Use of Geobotanical Maps and Automated Mapping Techniques to Examine Cumulative Impacts in the Prudhoe Bay Oilfield, Alaska

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INTRODUCTION

Importance of Cumulative Impact Research in the Arctic

In the past 20 years, great strides have been made in the understanding and protection of arctic ecosystems, but the rate, extent, and intensity, of development on the Arctic Coastal Plain of Alaska is so unprecedented that grave loss of regional environmental quality and habitat, wildlife, and subsistence values, is certain unless steps are taken to avoid such consequences. Those steps should include continued ecological research, improved engineering methods, revised regulatory policies, and better-than-formerly management implementation. The study of cumulative impacts on terrestrial ecosystems is a leading aspect of the required ecological research.

Cumulative impacts are defined here as the total current and future interactive impacts on fish and wildlife populations and habitats (Horak *et al.*, 1983). Although environmental legislation in the United States requires evaluation of cumulative impacts (Council on Environmental Quality, 1978), very few US environmental impact statements treat the problem adequately, because agreed methods and a comprehensive approach to address it are largely lacking. Most evaluations and reviews only address impacts in generalities, because the details of subsequent development are not precisely known, and hence associated impacts are difficult to predict. Such evaluations usually fail to consider indirect or induced effects which may occur even years after the direct disturbance.

The first step towards predicting the future effects of development must be based on our knowledge of what has already occurred. One approach is through the development of models which depend on determination of the rate and extent of the impacts that have already occurred, and analysis of the effects of such impacts on various components of the immediate ecosystem. The present paper analyses past physical disturbances in the Prudhoe Bay region. Recent advances in computerized cartography and geographic information systems (GISs) lend themselves well to such 'historical' studies of changes in terrain. This analysis combines detailed geobotanical mapping 'legends' that have been developed for the Prudhoe Bay region (Walker *et al.*, 1980) with automated mapping techniques.

The Prudhoe Bay region of northern Alaska (Fig. 1) is the site of the largest oilfield in the United States. This field, which now covers an area of approximately 300 km^2, has been developed entirely within the past 16 years on a remote arctic site that, prior to development, was virtually unknown except to the native Inuit (Eskimo) population. The oilfield now consists of a vast network of roads and

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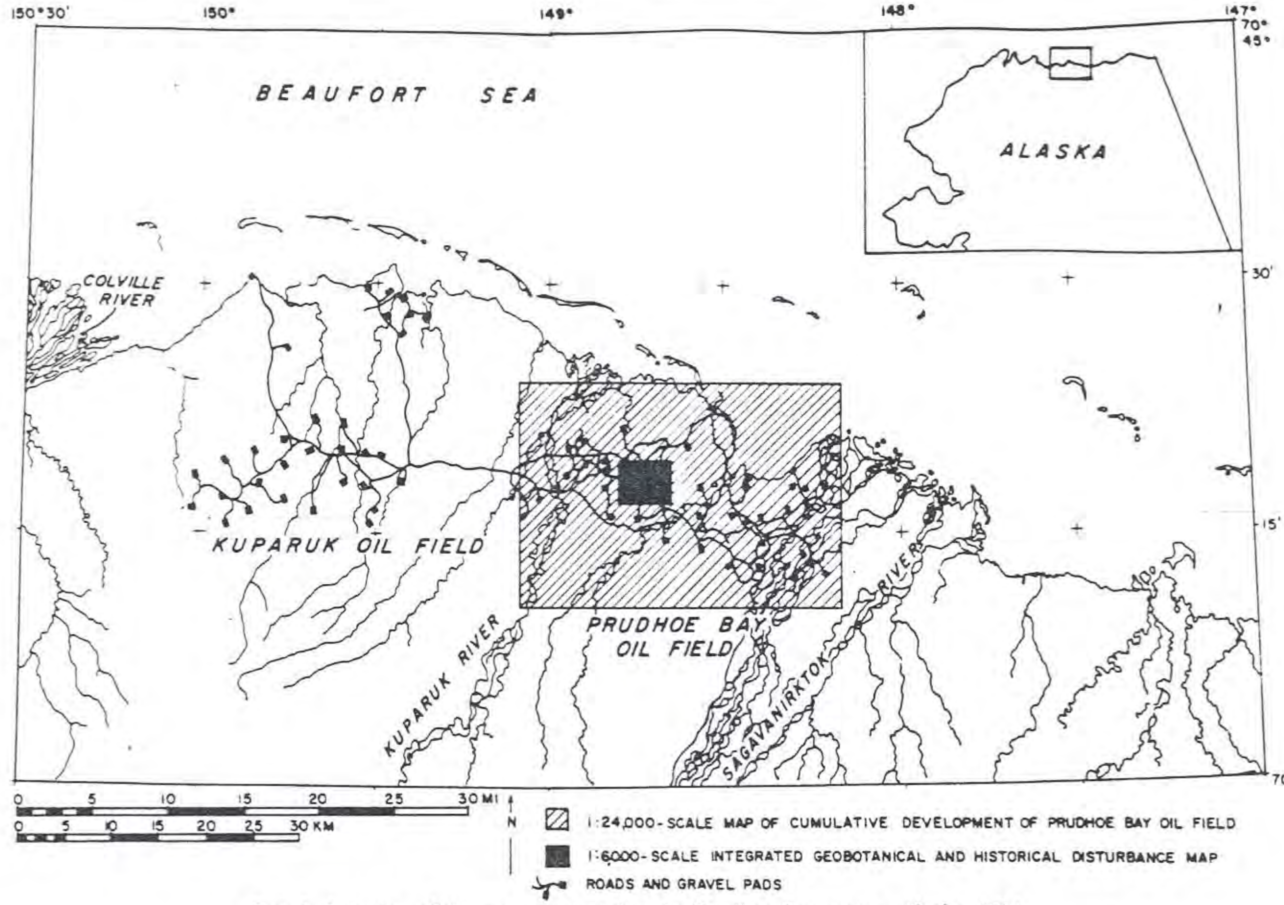

