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HISTORY AND PATTERN OF DISTURBANCE IN ALASKAN ARCTIC TERRESTRIAL ECOSYSTEMS: A HIERARCHICAL APPROACH TO ANALYSING LANDSCAPE CHANGE

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SUMMARY

(1) The history, types, and scales of disturbance in Arctic Alaska are reviewed and disturbances organized according to the spatial and temporal domains of Delcourt, Delcourt and Webb. This system is also used as a framework for a regional hierarchical geographic information system (GIS).

(2) Natural disturbances vary from frequent small disturbances, such as needle-ice formation, to infrequent large disturbances, such as major glaciations. Most natural disturbances are either directly or indirectly climatically driven and are affected by climate changes, particularly changes to hydrologic regimes. The latter could be influenced by changes in either summer or winter precipitation patterns; increased temperature, which would melt ground ice; or changes in vegetation, which would affect evapotranspiration and run-off.

(3) Most anthropogenic disturbances are microscale (10^{-1} to 10^{6} m^2) phenomena, but cumulative impacts associated with large developments, such as the Prudhoe Bay Oil Field, have affected mesoscale regions ($10^{6}-10^{10}$ m^2), and global warming could affect the tundra ecosystem at the macroscale level ($10^{10}-10^{12}$ m^2).

(4) In the Arctic, recovery of the vegetation following disturbance is particularly closely linked to recovery of the physical system because of the presence of ice-rich permafrost. Maps of terrain sensitivity to disturbance must consider the influence of ground ice and heat flux to the system following disturbance.

(5) A three-tiered GIS hierarchy with five sublevels is presented, with examples of typical scientific questions being addressed at each level, scales and types of databases, and linking elements between levels.

(6) At the regional (macroscale and mesoscale) levels, the primary data sources are satellite-derived digital data. At the site level, integrated geobotanical databases derived from field surveys and photointerpretation are used in combination with digital terrain models. At the most detailed (plot or microsite) level, point sampling is used to portray vegetation structure and species composition in 1-m^2 plots.

(7) Linking or 'scaling-up' elements that affect landscape patterns at all scales are hydrology, geochemistry, and primary production.

INTRODUCTION

Historically, most disturbance and recovery research in tundra regions has been at the plot level, but concerns about cumulative impacts of large oil fields and the possible effects of climate change have caused ecologists to search for tools to examine impact over large areas and to 'scale up' plot- and watershed-level investigations to broader regions. Recent developments in the fields of landscape ecology, geographic information systems (GISs), remote sensing, and hierarchy theory are beginning to provide the means to accomplish this task. There is a need for a common conceptual framework to compare scales of disturbances and to help organize our thinking regarding the great diversity of disturbances operating at widely ranging scales and to select appropriate spatial analytical tools.

In this paper, we use the Delcourt, Delcourt and Webb (DDW) (Delcourt, Delcourt & Webb 1983; Delcourt & Delcourt 1988) system of spatial and temporal domains to examine natural and anthropogenic disturbances on the Alaskan North Slope. We also use the system as a framework for a regional hierarchical GIS. We first present an overview of history, types, and scales of disturbance in northern Alaska and place natural and anthropogenic disturbances within the context of the DDW domains. Much of the tundra disturbance-and-recovery information is in so-called 'grey' literature generated by government agencies and private consulting firms. We therefore restrict this review to Alaska, and even here we selected only key references for some topics. We then present a hierarchical GIS for the North Slope with details regarding scales, topics of investigation, and examples of databases at each scale.

DISTURBANCE AND RECOVERY RESEARCH IN NORTHERN ALASKA

History of research

The discovery of oil at Prudhoe Bay in 1968 and the National Environmental Policy Act in 1970 marked the beginning of an era of unprecedented environmental research in the Arctic. This was a response to increased public awareness of the consequences of unbridled development, and a recognition by industry and government of the need for sound environmental information to minimize impacts and to protect themselves during legal challenges. Some of the most prominent research programmes were the Atomic Energy Commission (AEC) research at Cape Thompson in the 1960s (Wilimovsky & Wolfe 1966), the International Biological Programme (IBP) research at Barrow (Tieszen 1978; Brown *et al.* 1980) and Prudhoe Bay (Walker *et al.* 1980), the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) research along the Dalton Highway (Brown & Berg 1980) and the National Petroleum Reserve–Alaska (NPR–A) (Lawson *et al.* 1978; Lawson 1982), the Research in Arctic Tundra Environments (RATE) programme at Atkasook and Toolik Lake (Batzli 1980), the environmental monitoring and revegetation studies sponsored by Alyeska and the oil industry (e.g. U.S. Army Corps of Engineers 1983; Johnson 1984; Gallaway & Johnson 1985; Dames & Moore Inc. 1986; Densmore *et al.* 1987; Jorgenson 1988a, b), the monitoring sponsored by the U.S. Geological Survey in the National Petroleum Reserve–Alaska (NPR–A) (Tetra Tech 1983; Gryc 1985), environmental research in the '1002 Area' of the Arctic National Wildlife Refuge (Clough, Patton & Christiansen 1987), and the Department of Energy's R4D Program (Response, Resistance, Resilience to, and Recovery from Disturbance in Arctic Ecosystems) (Oechel 1989). Much of this work has been reviewed by Walker *et al.* (1987a).

Definitions

Here we use the term *disturbance* in the sense proposed by Pickett *et al.* (1989): 'Disturbance is a change to the minimal structure [of a system] caused by a factor external to the level of interest.' In our treatment, the system of interest is ecosystem spatial pattern at all scales. The minimal structure is the pattern of plant species at the plot level, plant communities at the site level, or physiognomy and production at the regional level. Thus, glaciations and loess deposition, which operate over large regions and long time-spans, are disturbances when viewed in terms of the entire history of the region, as are the microdynamics of systems associated with vole outbreaks and ground squirrel activity. The effects of disturbance on other hierarchical aspects of system structure and processes, such as energy capture by plants, resource partitioning, or nutrient flow (Rykiel 1985; Pickett *et al.* 1989), are not considered here, although the spatial hierarchy may also play an important role in these other ecological hierarchies.

To gain insight to the factors controlling the response of the system to anthropogenic disturbances, it is important to understand how the vegetation evolved in concert with the terrain. The dynamic character of terrestrial ecosystems is a function of natural disturbance regimes operating over a broad range of spatial and temporal scales (White & Pickett 1985). Analysis of human-caused (anthropogenic) impacts in tundra ecosystems requires a means to compare the effects of these disturbances with natural ones. The distinction between natural and anthropogenic disturbances is made in order to clearly separate those that were part of the landscape before the appearance of man from those that are the results of man's activities. Most anthropogenic disturbances have natural analogues, but the scale or extent of the analogues may be radically different. In fact, natural and anthropogenic disturbances differ most in magnitude of energy input because in most cases man and Nature are dealing with the same materials.

Important aspects of disturbance and recovery in permafrost regions

The physical system

Ice-rich permafrost is a major factor controlling disturbance and recovery in the Arctic. If the permafrost thaws, thermokarst (the collapse of the surface due to melting of massive ground ice) can be initiated on a large scale, and a critical point is reached where it is difficult or impossible to return the site to its original state within a few decades because of continued subsidence. The thawing of ground ice causes (i) hydrologic changes due to the impoundment of water or creation of flowing water, (ii) thermal changes by decreasing the albedo of the surface and increasing heat flux to the site, and (iii) geochemical changes, usually in the form of increased availability of nutrients. Three major attributes of the physical system contribute to thermokarst in permafrost regions: (i) volume of ground-ice in the near surface sediments, (ii) steepness of the terrain, and (iii) grain size of the sediments (Lawson 1986). Disturbances in areas with high amounts of ground ice, rolling topography, and fine-grained sediments may not stabilize even 30 years after the disturbance. The grain-size and steepness of the terrain can normally be determined from surficial geology maps and digital terrain models (DTMs). Currently, the volume of ground ice can only be determined by coring the subsurface sediments. However, statistical probabilities can be used to predict ground-ice content based on numerous other factors, such as terrain age, type of surficial deposit, vegetation mantle, microtopography, slope position, and aspect (Kreig & Reger 1976, 1982).

Modification of the site following disturbance can follow a variety of pathways eventually returning the site to thermal equilibrium. If heat flux to ice-rich terrain is increased by any of a variety of means, such as changes in surface albedo, hydrologic conditions, thermal conductivity of the active layer, snow regime, or local sources of heat, thermokarst is the likely result. The controls on heat flux are complex. The radiation balance and thermal properties of the soil are affected by topographic position (slope and aspect), depth of the moss carpet, bulk density of the soil, vegetation cover, snow cover, and moisture regimes (Weller & Holmgren 1974; Smith 1975; Pavlov 1978; Jorgenson 1986). Deep organic layers and thick moss carpets are good insulators against heat flux unless the organic material is saturated, as is often the case in low microsites. Physically based models of heat flux now offer predictions of changes to annual thaw depth in response to climate change (Kane, Hinzman & Zarling, in press; Hinzman *et al.*, in press). The thermal stability of the site constrains the time required for vegetation recovery and the type of vegetation that will reoccupy the site. Perhaps nowhere on earth is the synergistic link between physical stability of the substrate and vegetation recovery more evident than in permafrost regions.

