ARCTIC ALASKAN VEGETATION DISTURBANCE AND RECOVERY

A Hierarchic Approach to the Issue of Cumulative Impacts

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1. Introduction

This paper briefly summarises the vegetation disturbance and recovery research in northern Alaska. It uses an hierarchic approach to organise the discussion according to the scales of disturbance and emphasizes that the scales have changed dramatically in recent years. It emphasizes a need for more attention to the issues of cumulative impacts and sound long-term ecosystem management plans based on a hierarchic series of geo-referenced databases for Alaska and the Arctic as a whole.

2. A BRIEF HISTORY OF DISTURBANCE AND RECOVERY RESEARCH IN NORTHERN ALASKA

During 1943-53, the US Navy explored the Naval Petroleum Reserve Number 4 in Northwest Alaska (Pet-4, later named the National Petroleum Reserve in Alaska, NPRA) [66]. Little attention was paid to environmental concerns during this period, but in 1974-1982 additional exploration by the US Navy and Geological Survey in NPRA was accompanied by a major clean-up and re-vegetation campaign [35] and sponsorship of numerous environmental studies at old drill sites [26,49,50,26]. Interest in disturbance and recovery of Alaskan arctic ecosystems began in 1958, when the US Atomic Energy Commission proposed construction of a deep-water harbour using nuclear explosives at Cape Thompson [55] , and a detailed bio-environmental assessment was conducted during 1959-1963 [97]. In 1980, Cape Thompson was revisited 18 years after abandonment to assess the long-term recovery [31]. Other studies of vegetation impacts associated with oil-field development followed the discovery of oil at Prudhoe Bay in 1968 and were part of the International Biological Programme (IBP) Tundra Biome studies at Point Barrow and Prudhoe Bay [13,53,78,84,86,93,86,,84,53] and in similar studies in Canada [10,11]. During the late

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1970's and early 1980's, studies focused on the effects of the Dalton Highway and trans-Alaska pipeline [15,39,61,83], and seismic operations in NPRA and the Arctic National Wildlife Refuge (ANWR) [28,32,]. More recently, scientific interest turned to the broader-scale issues related to basic ecosystem processes involved in disturbance and recovery [17,18,20,21,56,67] cumulative impacts of large oil-field developments [86], restoration and rehabilitation of impacted areas [43,98], effects of the atmospheric contamination of the Arctic from sources at lower latitudes [48], and issues related to climate change [22,37,94]. A recent review of the Alaskan disturbance and recovery literature is in Walker [82].

3. Scales of Disturbances

Anthropogenic disturbances to arctic tundra span a wide range of spatial scales from bits of trash (10^{-1} m^2) to landscapes affected by oil fields (10^8 m^2) to large regions that could be affected by climate change (10^{11} m^2). A multi-scale framework based on the spatial hierarchy of Delcourt and Delcourt [24] is useful to conceptually deal with disturbances at widely divergent scales (Walker and Walker, 1991; Table 1, Figure 1). The hierarchy contains four domains and eight sub-levels. Natural disturbances span a full range of spatial and temporal scales from the micro-site disturbances of needle-ice formation (10^{-2}-10^{-1} yr. and 10^{1}-10^{-4} m^2) to macro-scale glaciations (10^4-10^6 yr. and 10^4-10^{11} m^2) (Figure 1a). On the other hand, most anthropogenic disturbances prior to modern oil field developments fall within a comparatively narrow range of spatial scales in the micro-scale portion of the Delcourt hierarchy (10^{-1}-10^5 m^2). More recent large-scale disturbances, modern oil fields, long transportation corridors, and climate change affect very large landscapes and regions, corresponding to the meso- and macro-scale portions of the Delcourt hierarchy (10^4-10^{11} m^2).

4. Summary of Anthropogenic Disturbance to Tundra Vegetation

4.1. MICRO-SCALE DISTURBANCES (10^{-1}-10^6 m^2)

Most of the disturbances associated with the early period of oil exploration were micro-scale disturbances affecting areas less than a few thousand square meters (Figure 2). Exceptions were the long seismic trails and roads that were bulldozed into the tundra. Exploratory drilling sites in NPRA and elsewhere on the North Slope were locations of a wide variety of disturbances [27,49,50,27]. The most long-lasting effects of this early exploration were subsidence due to thermokarst, and debris such as construction materials, oil drums, and small hydrocarbon spills. Successional processes involved with recovery of bulldozed trails and thermokarst caused by oil development were studied at Fish Creek and Oumalik [26,38,46,49,50]. More recently, regulations regarding summer and winter activities on the tundra have limited the impacts of off-road vehicle travel and the bulldozing of tundra. Contaminants are still occasionally spilled during exploration and development [12,43,39,63,76] . The oil industry has developed effective methods of spill prevention, containment, and clean-up [43] Table

2). Of greatest concern are large oil spills that saturate the tundra and are difficult to re-vegetate. Recovery on diesel-fuel spills is extremely slow [30]. Other common contaminants include reserve-pit fluids [3,34,42] and salt water used in water flooding operations [42,72].

The past 25 years of geobotanical research in northern Alaska have revealed the Alaskan arctic vegetation to be far more diverse than previously thought. This knowledge should be utilised for re-vegetation and rehabilitation efforts. Just as the High Arctic has been shown to have very different re-vegetation potential than the Low Arctic [9], climate and soil variations within the Low Arctic create a continuum of conditions for re-vegetation efforts. The suite of rehabilitation methods developed in the Prudhoe Bay region now needs to be expanded to consider a full range of soil and climate conditions within the circumpolar arctic.

4.2. MESO-SCALE DISTURBANCES (10^6-10^{10} m^2) AND THE ISSUE OF CUMULATIVE IMPACTS

During the early phase of oil exploration in Alaska, meso-scale disturbances were associated with long bulldozed trails, such as the Oumalik trail from Barrow to Umiat and the Hickel Highway from the Yukon River to the North Slope [66]. With the development of the Prudhoe Bay oil field, more extensive regional-scale impacts occurred in association with networks of roads and pipelines within oil fields and long transportation corridors (Fig. 3; [86]).

Mesoscale disturbances occurred along seismic trails [28,32,65], long gravel roads [15,93], and in association with road dust [2,95,74,75,83], roadside impoundments [45,86]), and large gravel mines [25,40,41,43,44]. Extreme examples of cumulative impacts to tundra systems have been described from the oil and gas fields in the northern Tyumen Oblast near the Ob River embayment in North-western Siberia [81]. The oil industry is developing methods to re-vegetate and reclaim large gravel pads, roads, and gravel mines [43]. However, perhaps the greatest long-term effects of large developments are the incremental disturbance to vast areas of undisturbed tundra, the additional pressures placed on wildlife populations that require large areas to exist, and the tendency for development to focus in sites that also have high wildlife and vegetation diversity, such as river corridors and coastal areas.

