There is inadequate knowledge of the economic value of North Slope wildlands.
- Oil prices will depend primarily on circumstances far from the North Slope. The social cost of alterations to the landscape caused by oil and gas development that are long-lived or irreversible, such as seismic trails and gravel roads and pads, will continue long after the private returns from oil and gas extraction on the North Slope cease. Therefore, the social costs of development in new areas of public land should play a central role in determining whether exploration and extraction in previously undeveloped public lands are economically warranted.
- The full economic costs associated with environmental effects of oil development on Alaska's North Slope have not been quantified.
- Human-health effects, including physical, psychological, cultural, spiritual, and social, have not been adequately addressed or studied.
- A slope-wide, jurisdictionally coordinated framework for wildland evaluation, mapping, ranking, impact analysis, and planning would help decision-makers identify conflicts, set priorities, and make better-informed decisions.

RECOMMENDATIONS

- Research should identify the specific benefits and threats that North Slope residents believe are posed to their ways of life by oil and gas development. This research should target how much oil and gas activities, as distinguished from other factors, are associated with rising levels of sociocultural change. Research on the North Slope, regardless of its subject matter, needs to occur as a cooperative endeavor with local communities. Traditional and local knowledge and language involves rich, detailed information about the physical environment, the biota, and the human communities of the North Slope. That information should be incorporated into research—from identification of topics and study design through interpretation and presentation of results.

- The research community should focus on developing ways to translate theoretical wildland concepts and values into concrete terms that can be used in environmental assessments and other contexts.
- Research should identify the specific human-health effects (physical, psychological, cultural, spiritual, social) that North Slope residents believe they experience as a result of oil and gas development.