Vegetation recovery

The possible outcomes of vegetation recovery following disturbance are dependent on a large number of factors, many of which are related to the initial physical characteristics of the site discussed above. Important factors include the composition of the original vegetation (Komárková, Ebersole & Webber 1987); presence or absence and depth of snow cover at the time of disturbance (Felix & Raynolds 1989a); the type, frequency and severity of disturbance (e.g. Abele 1976; Rickard & Brown 1974; Walker *et al.* 1977, 1978); moisture and biogeochemical regime of the site (Chapin & Van Cleve 1981; Chapin, Vitousek & Van Cleve 1986; Chapin *et al.* 1987, 1988; Everett, Marion & Kane 1989; Kane, Hinzman & Zarling, in press; Marion & Everett 1989; Oberbauer *et al.* 1989); temperature regime of the site (Bliss 1962; Billings & Mooney 1968; Savile 1972; Chapin, Van Cleve & Chapin 1979; Chapin 1983a; Shaver, Chapin & Gartner 1986; Shaver 1987); buried seed bank (Chester & Shaver 1982; Gartner, Chapin & Shaver 1983; Shaver & Gartner 1987; Ebersole 1989), availability of native seed (Cargill & Chapin 1987); nature of revegetation efforts (Densmore *et al.* 1987; Densmore & Holmes 1987; Johnson, Shaver & Gartner 1987); and natural successional processes (Bliss & Cantlon 1957; Billings & Peterson 1980; Chapin & Chapin 1980; Shaver *et al.* 1983; Kershaw & Kershaw 1987; Svoboda & Henry 1987). All of these factors contribute to the resistance and resilience of the vegetation and the possible outcomes of the recovery process. [*Resistance* is the property of a system to withstand disturbance without changing its initial state, and *resilience* is the characteristic of a system to return toward the original state once a change has occurred (Holling 1978; Vitousek *et al.* 1981)]. Disturbance in general creates surfaces with warmer soils, lower organic matter, and higher nutrient regimes (Dowding *et al.* 1981; Ebersole 1985; Chapin *et al.* 1988; Komárková & McKendrick 1988).

The native vegetation type is the most telling factor for predicting response to disturbance because it is an integrated expression of the system's reaction to existing site factors, including temperature, nutrients, exposure to wind, snow cover, and natural disturbance regimes (Braun-Blanquet 1932; Major 1951; Chapin *et al.* 1987; Küchler & Zonneveld 1988). Numerous mapping systems combine vegetation, soil, climate, and site factors to produce integrated classifications, such as the vegetation–soil surveys in California (Wieslander 1935; Colwell 1977); ecological land classification in Canada (Rubec 1979; Rowe & Sheard 1981); geoecological maps in the discontinuous permafrost zone of Canada (Crampton & Rutter 1973); integrated terrain unit maps (ITUMs) developed by the Environmental Systems Research Institute (Dangermond, Derrenbacher & Harden 1982 unpubl.); biogeoclimatic classifications of the British Columbia forests (Krajina 1965; Klinka 1976; Pojar, Klinka & Meidinger 1987); and geobotanical maps in northern Alaska (Walker *et al.* 1980, 1986). Cartographic models combine various portions of an integrated classification — such as vegetation, slope, microtopography and soil texture — to produce terrain sensitivity maps (Walker *et al.* 1980; Green *et al.* 1984). For example, maps of sensitivity of tundra to off-road vehicle traffic are based primarily on vegetation and microtopography (Slaughter *et al.* 1990. Some of the most easily disturbed vegetation types are the most resilient (Komárková 1983; Komárková, Ebersole & Webber 1987). For example, wet tundra is easily disturbed (low resistance), but it recovers considerably faster than mesic uplands following a disturbance by off-road vehicles (high resilience) (Komárková 1983). This characteristic is not unique to the Arctic, but it is closely related to the site moisture conditions and the flux of nutrients (Holling 1973; Chapin *et al.* 1988).

In summary, although detailed investigations of succession following disturbance are generally lacking for most native Alaskan tundra communities, we do have a great deal of information regarding general patterns of resistance and resilience in relation to site factors to give us a starting point for models of terrain sensitivity. The most critical factor for these models, however, is determination of ground-ice and heat-flux conditions at a site. It should be possible to model these based on terrain variables and remotely sensed information at a variety of scales. Many basic concepts of disturbance and recovery in the permafrost regions have been formulated during the past three decades. The complexity of and close synergism between physical and biological factors point to the need for multivariate hierarchical databases to predict terrain sensitivity.

SCALES OF DISTURBANCE

Recent concerns regarding the consequences of global climate change have forced ecologists to consider tundra ecosystems at previously unmanageable scales. For example, the effects of feedback associated with climate change resulting from increased atmospheric greenhouse gases is a major concern in tundra ecosystems (Chapin 1983b; Prudhomme *et al.* 1983). An estimated 10–27% of the world's stored carbon is in the peat of northern ecosystems (Prudhomme *et al.* 1983). To understand the response of peat to climate change and the feedback of greenhouse gases to the atmosphere, detailed studies of biophysical processes and plant species dynamics need to be linked to plot-, landscape-, regional- and global-level investigations.

It is difficult to deal experimentally with the variation in natural and anthropogenic

TABLE 1. Spatial hierarchy of Delcourt & Delcourt (1988)

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

disturbances at widely divergent scales and across a wide range of tundra types. Cantlon (1961) recognized the need for a hierarchical approach to examine the vegetation of the North Slope nearly 30 years ago and succeeded in identifying micro-, meso- and macroscale factors controlling tundra vegetation patterns. More modern approaches have utilized the concepts of hierarchy theory (Allen & Starr 1982; O'Neill *et al.* 1986; Urban, O'Neill & Shugart 1987; Rosswall, Woodmansee & Risser 1988). One particularly useful concept is the standardization of spatial and temporal scales across ecosystems (Table 1; Delcourt, Delcourt & Webb 1983; Delcourt & Delcourt 1988; O'Neill 1988). The DDW system is based on a logarithmic separation of spatial and temporal levels within the hierarchy. A similar 'G' scale has been suggested by geographers to scale all geographic measurements to the Earth's surface area (Haggett, Chorley & Stoddart 1965). The hierarchy was developed as a paradigm to aid communication and thinking with regard to environmental forcing functions, biotic responses, and patterns of organization of communities on terrestrial landscapes at all space and time scales (Delcourt & Delcourt 1988).

Natural disturbances

Successional sequences, possibly spanning thousands of years, must be considered in the Arctic because of the exceptionally short growing season and generally poor nutrient regimes (Table 2). Truly stable vegetation is non-existent and all areas are in a state of patchy succession. Even *Eriophorum vaginatum* tussock tundra, which at first glance appears to be a stable vegetation type covering vast areas of the North Slope, is composed of a closely spaced mosaic of successional plant assemblages mostly associated with frost scars (Johnson & Neiland 1983; Gartner, Chapin & Shaver 1986).

At coarse spatial scales, landscape evolution is often not evident but occurs nearly everywhere at widely divergent time-scales. For example, in the Arctic Foothills, differences in terrain morphology and vegetation occur across glacial boundaries separating late-Pleistocene (8–12 ka) surfaces from mid-Pleistocene (about 125 ka) surfaces (Hamilton 1986; Walker *et al.* 1989). On the Arctic Coastal Plain, most surfaces have been affected by lacustrine, eolian, and fluvial processes. Here, the majority of the surfaces have been influenced by the 'thaw-lake cycle', a term used to describe the development, growth, drainage, and re-establishment of thaw lakes, with a time-span estimated to be several hundred to thousands of years (Hopkins 1949; Britton 1967; Everett 1980a; Billings & Peterson 1980). Nearly as extensive are braided-river systems that eventually evolve into thaw-lake plains over the course of several thousand years (R.I. Lewellen unpublished; Walker 1973; Rawlinson 1983). Floodplains have affected most of the eastern portion of the coastal plain, and terraces of various ages have distinct patterns of vegetation. Eolian activity is another important disturbance; parts of the large 7000-km^2 stabilized Pleistocene sand sea west of the Colville River are continuously being reactivated and restabilized (Black 1951; Péwé 1975; Carter 1981; Hopkins 1982; Komárková & Webber 1980; Komárková & McKendrick 1988). In the northern foothills and the central and eastern portion of the coastal plain, modern windblown silt (loess) covers large areas (Carter 1988). Eolian and fluvial disturbances cover a wide range of spatial scales. The type, frequency, and amount of eolian deposition is strongly related to distance from the eolian material source (Walker & Everett, in press). Similarly, the spatial and temporal scales of fluvial activity are strongly related to stream size and climatic events such as storms and deglaciation.