The cumulative effects of large developments are difficult to assess because of their scale and the multiple and interacting types of impacts. Cumulative impacts are of concern to vegetation, aquatic, and wildlife ecologists [54,70,76,86,87]. Road and pipeline networks are of most concern [5,15,40,61] For example, the Prudhoe Bay Oil Field, Kuparuk Oil Field, and several nearby smaller oil fields affect approximately 1000 km^2, and contain the most extensive road network in the North American Arctic. An analysis of the cumulative impacts was conducted at two scales: 1:25,000 for the entire oil field and 1:6000 for three of the most heavily impacted areas [86,87]. As of 1993, approximately 5,675 ha. had been directly impacted by gravel filling or gravel mines [43]. In addition to these direct impacts, indirect impacts such as impoundments and flooding cover more than twice the area covered by fill within the most heavily developed portion of the field [86]. The physical disturbances related to roads include elimination of habitat beneath the roadbed, dust-fall, roadside trash, and deposition of gravel from snow-ploughed materials. The historical record of gravel placement and construction-related impoundments could provide a useful model for predicting the pace of development in new oil fields (Figure 4). However, the impacts vary considerably according to different landscape typesAlso new technology has changed the many of the construction methods in oil fields so that some impacts could be substantially reduced.

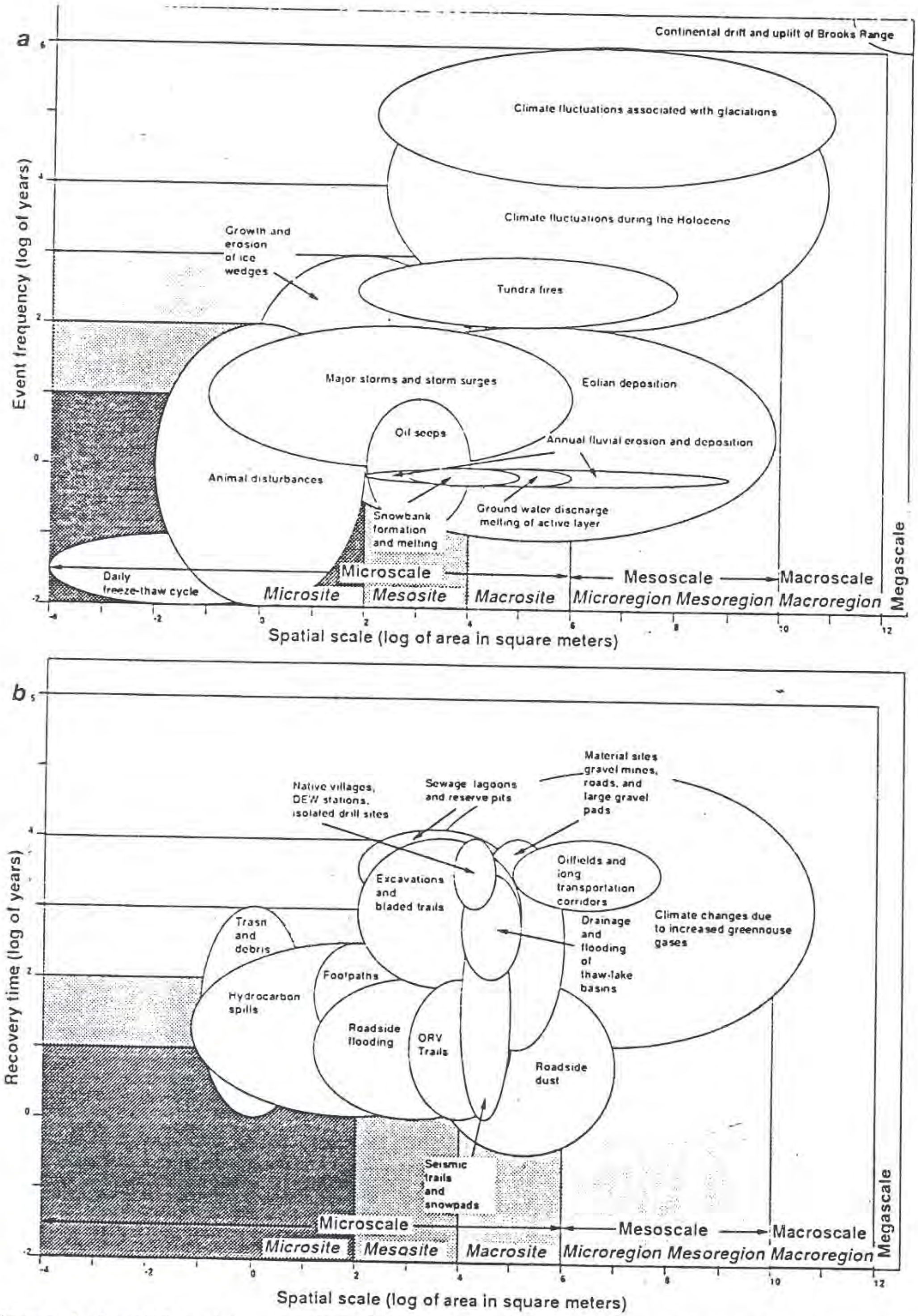

Figure 1. Spatial and temporal scales of natural (a) and anthropogenic (b) disturbances to Alaskan tundra vegetation. (Modified from Walker and Walker, [81])

Table 1. Spatial hierarchy of Delcourt and Delcourt [24]

Hierarchical domains	Sublevels	Area (m^2)	Map scale
		$1{\cdot}5 \times 10^{14}$	Smaller scale
	Global		
Megascale		10^{14}	1:20 000 000
	Continent		
		10^{12}	1:2 000 000
Macroscale	Macroregion		
		10^{10}	1:200 000
	Mesoregion		
Mesoscale		10^{8}	1:20 000
	Microregion		
		10^{6}	1:2000
	Macrosite		
		10^{4}	1:200
Microscale	Mesosite		
		10^{2}	1:20
	Microsite		
		10^{0}	1:2

An oil field is an accumulation of many smaller disturbances. Nearly all regulation is aimed at controlling these individual disturbance events rather than examining and managing the accumulated effects. Cumulative impacts differ from simple additive effects in five major ways: (1) time-crowded perturbations (disturbances are so close in time that the system cannot recover); (2) space-crowded perturbations (disturbances are so closely spaced that the effects are not fully dissipated between them); (3) synergistic effects (combinations of disturbances produce different effects than those of any single disturbance); (4) indirect effects (effects delayed in time or space from the original disturbance); and (5) nibbling (large regions affected by many seemingly insignificant perturbations) [4].