At finer scales, important natural disturbances are: the growth and erosion of ice-wedges (Lachenbruch 1966); tundra fires (Wein & Bliss 1973a; Wein 1976; Hall, Brown & Johnson 1978; Racine 1981, 1987; Racine, Patterson & Dennis 1983, Gabriel & Tande 1983; Johnson & Viereck 1983; Racine, Johnson & Viereck 1987); storm surges (Hartwell 1972; Short 1973; Barnes & Reimnitz 1974; Harper 1978; Hopkins & Hartz 1978; Owens, Harper & Nummedal 1980); river bank erosion (Lawson 1983; Walker 1983), snowbanks and associated run-off (Komárková & Webber 1978, 1980; Walker 1990); animal disturbances (Bee & Hall 1956; Wiggins & Thomas 1962; Pitelka 1964; 1973; Shultz 1964, 1969; Gersper *et al.* 1980; Batzli *et al.* 1980; Walker 1985); ground water discharge, which is responsible for features such as solifluction lobes, slope failures, springs, and icings (aufeis) (Washburn 1980); the diurnal freeze–thaw cycle, which is responsible for features ranging in scale from frost scars to needle-ice hummocks (Washburn 1980; Gartner 1982; Johnson & Neiland 1983; Gartner, Chapin & Shaver 1986).

When the information in Table 2 is plotted in log–log space with the DDW spatial and temporal domains as a background (Fig. 1), most natural disturbances fall along a diagonal, with small frequent disturbances at one end and large infrequent disturbances at the other end. This is largely a function of the log–log scale which will straighten out most sets of points. Exceptions to this pattern include yearly events with a wide range of spatial scales, such as the spring flood, which affects all active floodplains and deltas on the North Slope for a short time in the spring of every year, and loess deposition, which occurs several times per year and affects large areas of the North Slope. The effect of loess, however, is generally only noticeable when it accumulates over long periods of time.

Nearly all natural disturbances are either directly or indirectly climatically driven and are primarily hydrologically mediated. Most of the vegetation and geomorphic effects in Table 1 have a hydrologic component connected to either the melting of

TABLE 2. North slope natural disturbance hierarchy

Hierarchical domain (Delcourt & Delcourt 1988)	Disturbance	Geomorphic effect	Vegetation effect	Spatial scale (m^2)	Event frequency (years)
Megascale (continental to global)	Continental drift and uplift of Brooks Range	Formation of physiographic provinces and bedrock types, establishment of regional drainage patterns	Evolution of arctic flora	$>10^{12}$	$>10^6$
Macroscale (regional)	Climatic fluctuations associated with ice ages	Formation of glacial surfaces, marine terraces, Sand Sea, loess deposits, alluvial deposits, regional paludification, sediment deposition, development of second-order and higher drainages	Speciation and extinction; development, movement, and displacement of plant communities	10^4–10^{11}	10^4–10^6
Mesoscale (regional)	Climatic fluctuations during the Holocene	Development and alteration of permafrost, colluviation of steep slopes, development and alteration of many periglacial features (e.g. ice-wedges, pingos), thaw-lake cycle, development of water-tracks and first-order drainages, soil formation	Species migration, ecotone displacement, changes in landscape mosaic, movement of treeline	10^2–10^{10}	10^3–10^5
	Loess deposition	Alkaline silty soils, dilution of organic matter	Addition of nutrients, calciphilous flora	10^6–10^{10}	10^{-1}–10^2
Microscale (site)					10^3–10^4
Macrosite	Tundra fires	Local fluvial and thermal erosion	Burning, recycling and loss of nutrients, opening of canopy	10^4–10^8	
Mesosite	Growth and erosion of ice-wedges	Formation of ice-wedge-polygon microtopography, thermokarst pits	Changes in vegetation mosaic by alteration of microenvironment	10^0–10^3	10^0–10^4
	Major storms and storm surges	Debris flows, large rock falls, floodplain alteration, coastal erosion, rill formation	Burial and removal of vegetation, salt-kill in coastal areas	10^{-1}–10^6	10^0–10^2

TABLE 2. (cont.)

Hierarchical domain (Delcourt & Delcourt 1988)	Disturbance	Geomorphic effect	Vegetation effect	Spatial scale (m^2)	Event frequency (years)
Mesosite (cont.)	Annual snow and run-off cycle:				
	Ground water discharge, melting of active layer	Springs, icings, solifluction features	Summer-long water source, alteration of soil temperature and growing-season length	10^4-10^6	10^0
	Snowbank formation and melting	Annual erosion and sedimentation, formation of nivation hollows	Unstable substrate, short growing season, summer-long water source, winter protection	10^2-10^5	10^0
	Spring flood	Fluvial erosion and sedimentation,	Addition of nutrients, burial, removal of plants	10^2-10^9	10^0
	Oil seeps	Deposition of hydrocarbons	Killing of vegetation	10^2-10^4	$10^{-2}-10^1$
Microsite	Animal disturbances	Caribou trails, animal dens, craters, local erosion, krotovinas	Removal of plants, addition and recycling of nutrients	$10^{-2}-10^2$	$10^{-1}-10^2$
	Daily and annual free–thaw cycle	Needle ice formation, frost scars	Physical disturbance of plant roots and seedlings	$10^{-4}-10^1$	$10^{-2}-10^0$

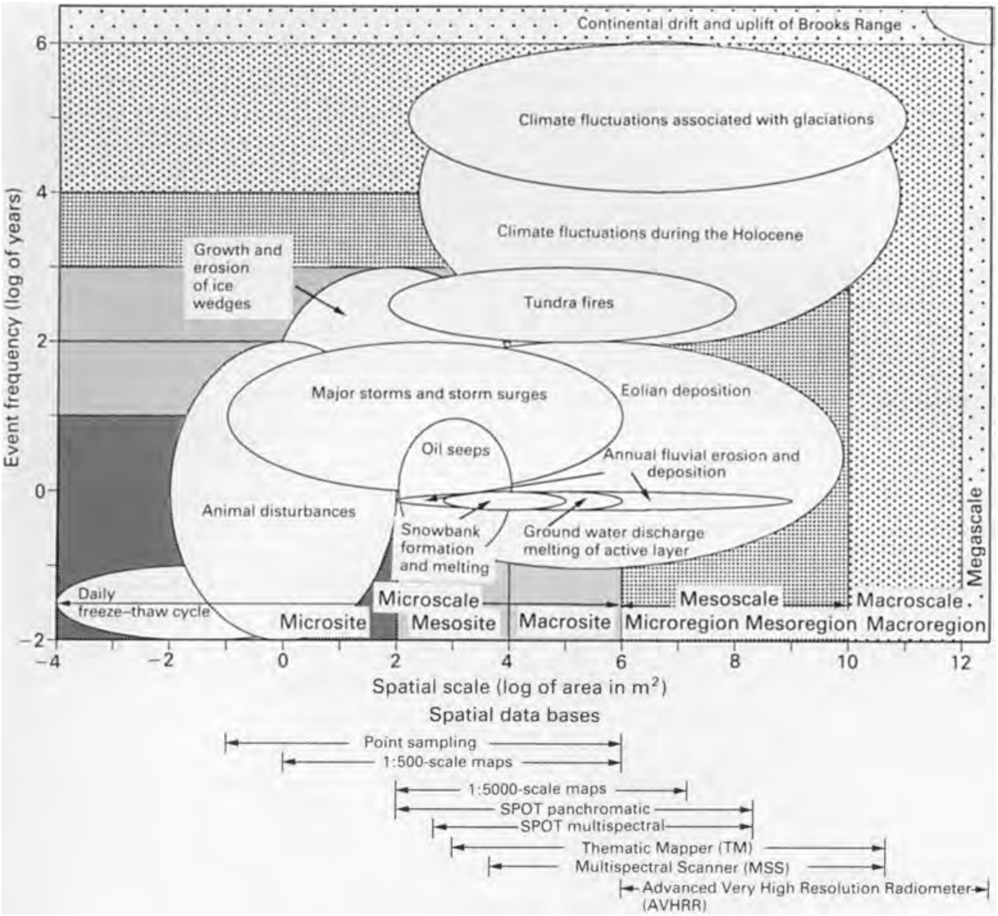

FIG. 1. Spatial and temporal scales of natural disturbances on the North Slope, based on information in Table 2. Scales of various data collection methods are shown along the x-axis. The lower scales (left arrow) of the satellite sensors are the minimal sample area, or pixel size, of each sensor. The upper limit (right hand arrow) is the size of a standard image.

ground ice or precipitation effects. Snowpack, soil moisture, and run-off patterns control the vast majority of vegetation patterns, primary production, and the patterns of animals. Only the megascale disturbances associated with continental drift and tectonism are not closely tied to climate and precipitation.