Cumulative impacts go beyond ecological issues because of socio-economic, legal, jurisdictional and policy issues which are affected by and which control ecosystem impacts [23,52,77]. Landscape and regional perspectives are needed to expand the area of concern beyond the immediate site of impact [64,98]. To date, cumulative-impact research has focused on enumerating and mapping the history of development in the region [86,87], effects on shorebirds [54], caribou 70] and discharge of reserve pit fluids into tundra wetlands [96]. There has not, however, been a synthesis of the total cumulative impact (including water quality, air quality, physical impacts, and effects on wildlife and native populations) of the Prudhoe Bay and neighbouring oil fields that spans the entire exploration, development, and operations phases of the oil fields. Such an analysis should be possible considering the relatively recent history of the field and good documentation of events contained on aerial photographs, and historical records.

TABLE 2. Six strategies for rehabilitating lands disturbed by oil development in arctic Alaska [43].

Disturbance	Strategy	Examples of Techniques	Key Taxa (scientific names cited in text)
Mine Pits	Flood to create fish habitat	Creation of connecting channels to streams Excavation of littoral zone Transplanting fish	**Fish**: arctic cisco, broad whitefish, round whitefish, least cisco, burbot, ninespine stickleback, Dolly Varden char, arctic grayling, slimy sculpin, and fourhorn sculpin
Overburden stockpile	Create wetlands in perched ponds	Creation of berms and basins Transplanting of aquatic graminoids Transplanting of aquatic invertebrates	**Plants:** pendent grass, tall cottongrass, water sedge, Dupontia **Aquatic invertebrates:** physid snails, aquatic worms, seed shrimp, non-biting midges, water fleas, copepods **Birds:** Canada goose, greater white-fronted goose, northern pintails, Pacific loon, semipalmated sandpiper, dunlin, and red-necked phalarope
	Same as for gravel	See techniques listed below for gravel	See taxa listed below for gravel
Gravel Roads and Pads	Revegetate to compensate for lost habitat	Creation of berms and basins Topsoil application Sludge application Fertilization Seeding of native grasses Seeding with native legumes and other forbs Transplanting willows	**Plants:** Tundra Bluegrass, Arctared Fescue, Alyeska Polargrass, Norcoast Hairgrass, arctic alkaligrass, arctic wormwood, alpine milkvetch, deflexed oxytrope, viscid oxytrope, northern sweet-vetch, feltleaf willow, roundleaf willow **Birds:** Canada goose, greater white-fronted goose, Lapland longspur, and snow bunting **Mammals:** Caribou
	Remove gravel to promote wetland restoration	Remove gravel Create basins Fertilization to promote natural colonization Seed with native grasses Transplant sod and sprigs Transplant willow cuttings	**Plants:** pendent grass, tall cottongrass, water sedge, Dupontia, Tundra Bluegrass, Arctared Fescue, Alyeska Polargrass, Norcoast Hairgrass, arctic willow **Aquatic invertebrates:** physid snails, aquatic worms, seed shrimp, non-biting midges, water fleas, copepods **Birds:** Canada goose, greater white-fronted goose, northern pintails, Pacific loon, pectoral sandpiper, semipalmated sandpiper, American golden-plover, dunlin, red-necked phalarope
Minor Disturbances	Promote natural recovery	Leave as is Reestablish natural drainage Fertilization	Reestablishment of original communities of plants, invertebrates, birds, and mammals
Contaminants	Remediate to acceptable contaminant levels	Excavation and thermal treatment Soil washing Passive bioremediation Landfarming Bioventing, Air sparging	not applicable

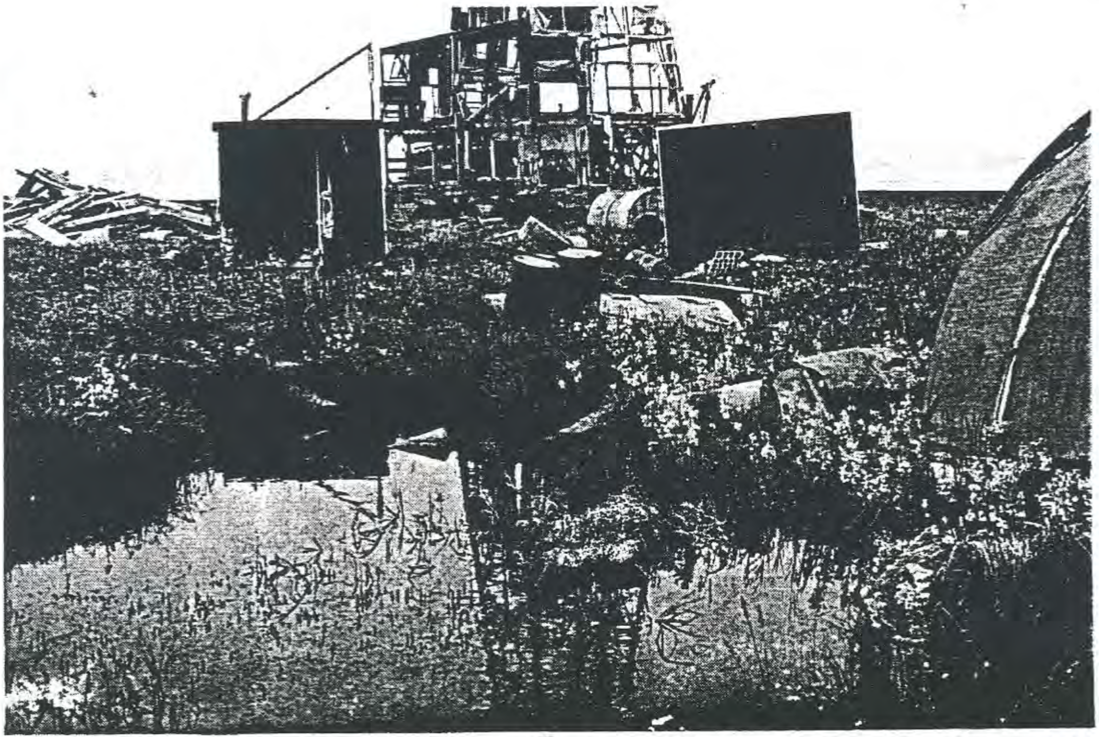

Figure 2. Debris from 1960s drilling operation about 60 km south of Prudhoe Bay near the Kuparuk River. Note the wooden derrick in the background, thermokarst, and lush vgetation caused by altered hydrology. Such microscale disturbances were typical of the early phase of oil development on the North Slope.

Figure 3. A portion of the Prudhoe Bay Oil Field including networks of pipelines, roads, and gravel pads. The large rectangular gravel pad on the left side is a drill site with 14 well heads and two reserve pits. Complex cumulative impacts are associated with such large developments.

The prospect of oil development in the Arctic National Wildlife Refuge (ANWR) has raised the issue of cumulative impacts in a pristine wilderness area, where much lower levels of impact are acceptable to the public. Aesthetics is a major consideration in highly protected areas such as national parks, refuges and wilderness areas. For example, the visible impacts caused by seismic operations in the ANWR were substantial. Despite efforts to minimize damage in the ANWR during the 1984-1985 seismic campaign, long-term damage to the tundra occurred and is likely to remain for many years [28] (Fig. 6). Over 2000 km of seismic trails were traversed within the refuge. In many areas, winter snow cover was not sufficient to protect the tundra. US Fish and Wildlife Service (USFWS) studies showed that 29 percent of the trails sustained medium to high levels of impact [65]. After eight years, damage persisted in many areas and thaw settlement had not stabilised [28]. The ANWR experience points to the need for more stringent sets of standards in the most highly protected areas and the necessity to look far into the future regarding the series of events that are likely to follow should oil be discovered.

4.3. MACRO-SCALE DISTURBANCES ($>10^{10}$ m^2)

Macro-scale impacts are only indirectly related to oil-field development. The global use of energy derived from arctic sources is contributing to the rise in atmospheric greenhouse gases. Alterations of arctic vegetation and soils caused by climate change could lead to major feedbacks to the global climate system [6,7,71,57].

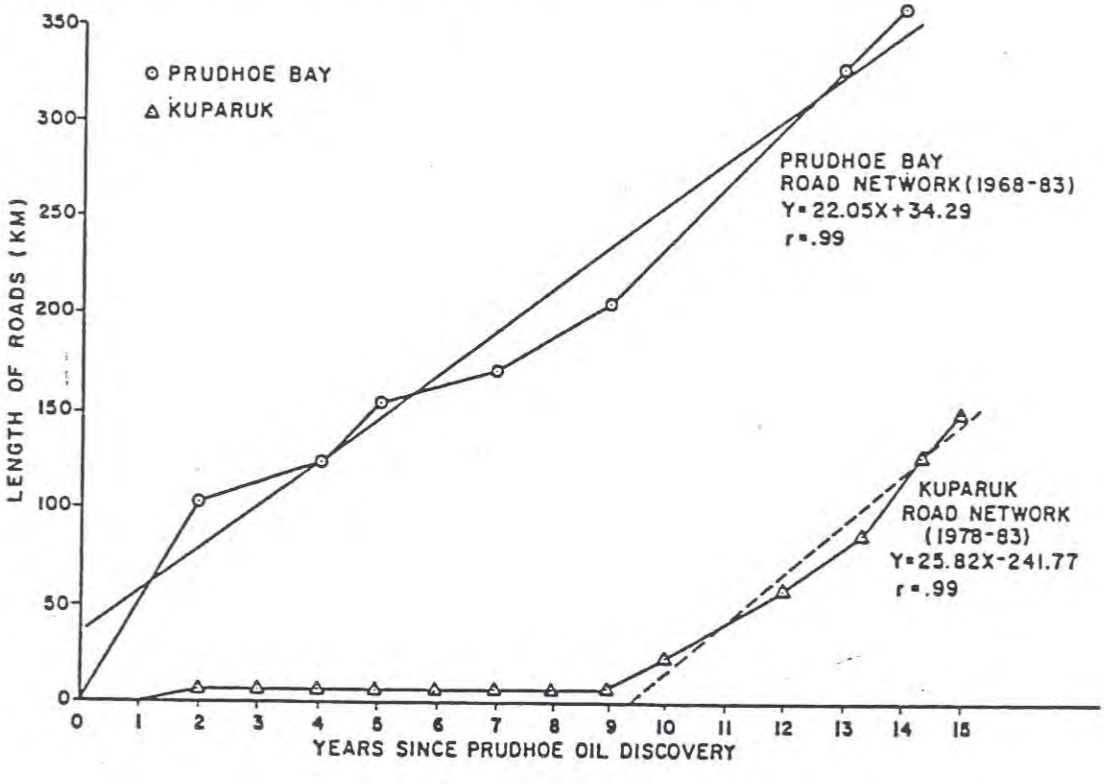

Figure 4. Comparison of growth of the Prudhoe Bay and Kuparuk oil-field road networks as of 1983. The Prudhoe Bay road network began expanding in 1968 with the discovery of oil. The Kuparuk field began to expand in 1978. The similar slope of the two lines suggests that the growth of road networks may occur at a predictable rate. (From Walker et al. 1986.)