Anthropogenic disturbances

History

Three distinct periods of modern anthropogenic disturbances have occurred on Alaska's North Slope: (i) the pre-World War II period, during which disturbances were mainly limited to activities around native villages and hunting camps; (ii) the World War II and early exploration period, including the building of the radar sites of the Distant Early Warning (DEW) system and the hydrocarbon exploration in

Naval Petroleum Reserve-4 (PET-4) from 1943 to 1953 (Schindler 1983; Gryc 1985, 1988), all of which predates the era of national environmental consciousness; and (iii) the period starting with the discovery of oil at Prudhoe Bay in 1968 to the present. The disturbances discussed in this study are related primarily to oil exploration of the 1940s to the present.

Many disturbances are still visible from the earliest period of oil exploration when tracked vehicles were used to transport seismic and drilling equipment during the summer across the tundra. During the exploration of PET-4 (1944–53) and the exploration of the central coastal plain and the foothills during the 1950s, trails were often bulldozed across the tundra during both summer and winter (Reed 1958). Drilling sites were locations of a wide variety of disturbances (Lawson *et al.* 1978; Lawson 1982; Ebersole 1987). The most long-lasting effects were subsidence due to thermokarst, and debris such as construction materials, oil drums, and small hydrocarbon spills. Most of these have recently been cleaned up by the U.S. Geological Survey and the U.S. Navy (Gryc 1985). Investigations regarding long-term (30-year) recovery of vegetation and terrain have been conducted at Fish Creek Test Well 1 (Lawson *et al.* 1978), Oumalik (Ebersole 1985), East Oumalik (Lawson 1982), and Cape Thompson (Everett *et al.* 1983).

During the most recent period of oil exploration, there has been a heightening of environmental concern and the development of techniques to minimize disturbance to the tundra, but we have concurrently seen an increase in the size of areas affected. Large oil fields and long pipelines create fundamentally different ecological concerns than those resulting from the early oil exploration. Past disturbances were not as frequent, as intense, nor as large as those of today. Concerns over water pollution (West & Snyder-Conn 1987), air pollution, disposal of hazardous waste (Speer & Libenson 1988), and cumulative impacts to wildlife and the landscape (Shideler 1986; Walker *et al.* 1987b) have added to engineering concerns about how to construct thaw-stable roads, pipelines, and buildings in a permafrost environment. Some of the most difficult questions are those regarding land-use planning of vast pristine landscapes, where to locate facilities in these landscapes, and which areas should be protected from all development.

Types of anthropogenic disturbance

The complexity of modern oil fields, such as the Prudhoe Bay oil field, makes summary statements regarding their environmental impact difficult. Walker *et al.* (1987a) reviewed most of the available literature on the impacts of permanent structures, such as roads, pipelines, powerlines, airstrips, and gravel pads. Most research has focused on the effects of roads, including the elimination of habitat beneath roads (Walker *et al.* 1987b), road dust (Everett 1980b; Werbe 1980; Spatt & Miller 1981; Klinger, Walker & Webber 1983; Walker & Everett 1987; Meininger & Spatt 1988), shorebird habitat (Meehan 1986; Troy 1988), waterfowl (Murphy *et al.* 1989) roadside erosion and thermokarst (Berg 1980; Walker & Everett 1987), impoundments (Klinger, Walker & Webber 1983), the effect of roads on caribou (Cameron 1983; Robus & Curatolo 1983; Smith & Cameron 1985; Shideler 1986; Curatolo & Reges 1986), roadside snowbanks and early snowmelt due to the low albedo of dust-covered snow (Benson *et al.* 1975; Klinger, Walker & Webber 1983), the migration of weeds along transportation corridors (Johnson & Kubanis 1980 (unpubl.); Kubanis 1980), and revegetation of abandoned roads, gravel pads and material sites (Brown & Berg 1980; Johnson 1981; Johnson 1987, Johnson, Shaver & Gartner 1987; Densmore *et al.* 1987; Jorgenson 1988a, b).

Disturbances not associated with permanent structures include terrestrial oil spills (McCown *et al.* 1973; Wein & Bliss 1973b; Deneke *et al.* 1975; Mackay & Mohtadi 1975; Freedman & Hutchinson 1976; McGill 1977; Everett 1978; *Arctic*, **31** (3), 1978; Johnson *et al.* 1980; Linkins *et al.* 1984; Holt 1987; McKendrick 1987); salt-water contamination associated with waterflood pipelines (Simmon *et al.* 1983), sewage lagoons and reserve pit fluids (French 1985; West & Snyder-Conn 1987; Myers & Barker 1984); off-road vehicles (Abele & Parrott 1972; Abele *et al.* 1978; Walker *et al.* 1977; Challinor & Gersper 1975; Gersper & Challinor 1975; Chapin & Shaver 1981; Abele, Brown & Brewer 1984; Linkins *et al.* 1984; Racine & Johnson 1988; Slaughter *et al.* 1990); winter trails and ice-roads (Buttrick 1973; Gas Arctic-Northwest Project Study Group 1973; Adam 1974; Adam & Hernandez 1977; Racine 1977; Brown & Berg 1980; Johnson & Collins 1980); and seismic trails (P.C. Reynolds, unpublished; Geophysical Services Inc. 1984; Felix & Raynolds 1989a, b).

Scales of anthropogenic disturbances

As with natural disturbances, it is often difficult to determine what is a discrete anthropogenic disturbance event. For example, an oilfield is an accumulation of many smaller disturbances, but when considered over the time-span of decades to centuries, it becomes a single disturbance. Similarly, in the case of road dust, the passage of a single truck with its associated dust plume is a discrete disturbance, but the effects are hardly noticeable until the accumulated dust of many years is considered. Estimates of the spatial scale of disturbances and their times of recovery (Table 3, Fig. 2) are based, as much as possible, on the literature discussed above. Generally, the lower limits of the spatial scales are determined by the smallest area that would be considered a discrete example of the disturbance, such as a single piece of trash (10^{-1} m^2), a 100-m-wide swath of dust adjacent to a 1-km-long road (10^5 m^2), a single small roadside impoundment (10^2 m^2), a small native village or drill site (10^4 m^2), and a small oilfield consisting of two gravel pads and a connecting road (10^5 m^2). The minimum area for the effects of climate change due to increased greenhouse gases was considered to be a small vegetation community (10^2 m^2).

The upper limits of the spatial scales were based on the largest known examples on the North Slope, such as the 100-m dust swath along the 290-km North Slope portion of the Dalton Highway (10^7 m^2), the estimated total area of Prudhoe Bay oilfield disturbances based on Walker *et al.* (1987b) (10^8 m^2), and the 1977 Franklin Bluffs oil spill (10^5 m^2). The upper limit for ORV and seismic trails was considered to be 50 km with a disturbed width of 2 m for ORVs and 20 m for seismic trails. The maximum geographic entity that would be affected by a climate change was considered to be the entire North Slope (10^{11} m^2).

Recovery times are also based on literature and knowledge of succession in natural ecosystems of northern Alaska. Lower limits of recovery are in most cases 1 year or less. Major impacts, such as roads, gravel pads, villages, and drained thaw-lakes, require extended periods of succession, usually exceeding 100 years. Full recovery is not likely to occur on some disturbances, such as roads, pads, and many material sites; so length of time to achieve functional recovery is used. Functional recovery is the process leading to a stable functional ecosystem that is different from the original (Walker *et al.* 1987a). Oilfields, gravel mines, and roads are considered