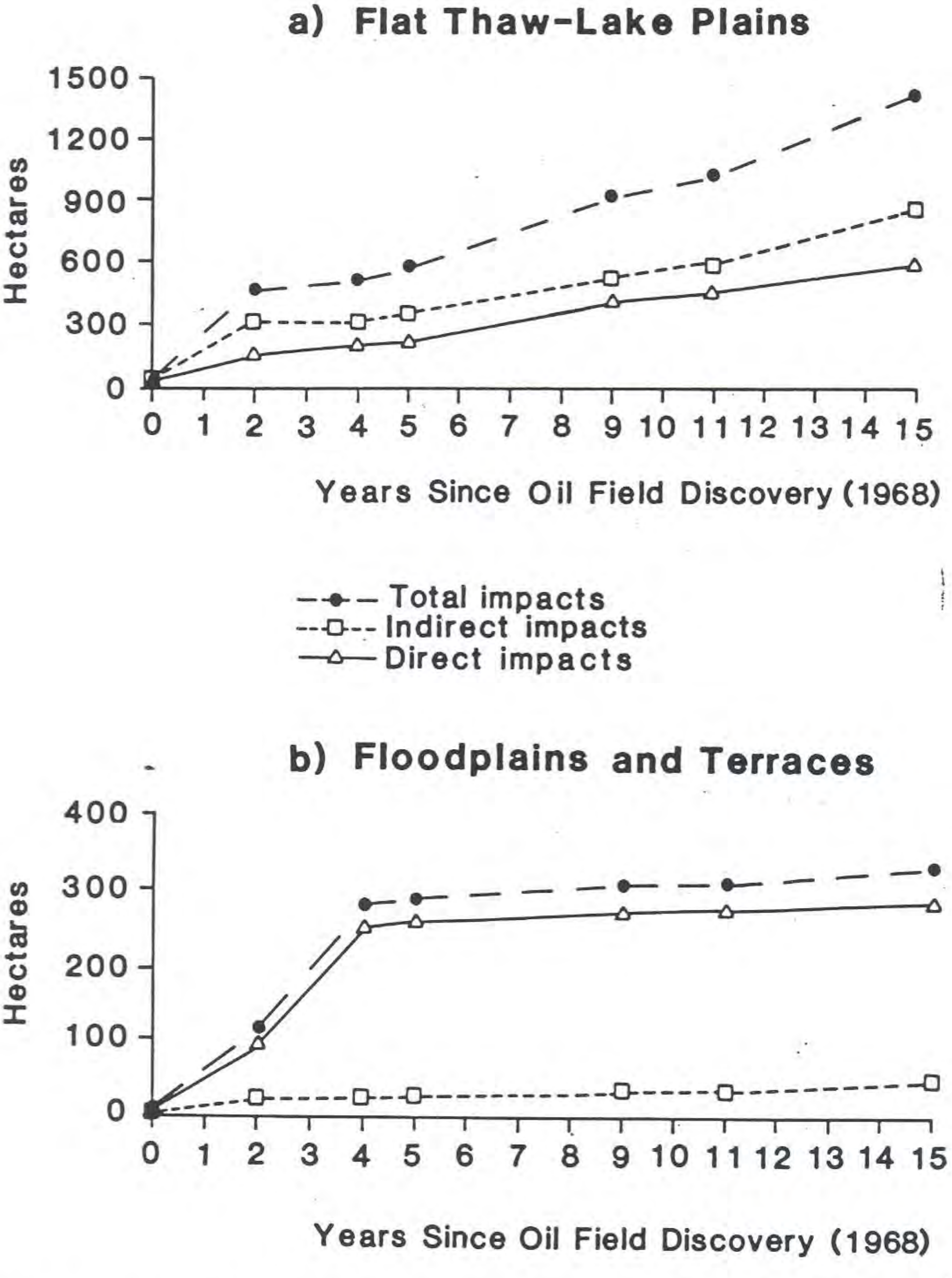

Figure 5. Progression of direct and indirect anthropogenic disturbances on the principal two landscape units in heavily developed areas of the Prudhoe Bay Oil Field: (a) flat thaw-lake plains, (b) floodplains and terraces. Direct impacts are roads, pads, and excavations; indirect impacts include flooding and thermokarst. Indirect impacts exceed direct impacts on flat thaw-lake plains, but the reverse is true on floodplains and terraces.

Predictive ecosystem models require a better understanding of the total amount and types of carbon stored in arctic soils as well as a better understanding of the aboveground biomass and patterns of plant communities as they relate to environmental gradients [94]. It is also unclear whether climate change will produce predictable responses of vegetation that correspond to today's vegetation distribution along climatic gradients [89,99], or responses related to ongoing millennia-long trends of vegetation succession associated with the glaciation and deglaciation of the arctic regions [16,89], or a combination of both. Scientists are also interested in how individual plant species will respond to changes in temperature and precipitation patterns and how the total biodiversity of these regions will respond to changes in plant community composition and structure [19,37]. Answers to these questions require fundamental understanding of the relationship of vegetation to modern environmental gradients that can be portrayed and experimentally manipulated using GIS in combination with climate-change scenarios.

Figure 6. Early impacts associated with the oil-field exploration in the Arctic National Wildlife Refuge. A winter seismic trail created in 1984 near the Hulahula River is part of 2000 km of trails arranged on a 5x10-km grid. Multiple tracks by many vehicles created trails over 10 m wide. The aesthetic impacts of the such trails are a major consideration for development in highly protected areas such as national parks, refuges, and monuments.

5. A Hierarchy of Geo-referenced Data to Help Manage Arctic Development and Detect Change

Controlling cumulative impacts is extraordinarily difficult. Although the desirability of not degrading the Earth's few remaining pristine habitats is hardly debatable, it is difficult to translate this to political decisions at the local level where other influences become more apparent, such as the need for jobs. One hope is to develop long-term ecosystem-management strategies that use the characteristics of the landscape to guide development. The future direction for controlling and detecting disturbance to arctic landscapes will depend heavily on digital geo-referenced information. In a recent symposium on ecosystem management at the Smithsonian Institution, it was noted that virtually all land management agencies are employing geographic information systems to assemble and manipulate data so that local ecosystem configurations and the consequences of development can be made visually explicit. The World-Wide Web is making it much easier to share digital geo-referenced information between all involved in land management decisions. Simulation models and data analysis linked to geo-referenced data bases offer the best, and perhaps the only, hope of forecasting the consequences of our decisions [62].

5.1. A MODEL FROM THE ARCSS FLUX STUDY

A key element in ecosystem management for the Arctic will be the development of a hierarchy of geo-referenced databases so that management decisions can be translated across scales and across political boundaries. A possible model for such a hierarchic database is being developed for the Arctic System Science (ARCSS) Land-Atmosphere-Ice Interactions (LAII) Flux Study [94]. A hierarchic geographic information system (HGIS) for the Kuparuk River basin is being used to translate the findings from the plot-level investigations to regional scales [88] (Figure 7). When completed, the GIS will allow comparative studies of the same piece of ground at six scales (1:10, 1:500, 1:5000, 1:25,000, 1:250,000, and 1:2,500,000). In 1995, the 1:25,000-scale database of an 850 km^2 area surrounding the upper Kuparuk River basin (Figure 8) and a 1:250,000 preliminary Landsat-derived vegetation classification of the entire 8,400 km^2 Kuparuk watershed (Figure 9) were completed. The 1:25,000-scale database includes integrated geobotanical maps of vegetation, surface geomorphology and geology, landforms, glacial geology, hydrology, satellite-derived multispectral data, anthropogenic features, and a digital terrain model. Nested within this area are geobotanical databases for the Department of Energy R_4D (Response, Resistance and Resilience to and Recovery from Disturbance in arctic ecosystems) study site at Imnavait Creek and the National Science Foundation Long-Term Ecological Research (LTER) study site at Toolik Lake (Figure 6). Research at the R_4D site showed that vegetation patterns accurately portray hydrologic, geochemical, and snow gradients [29,59,85]. This information can be extremely valuable for predicting landscape consequences of altered drainage patterns or the influence of pollutants such as road dust [47,51].

The next step will be a classification for the entire Alaskan North Slope derived from Advanced Very High Resolution Radiometer (AVHRR) data. The data bases are being designed using a ground-up approach for the micro- to meso-scale databases. Classical methods of vegetation classification and gradient analysis are the foundation of the multiple-scale research [90]. Detailed field descriptions of the vegetation composition, soils, and environmental site factors support the mapping and ecosystem studies.