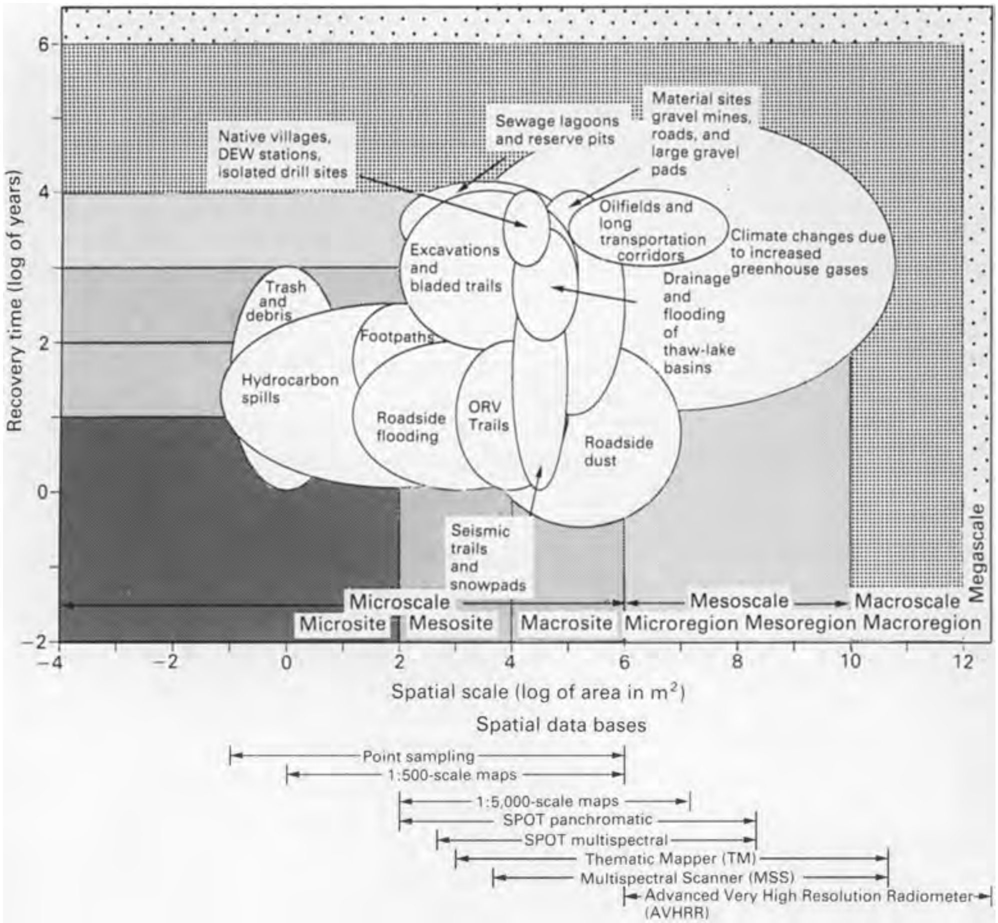

FIG. 2. Spatial scales and estimated recovery time for anthropogenic disturbances on the North Slope, based on information in Table 3.

comparable to fresh glacial outwash with the exception that the till has a higher proportion of fine soil particle sizes (<2 mm diameter), and therefore, succession pattern and rates will be somewhat different due to better nutrient and water retention. Recovery to a condition similar to Itkillik-age till is estimated to be at least 10^4 years. Recovery from a major climate change conceivably could be equivalent to that of a major glaciation (10^5 years).

The following summary is based on Table 2 and the log–log plot of its information (Fig. 2). (i) All the disturbances of the early years of native villages, DEW-line stations, and oil exploration, as well as most modern disturbances, are microscale-level phenomena. (ii) Mesoscale events are associated only with large oilfields and extended transportation corridors. (iii) Road dust is a mesoscale phenomenon when considered over the entire North Slope portion of the Dalton Highway. (iv) Landscape change associated with major anthropogenic climate shift could have macroscale effects.

TABLE 3. North slope anthropogenic disturbance hierarchy

Hierarchical domain (Delcourt & Delcourt 1988)	Disturbance	Geomorphic effect	Vegetation effect	Spatial scale (m)	Recovery time (years)
Macroscale (regional)	Climate change due to increased greenhouse gases	Alteration of permafrost table, colluviation of steep slopes, alteration of periglacial features, thaw lake cycle, and coastal erosion	Species migration, ecotone displacement, changes in landscape mosaic, movement of treeline	10^2–10^{11}	10^3–10^5
	Air pollution, NO_2 and sulphur emissions	None	Unknown	?	?
Mesoscale (regional)	Oil fields, and long transportation corridors	Cumulative effects of many smaller disturbances (see below)	Introduction of weedy species, cumulative effects of many smaller disturbances (see below)	10^5–10^8	10^3–10^4
Microscale (site)	Macrosite Roadside dust	Thermokarst in very heavy dust areas	Smothering of vegetation, development of alkaline plant communities, toxic effects to acidiphiles, addition of nutrients	10^5–10^7	10^0–10^2
	Roads and large gravel pads	Changed substrate and microclimate, numerous secondary effects due to dust, flooding, and snow adjacent to pads	Burial of natural vegetation, numerous secondary effects due to run-off from road, dust, and flooding (which see), burial from gravel due to snow removal, barren dry surface for revegetation	10^4–10^6	10^4–10^6
	Seismic trails and snow pads	Altered microtopography	Compaction or removal of vegetation	10^4–10^6	10^0–10^3
	Material sites and gravel mines	Creation of lakes, removal of near-surface sediments, creation of overburden piles	Removal of vegetation, creation of barren surface for primary succession, burial of tundra adjacent to mines by gravel and overburden piles	10^4–10^6	10^1–10^4

TABLE 3. (cont.)

Hierarchical domain (Delcourt & Delcourt 1988)	Disturbance	Geomorphic effect	Vegetation effect	Spatial scale (m^{2})	Recovery time (years)
	Native villages, DEW stations, and isolated drill sites	Cumulative effects of many smaller disturbances (see below)	Cumulative effects of many smaller disturbances (see below)	10^4–10^5	10^3–10^4
	Excavations and bladed trails	Thermokarst, erosion, removal of near-surface sediment and vegetative mat, changed microtopography, creation of berms along trails	Compression, removal, and burial of vegetation, changed endpoint for succession due to new microclimate and soil character	10^3–10^5	10^2–10^4
Mesosite					
	Sewage lagoons and reserve pits	Formation of ponds and mud flats	Killing of vegetation	10^3–10^5	10^3–10^4
	Hydrocarbon and brine spills	Changed microtopography due to cleanup activities, thermokarst due to changed thermal regime	Total or partial killing of original vegetation, coating of vegetation in spray spills	10^3–10^5	10^1–10^3
	Roadside flooding	Thermokarst, formation of anaerobic soils, formation of lakes.	Drainage or flooding of wetlands, changed temperature and nutrient regimes	$10^{-}10^5$	10^0–10^3
	Off-road vehicle trails	Changed microtopography due to compression	Compression, displacement, and removal of vegetation	10^3–10^5	10^0–10^2
	Structures, sod houses, buildings	Changed microtopography, thermokarst in surrounding areas	Removal of vegetation, eutrophilcation of vegetation	10^2–10^4	10^3––10^4
Microsite					
	Footpaths	Elimination of hummocks, erosion, thermokarst	Trampling, compaction, and removal of vegetation	10^1–10^3	10^0–10^2
	Trash and debris	Local changes in microtopography	Killing of vegetation	10^{-1}–10^2	10^0–10^3

NORTH SLOPE GIS HIERARCHY

A hierarchical geographic information system (GIS) is currently under development for the North Slope. The purpose is to organize data at appropriate scales for addressing scientific questions related to energy development and climate change. One goal is the development of a series of spatial models that predict response of vegetation and landscapes to disturbances at several scales. The DDW spatial domains are the conceptual framework for the GIS. Models utilizing the GIS to portray nutrient and soil-water movement along slopes and through watersheds in permafrost regions are being developed at San Diego State University as part of the U.S. Department of Energy's 'Response, Resistance, Resilience to, and Recovery from Disturbance in Arctic Ecosystems' (R4D) programme, and at the Marine Biological Laboratory at Woods Hole as part of the National Science Foundation's Long-Term Ecological Research (LTER) programme. To date, most of the research has focused on detailed descriptions of the geobotany (Walker *et al.* 1989; Stow, Burns & Hope 1989) and application of the GIS to the analysis of the spatial relationships between terrain, snow distribution, and vegetation (Evans *et al.* 1989).

Scales and topics of investigation

The GIS consists of three primary tiers that correspond to the macroscale, mesoscale, and microscale domains of the DDW hierarchy (Table 1, Fig. 3). Databases are currently being constructed at five sublevels of the hierarchy (macroregion, mesoregion, microregion, macrosite, and microsite).

The scale of various spatial data gathering systems used for the GIS are shown along the x-axis in Figs 1 and 2. For example, we use point-sampling techniques for a wide variety of microscale studies, such as thaw-depth, snow-depth, and soil properties. Of course, point sampling is also used at much broader scales, but often it is not possible to make statistically sound extrapolations based on these samples. Photointerpreted geobotanical maps based on extensive ground surveys are being produced at mesosite to microregion scales. Again, photointerpreted maps are made of larger areas, but for the North Slope studies, they are currently restricted to microregion areas or smaller because of the labour involved in making accurate maps of larger areas. Satellite digital data are used for most regional studies (Figs 1 and 2). Although each sensor can be used for studies at a wide variety of scales, the scales at which the sensors are most appropriately used within the context of the hierarchical GIS are discussed below.

Regional level

Regional studies involve questions related to areas greater than 1 km^2. Specific scientific questions being investigated at the regional level are: (i) What are the large-scale and long-term patterns of vegetation succession and accumulation of peat and carbon on different-aged landscapes in the Arctic? (ii) What is the influence of modern loess on large-scale vegetation patterns? (iii) How do the patterns associated with landscape age and loess influence hydrology and stream- and lake-chemistry from water tracks to major river systems? (iv) How does primary production respond to the existing temperature and precipitation gradients associated with the Beaufort Sea and the Brooks Range? (v) Can these climatic gradients be used as appropriate

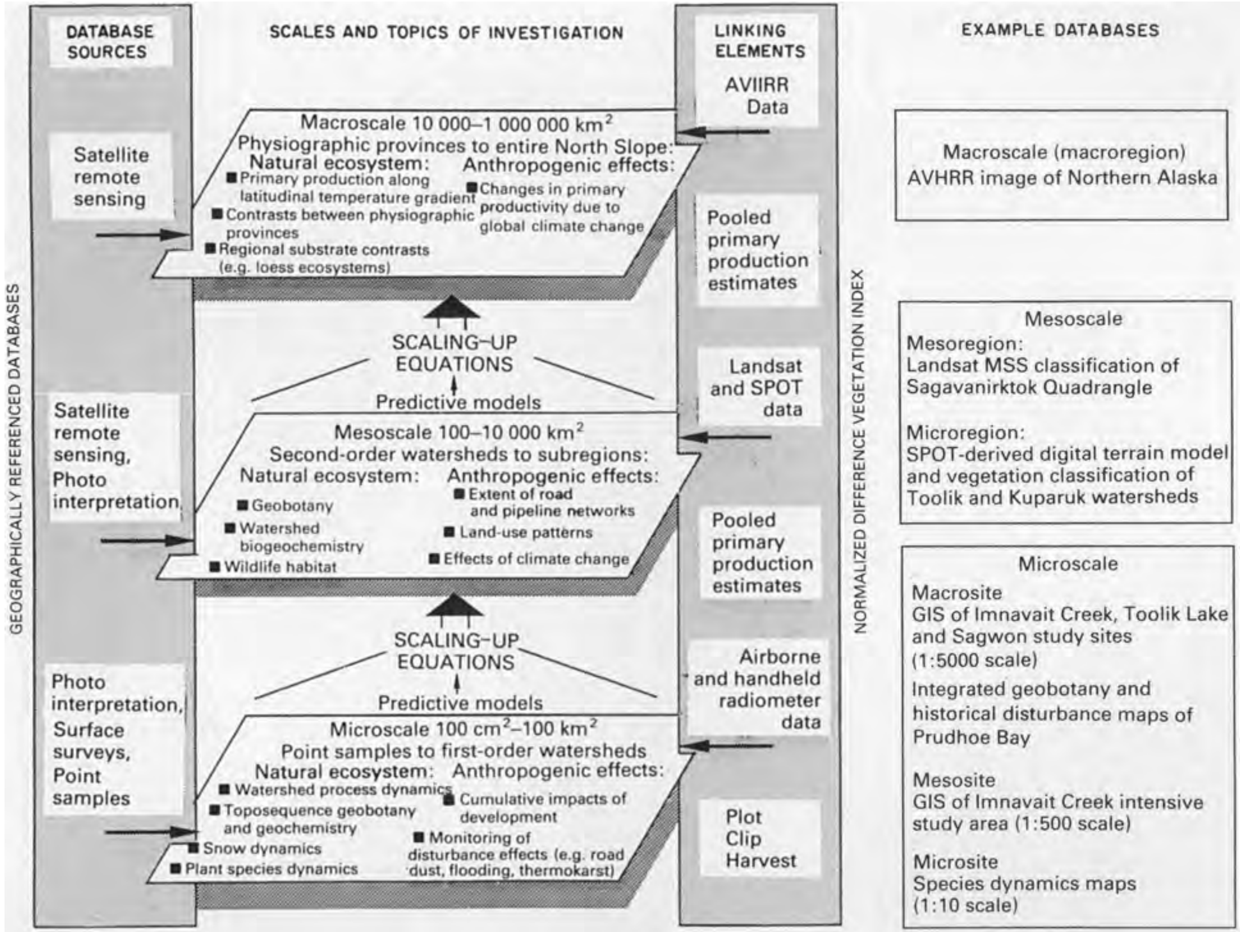

FIG. 3. North Slope GIS hierarchy. See text for discussion of scales, topics of investigation, and database sources, and linking elements for each level in the hierarchy.

analogs for future climate change? The regional level includes macroscale and mesoscale databases.

Macroscale (10^4–10^6 km²)

Macroscale (macroregion) databases involve physiographic provinces up to the entire North Slope (Fig. 4). The primary data source at this scale is digital information from the Advanced Very High Resolution Radiometers (AVHRR) aboard the NOAA (National Oceanic and Atmospheric Administration) satellites. The data are from five spectral bands (one in the visible, one in the near IR, and three in the thermal IR), with a spectral resolution (pixel size) of 1·1 km, a swath width of 2400 km, and coverage every 24 h (Lillesand & Kiefer 1987).

Because of the daily coverage and broad swath width, AVHRR data are particularly useful for examining temporal changes of primary production, snow cover, and regional differences in vegetation patterns that would be difficult to detect on mosaics of higher resolution satellite images (e.g. MSS or TM, see below). Topics of investigation for the natural ecosystem include seasonal and latitudinal changes in primary production, contrasts between physiographic provinces (Wahrhaftig 1965), and vegetational contrasts on major surficial deposits (e.g. sand sea, marine deposits, loess, and fluvial deposits). Anthropogenic influences analysed at this scale include climate change and its effects on timing of snow melt and seasonal changes along primary production gradients. AVHRR data have been used to detect major regions of minerotrophic vegetation associated with modern loess deposits on the Coastal Plain and in the Arctic Foothills (Walker & Everett, in press).

Mesoscale (10^2–10^4 km²)

At the mesoscale, topics of investigation involve second-order watersheds to subregions. Typical questions are related to large-watershed biogeochemistry, wildlife habitat, geobotany of large regions and long elevational gradients. Anthropogenic-disturbance questions include those related to the full extent of road and pipeline networks, land-use patterns, and the effects of climate change on primary production. The mesoscale domain is divided into the mesoregion and microregion sublevels.

The primary data sources at the mesoregion sublevel are derived from the Landsat-4 and -5 satellites, which include the multispectral sensor (MSS; two bands in the visible, two in the near-IR; 79-m pixel size; 185-km swath width; and coverage every 16 days) and thematic mapper (TM; three bands in the visible, one in the near IR, two in the mid IR, and one in the thermal IR; 30-m pixel size; and coverage every 16 days). MSS data have been used extensively on the North Slope for landcover classification (George, Stringer & Baldridge 1977; Nodler & Laperrier 1977; Morrissey & Ennis 1981; United States Geological Survey 1976, 1981; Walker *et al.* 1982; Walker and Acevedo 1987;). The TM sensor has more bands located in critical regions of the spectrum for detecting plant water stress, thermal mapping, and greater spatial resolution for better differentiability of surface features (Lillesand & Kiefer 1987). TM has proved particularly useful for differentiating snow from cloud cover and discriminating some rock types.

Microregion databases are being constructed using High Resolution Visible (HRV) data from the *Systeme Pour l'Observation de la Terre* or SPOT-1 satellite and integrated geobotanical maps made from low-elevation aerial photographs. The SPOT satellite has two modes of sensing: (i) a panchromatic (black and white) mode (one band in

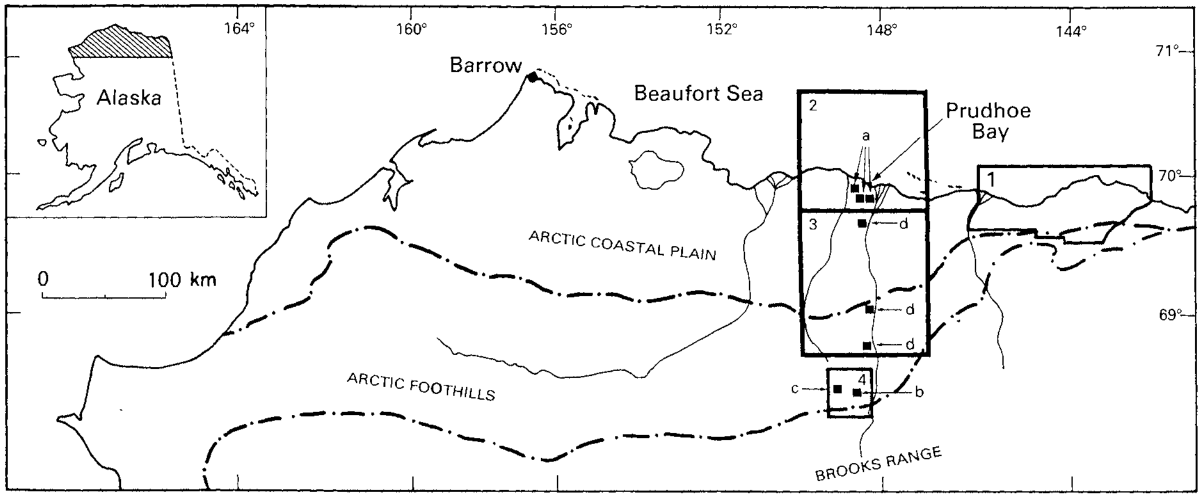

FIG. 4. The North Slope of Alaska. The macroregion database includes the Arctic Coastal Plain, Arctic Foothills, and Brooks Range and is covered on a single AVHRR scene (Walker and Everett, in press). Mesoregional databases are 1:250 000-scale Landsat MSS-derived vegetation classifications of (1) the Arctic National Wildlife Refuge '1002 Area' (Walker *et al.* 1982), (2) Beechey Point Quadrangle (Walker & Acevedo 1987), (3) Sagavanirktok Quadrangle (Walker 1988), and (4) Proposed Kuparuk River and Toolik Lake watersheds (Fig. 5). Microregional databases are 1:6000-scale photointerpreted integrated geobotanical maps of 22 km^2 areas of (a) three areas in the Prudhoe Bay Oil Field (Walker *et al.* 1987), (b) Imnavait Creek (Walker *et al.* 1989), (c) Toolik Lake, and (d) proposed sites along the Dalton highwav.