5.2. TOWARD A NEW HIERARCHIC GIS FOR CIRCUMPOLAR ECOSYSTEM MANAGEMENT

A circumpolar hierarchic GIS could be developed along the same lines as the Kuparuk Basin database, but addressing different questions and utilising different scales. At the highest level in the hierarchy, a circumpolar GIS database is needed for a wide variety of important circumpolar issues. Models of arctic ecosystems and their interactions with the global climate system, international decisions regarding management of habitat of large animals such as caribou, and global education all require consistent nomenclature and boundary delineation for the entire tundra region. Efforts are currently under way with several international initiatives to bring together all the existing information to construct a circumpolar database. For example, the Global Resource Information Database (GRID) is a network of 10 co-operating environmental data centres under the United Nations Environment Programme (UNEP). The GRID-Arendal facility in Arendal, Norway has geographic responsibility for the polar areas, and is building a database consisting of a over 2000 digital maps covering over 100 subjects (Smith, in press).

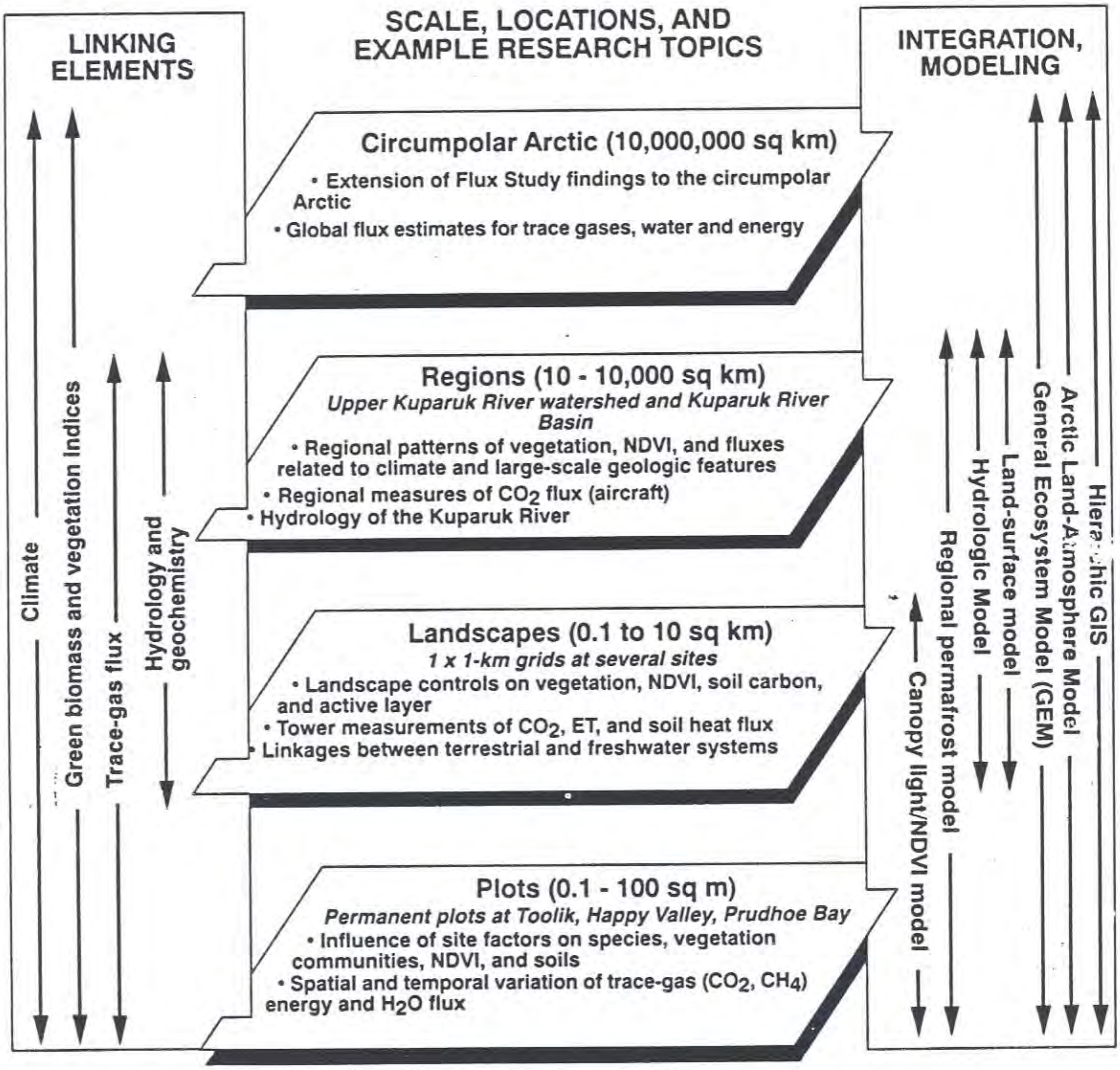

Figure 7. Conceptual diagram of the herarchic GIS for the ARCSS Flux Study in the upper Kuparuk River basin. The left-hand vertical bar of the diagram portrays physical variables that provide linkages between various levels of the hierarchy. The right-hand vertical bar displays some of the models being used in the ARCSS Flux Study and the levels at which they operate. The horizonatal tiers display the scales, locations, and example topics being addressed at different levels in the hierarchy.

A critical element will be a series of new circumpolar vegetation maps based on current knowledge of the arctic vegetation [89]. There is a need for two types of vegetation maps, one that displays the circumpolar distribution of biomass based on the Normalised Difference Vegetation Index (NDVI) [60] and a second depicting regions with characteristic sets of vegetation types based on plant physiognomy and floristic composition. The first is important for numerous studies related to global carbon budgets and climate change and can be derived rather quickly using remote-sensing technology. The second is needed for studies of issues such as biodiversity and regional habitat analyses and requires the synthesis of existing vegetation information contained in many existing maps plus mapping of previously un-mapped regions of the Arctic. Satellite-derived spatial databases and digital terrain models will form the base for both types of maps. One of the products of the project will be a false-colour mosaic of cloud-free false-colour images from the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA satellites (1.1-km pixel resolution). The image will be a polar projection of the terrain north of 50° latitude, and will be used as a base for the vegetation mapping. The first map products will utilise a Lambert azimuthal equal-area projection of the circumpolar region at a scale of 1:7,500,000. At this scale, the entire circumpolar Arctic north of treeline can be displayed on a single 100 x 100-cm map sheet. The projection is compatible with the Ecoregions mapping program [58} and the circumpolar permafrost mapping project [36].