the visible, 10-m pixel size, 117-km swath width), and (ii) a multispectral mode (two in the visible and one in the near-IR, 20-m pixel size, 117-km swath width). The sensors can be pointed off nadir so that images from passes on successive days can be used to produce stereoscopic coverage and three-dimensional images of the terrain.

We are currently building two microregional databases in the foothills of the Brooks Range to examine ecological differences in two watersheds on different-aged glacial surfaces (Fig. 5). These are nested within a planned mesoregion database that will enclose both watersheds. A SPOT-derived vegetation classification has been made for the R4D research site at Imnavait Creek (Stow, Burns & Hope 1989). This same area has been mapped using integrated geobotanical mapping techniques (Walker *et al.* 1989). The microregion GIS consists of the following layers: (i) the SPOT data; (ii) a digital terrain model (Fig. 6) which, in this case, is an array of terrain elevations sampled at 10-m $X-Y$ intervals, and (iii) an integrated geobotanical map (vegetation, terrain units, landforms, surface forms, and percentage water cover). Details of the geobotanical mapping methods and legends are explained in Walker *et al.* (1989).

Site level (microscale)

The microscale (10^0-10^6 m^2) level includes studies ranging in scale from 1-m^2 plots to first order watersheds. Currently, we are developing databases at the macrosite (10^4-10^6 m^2) and microsite (10^0-10^2 m^2) sublevels. Natural ecosystem questions being investigated at these levels are related to watershed-process dynamics, toposequence geobotany and geochemistry, snow dynamics, and plant species dynamics. Also, most anthropogenic disturbances can be investigated at the microscale level, including monitoring the effects of road dust, oil spills, roadside flooding, and thermokarst. Scientific questions at these scales include: (i) What is the influence of snow distribution on vegetation-community patterns, and how will they be altered by climate change? (ii) What are the influences of terrain age and loess on vegetation-community patterns and soil organic accumulation along toposequences? (iii) How do these patterns influence soil-water chemistry and the movement of nutrients downslope? (iv) What are the patterns of plant-species dynamics associated with existing disturbance regimes and how will these be influenced by climate change? (v) What are the microsite variations in primary production and vegetation structure, and how will these change with altered climate or other anthropogenic influences?

Macrosite (100 m^2–1 km^2)

Within each of the microregion areas, permanent 1000 × 1000-m grids have been surveyed with Universal Transverse Mercator (UTM) coordinates to provide a framework for macrosite investigations. The vegetation within each grid has been mapped at the plant association level (Braun-Blanquet 1932; Westhoff & van der Maarel 1973). The grid and the GIS are conducive to the collection of a highly integrated geographically referenced database. Current studies are focusing on the changes in plant growth forms, species composition, soils, and water chemistry along the toposequences.

Microsite (100 cm^2–100 m^2)

Detailed studies of vegetation structure and plant-species dynamics in response to

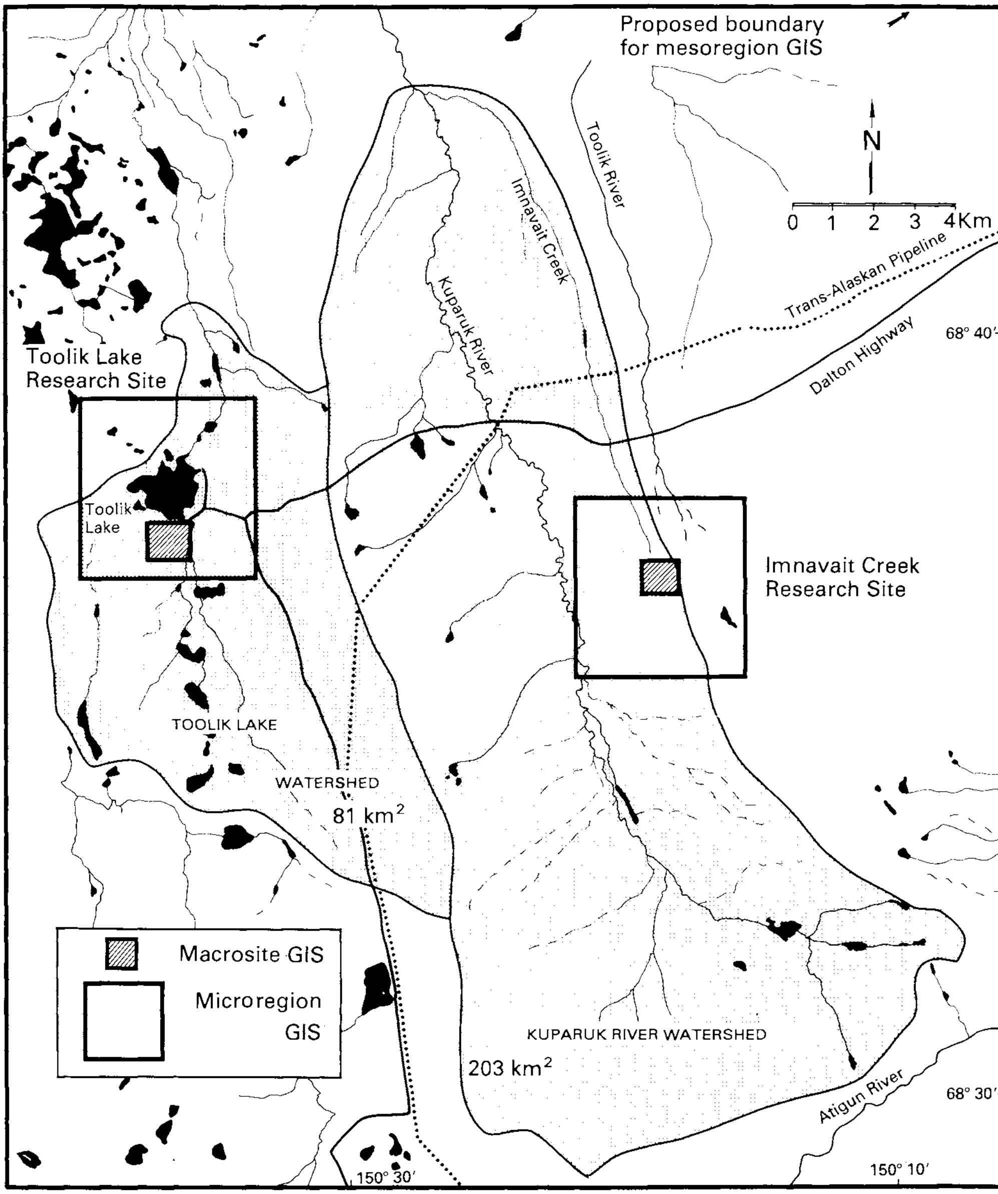

FIG. 5. Toolik Lake and Kuparuk River watersheds. Nested microregion, macrosite, and microsite GISs are being constructed at Imnavait Creek and Toolkik Lake. A mesoregional GIS (Fig. 6) will enclose both watersheds. The Imnavait Creek site is on a Sagavanirktok-age (mid-Pleistocene) surface, and the Toolik Lake site is on an Itkillik-age (late-Pleistocene) surface. The major questions being examined at these sites are, 'What are the long-term patterns of vegetation succession and accumulation of soil carbon on different aged landscapes? And how do these patterns influence soil and watershed geochemistry at various scales?'