Lower levels in the hierarchy could follow the basic approach being used in the Kuparuk Basin for the ARCSS Flux Study (Fig. 7). In areas of most intensive development a hierarchy consisting of five scales would be sufficient to address most development and conservation issues: (1) 1:500 scale for site-specific studies, such as planning around drill sites, habitat analysis on small landscape units (e.g., pingos, kames, smaller wetlands), and mapping fine-scale impacts such as vehicle trails, thermokarst, debris, etc.; (2) 1:5000 scale for studies of clusters of development, analysis of hydrological flow patterns, and habitat analysis for intermediate-size landscape units (e.g. small flood-plains, colluvial basins, intermediate-size wetlands); (3) 1:25,000 scale for cumulative impacts in large oil fields, habitat extent of larger animals and rare plants; (4) 1:250,000 scale for regional planning to identify and protect rarer habitats, planning for large oil fields and transportation corridors, and habitats of large migratory animals; and (5) 1:2,500,000 scale for circumpolar vegetation and geobotanical characterisation, course-scale framework for regional studies, international planning, and global ecosystem management.

6. Discussion and Conclusions

The Arctic is providing a large portion of the world's oil, and this portion is likely to increase in the future as other sources become depleted. Currently the USA obtains approximately 11% (1.53 million barrels per day) of its current oil supply from arctic sources [79]. This has declined from 1990 (1.77 mbpd), but substantial undeveloped oil reserves remain in arctic regions. Development of these resources is, however, expensive, technologically difficult, and fraught with ecological controversy. The arctic oil regions are among the most pristine regions remaining on the globe and hence also extremely valuable as wildlife habitat and wilderness. In the USA an ongoing controversy surrounds the question of whether or not to open the Arctic National Wildlife Refuge to oil exploration. Most of the pressure is based on projected short-term economic benefits. More difficult to assess are the long-term ecological costs of permanently altering one of the last remaining intact large ecosystems in the United States.

Sound ecosystem management methods could be developed to allow ecologically sound development of most of the Arctic's oil resources while simultaneously protecting the most valuable regions of wilderness and wildlife habitat. Some considerations for developing a new hierarchic approach for disturbance and recovery research include:

With respect to past disturbance and recovery research:

(1) The strong interconnections between the physical and biological components of arctic ecosystems influence the effects of disturbances at all scales. However, the linkages between arctic vegetation, permafrost, energy, and water budgets are poorly understood, and a GIS-based modelling approach that links these factors is essential for predicting the consequences of many forms of disturbance to permafrost-dominated terrain [60].

(2) The early impacts of oil exploration were primarily micro-scale phenomena, and most of the scientific issues relating to direct physical disruption of tundra ecosystems have been addressed during the past three decades [1,69]. The advent of environmental laws from 1960-1990s and environmental research programs of the oil industry has substantially changed the character of development on the North Slope and has reduced many of the types of impacts common in the early phase of oil exploration. However, the heightened environmental concern surrounding oil development has been accompanied by a many-fold increase in the size of areas affected.

(3) Re-vegetation of disturbed sites requires a fuller appreciation of varying rates and dynamics of succession on a variety of substrates and across the steep arctic temperature gradients. We need to re-evaluate the variation that exists within what was previously thought to be broad homogeneous regions of Arctic tundra.

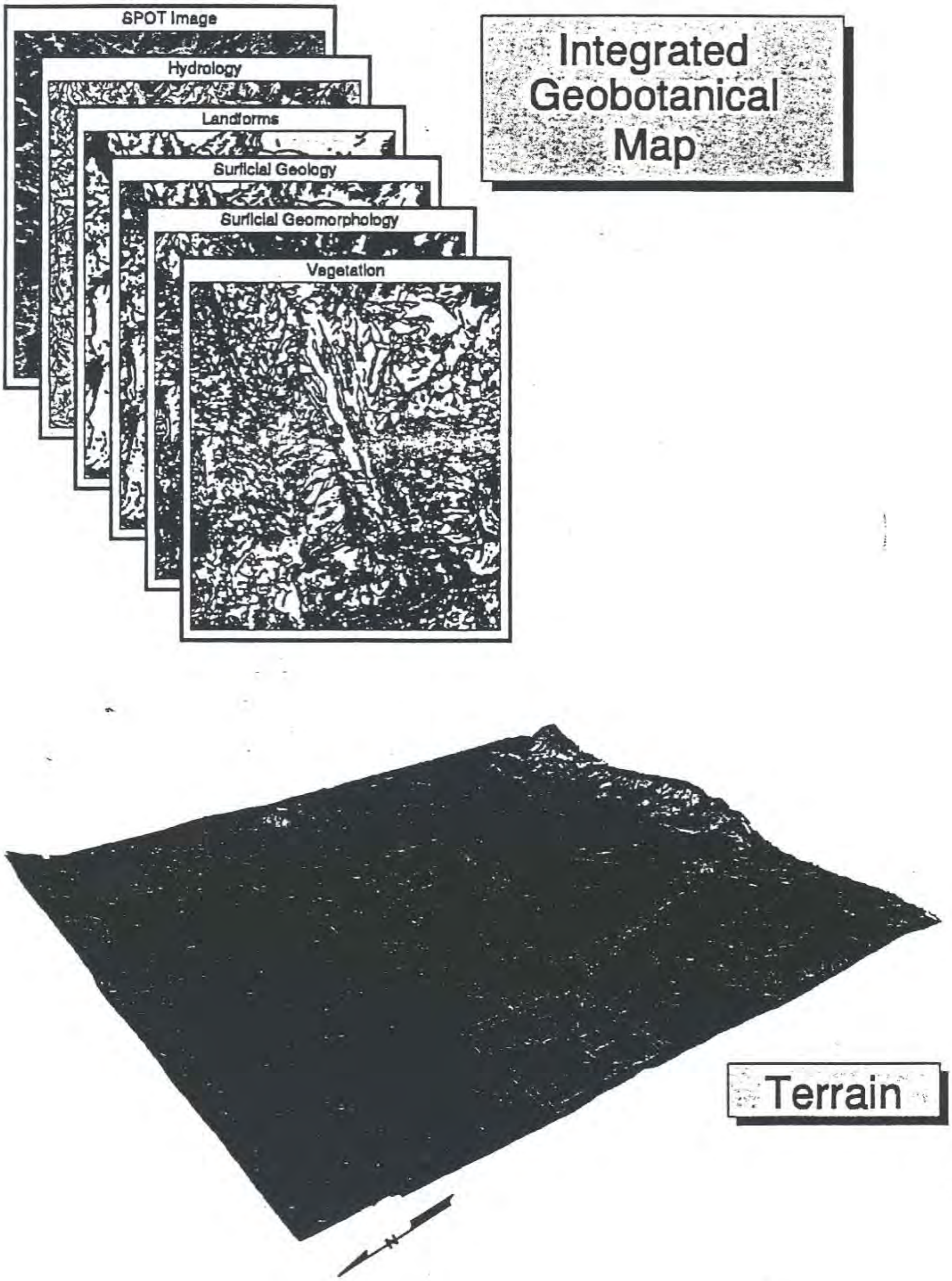

Figure 8. The 1:25,000-scale geobotanical database of the upper Kuparuk River basin. (b) The digital terrain model portrays the terrain of the region as viewed from the vicinity of Toolik Lake looking across the upper Kuparuk River watershed. Nested within the map area are the 1:500 and 1:5000-scale GIS databases at Imnavait Creek (white boxes, background) and Toolik Lake (foreground).

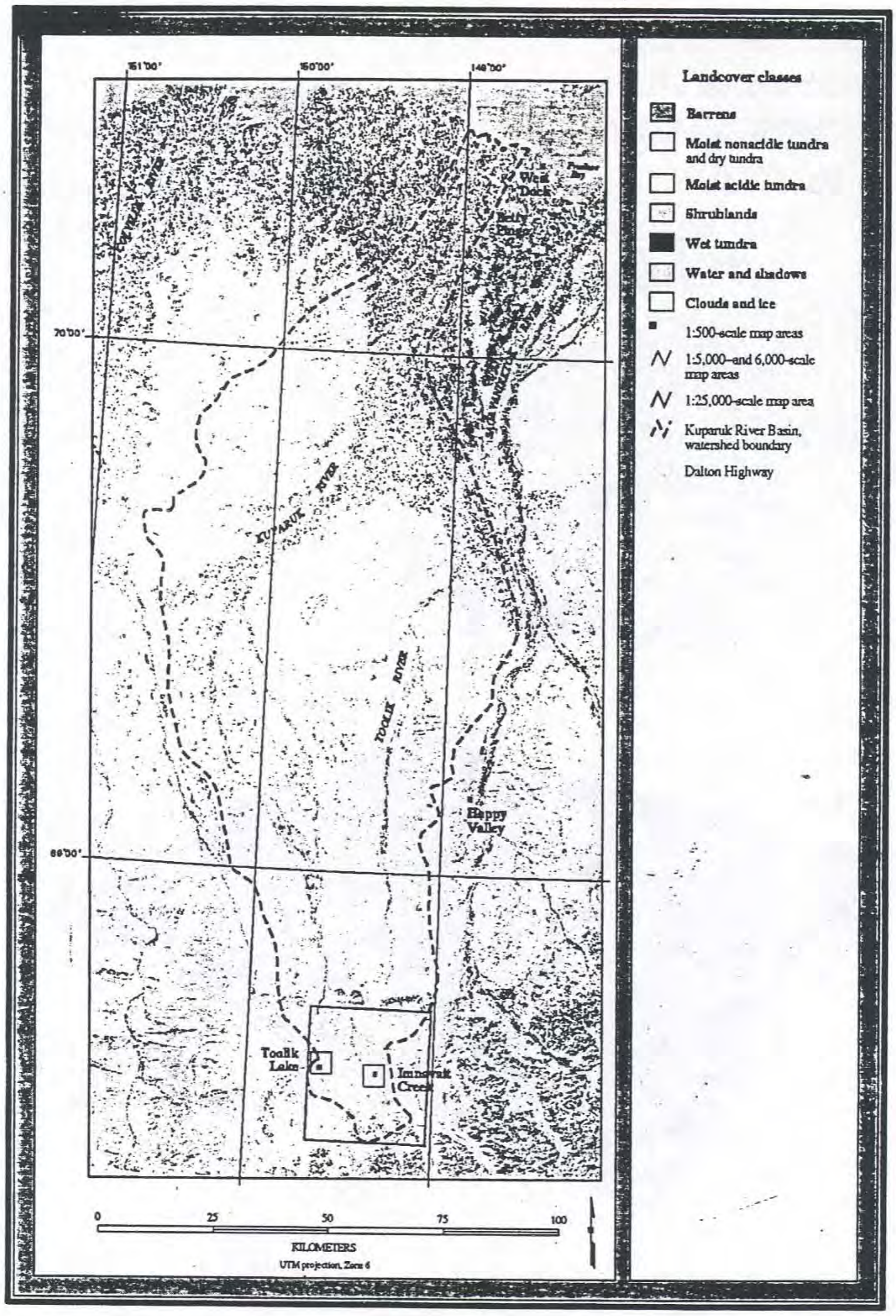

Figure 9 . Preliminary Landsat-derived vegetation map of the entire Kuparuk River Basin. Dashed line is the boundary of the 8400-km^2 basin. Nested within the area are the GIS databases in the upper Kuparuk River basin (Figure 8). The map includes seven broad units: (1) barrens, (2) moist nonacidic tundra and dry tundra, (3) moist acidic tundra, (4) shrublands, (5) wet tundra, (6) water and shadows, (7) ice.

6.1 NEW EMPHASES

(1) A broader perspective of tundra vegetation disturbance and recovery research requires expanding our current plot-level research to examine entire landscapes, regions, and the globe. A hierarchy of GIS databases with internally consistent terminology across spatial scales and focused in the regions of greatest resource-development potential, would permit sound ecosystem management at a variety of scales.

(2) A major new focus on issues related to cumulative impacts is needed. Although the concept of cumulative impacts is an intuitive one, there are currently no accepted scientific nor regulatory means to evaluate or predict cumulative impacts [98]. An analysis of the total cumulative impact of the Prudhoe Bay and neighbouring oil fields would be extremely informative and may help predict the outcome of future development scenarios.

(3) To be useful for ecosystem management, new GIS databases cannot simply digitise existing maps; they will have to develop and incorporate new maps at a range of spatial scales that reflect current knowledge of the variation in tundra ecosystems. This may require training a new generation of arctic ecologists broadly versed in classical methods of taxonomy, arctic ecosystem ecology, vegetation classification, and modern techniques of GIS and remote sensing.

(4) "The problems faced by ecosystem management derive from the complexities of both natural and social systems, particularly their intersection in policy decisions" [62]. Somehow, the planning of large developments has to become a more long-term interdisciplinary process that involves economists, social scientists, ecologists and politicians in a truly integrative fashion. One possible step toward this goal is examination of how past political and economic decisions influenced modern-day development patterns. For example, a comparison of the cumulative impacts of the North Slope oil fields with the those on the Yamal Peninsula in Russia, would provide insights regarding the consequences of development under different political, economic, social and environmental constraints.

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