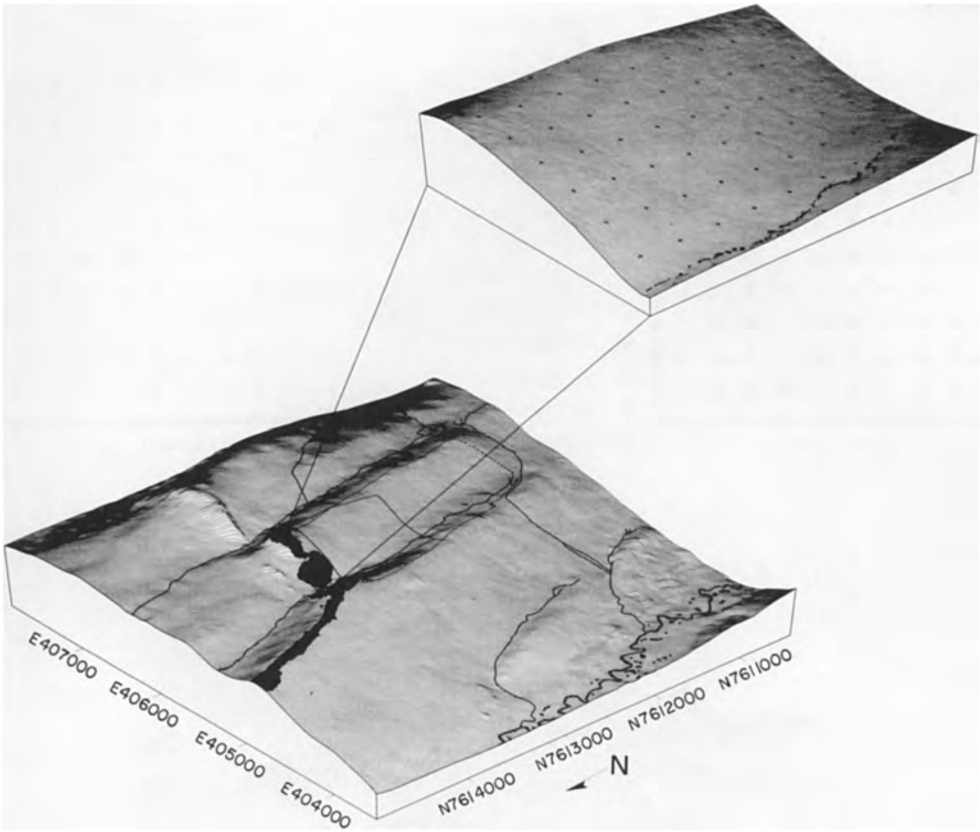

FIG. 6. Digital terrain models of the Imnavait Creek mesoregion (bottom) and macrosite (top) databases. The macrosite database encloses a 700 × 800-m UTM grid. Microsite databases are available for 1 × 1-m permanent plots at each grid point (Fig. 7). The dashed line in the bottom terrain model encloses the Department of Energy's R4D Imnavait Creek research watershed.

site factors, climate change, and anthropogenic disturbances are being conducted using permanent plots (1 × 1 m with 10-cm gridpoint spacing; Fig. 7). These plots are located at each of the 100-m gridpoints within the mesosite grids (above). The plots are particularly useful for long-term studies. Plant-species occurrence and height of the vegetation canopy are recorded and monitored at 5-year intervals to detect changes in species composition and vegetation canopy structure. Microsite databases are also being used to examine the response of vegetation to road dust and other anthropogenic disturbances.

Linking elements

Several characteristics of the ecosystem can be 'scaled up' to allow extrapolation from detailed plot-level studies to broader regions. For example, greeness indices, derived from spectral reflectance in the red and near-infrared bands, are used to estimate the leaf area index (Jordan 1969; Tucker 1979). Multispectral data can be collected at any scale in the hierarchy using hand-held, airborne, and satellite-mounted radiometers. Biomass from clip-harvest plots is used to calibrate the spectral

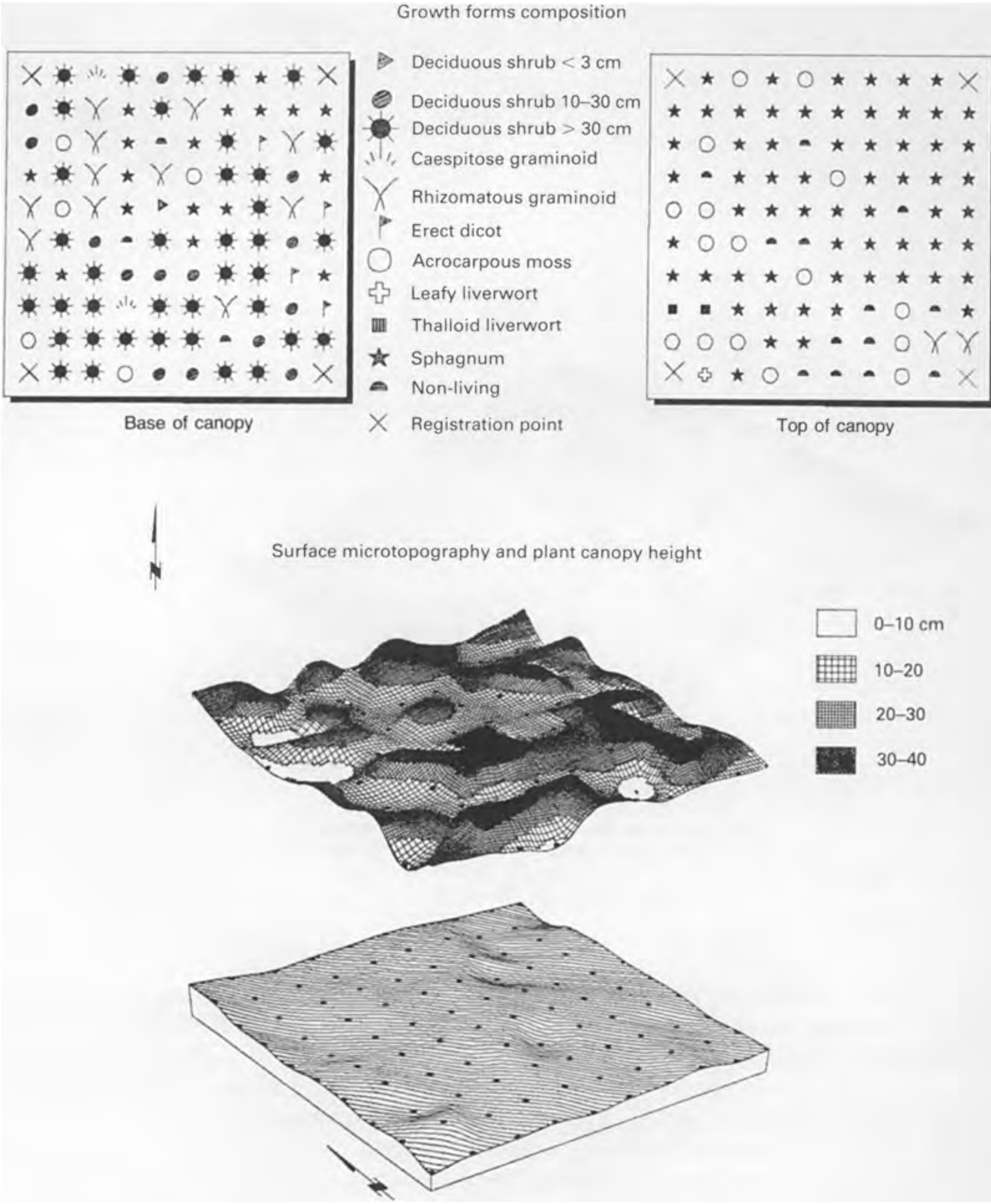

FIG. 7. Example of a microsite database from the Imnavait Creek site. The upper two squares portray the species composition and growth forms at 10-cm intervals within the plot. The bottom figure portrays the microtopography at the base of the plant canopy (lower layer) and the height of the vegetation canopy (upper layer). In a colour version, the species and growth forms can be portrayed in a single figure with the colour denoting the growth form and the shape of the symbol denoting the species.

information collected with hand-held and low-altitude aircraft-mounted radiometers. This information is pooled for primary production estimates at higher levels in the hierarchy (Hope 1988).

In forested ecosystems, investigators have successfully scaled-up canopy-chemistry characteristics (Wessman *et al.* 1988), evapotranspiration and net photosynthesis (Running *et al.* 1989) using remotely sensed information. Relationships have also been developed between spectral reflectance, canopy chemistry, and nitrogen cycling (Wessman, Aber & Peterson 1989), thus offering promise of remotely sensed images of ecosystem function. Other elements that can be linked between scales are water run-off and stream geochemistry. Soil run-off models are currently under development at San Diego State University (Ostendorf & Reynolds 1990) that will run at meso- to microscale levels using digital terrain data, maps of precipitation (snowpack and rainfall), and estimates of potential surface evaporation derived from radiation-budgets based on slope and aspect. Investigators at the Marine Biological Laboratory in Woods Hole are developing geochemistry models that will link the runoff models with GIS geobotanical characteristics.

The methods of scaling up to regional and global scales are still in their infancy, but they need to be developed if detailed process-level investigations are to be applied at broader scales. The hierarchical GIS presented here is a framework for this. The methods could also be applicable to other ecosystems.

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