FIG. 1. *Location of the map areas within the Prudhoe Bay region, Alaska, USA.*

pipelines that connect oil-wells and other facilities within the field. Two airports and numerous other facilities support many contractors and the two principal developers of the field, Arco Oil & Gas Company and Sohio Alaska Petroleum Company. The Dalton Highway parallels the trans-Alaska pipeline system and links Prudhoe Bay to Fairbanks, providing road access to this area which was previously accessible only by 'bush plane' or boat.

Development of the field has occurred at an extraordinary pace, and similar development is likely to occur in nearby areas where oil has recently been discovered. This is of particular concern to those natives who rely on the wildlife of the Alaskan Arctic Coastal Plain for subsistence. Various government agencies oversee development in areas of valuable national wildlife resources. The Environmental Protection Agency and the US Army Corps of Engineers are chiefly responsible for environmental regulatory surveillance of such wetland regions and, through the US Fish and Wildlife Service, have encouraged research regarding regional cumulative impacts.

Suitability of the Prudhoe Bay Data-set for Cumulative Impact Analysis

The Prudhoe Bay region is particularly well suited for the application of GIS technology to the problem of cumulative impact. The North Slope Borough, which is the local government authority, has made a long-term commitment to develop a geographic information system that will include the 'historical' development of the land. They have purchased a state-of-the-art GIS facility and data-base developed by the Environmental Systems Research Institute, of Redlands, California. The data-base of the system includes extensive and detailed terrain mapping capability at three scales: 1:250,000, 1:63,360, and 1:6,000. Most of the North Slope Borough (an area of about 225,000 km^2, or slightly smaller than Great Britain), is mapped at the 1:250,000 scale for soils, vegetation, geology, and several other terrain features. Smaller areas of specific interest are mapped at the larger scales. The 1:6,000 scale is most appropriate for analysing many of the terrain impacts related to development.

The landscape of the region is well known because of a heritage of geobotanical research that began in 1972 with the selection of Prudhoe Bay as a study area for the International Biological Programme (IBP) (Webber & Ives, 1978; Walker *et al.*, 1980). The IBP research included an extensive mapping programme which has continued up to the present with funding from many additional sources—including the oil industry, Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers, US Geological Survey (USGS), US Fish and Wildlife Service, and the North Slope Borough.

The Prudhoe Bay region may be the only large industrial complex in the world where the complete history of development can be traced in detail with the help of an excellent aerial-photographic record (Table I). The record began with US military photo flights in 1948, 1949, and 1955, that

TABLE I

Aerial Photographs used for 'Historical' Disturbance Mapping.

Date	*Source**	*Scale*	*Type†*	*Quality*	*Any Disturbances Visible*
?/7/49	US Navy	1:24,000	BW	Excellent	No disturbance
28/7/68	Arco	1:12,000	TC	Very good to excellent	No disturbance
26/6/70	US Geological Survey	1:76,000	BW	Excellent	Roads, gravel pads**, large flooded areas
15/7/72	CRREL	1:3,000	BW	Excellent	All types of disturbance are easily visible
15/7/72	US-IBP Tundra Biome	1:24,000	BW	Excellent	Roads, gravel pads**, flooding, debris >50 ft (15.2 m), excavations
26/7/73	Sohio	1:6,000	BW	Variable, somewhat fuzzy to very sharp	All types of disturbance are visible
26/7/73	Sohio (US-IBP study)	1:18,000	BW	Good—not crisp	Roads, gravel pads**, trails, flooding, thermokarst‡, debris
27/6/74	NASA U2	1:120,000	CIR	Very good	Roads, gravel pads**, major flooding
17/7/77	NASA U2	1:120,000	CIR	Very good	Roads, major flooding, gravel pads** are visible but may be difficult to map
24/7/77	Prudhoe Bay Unit	1:18,000	BW	Good—not crisp in all areas	All types of disturbance visible but vehicle tracks; some long strips next to roads difficult to map
13/7/79	Prudhoe Bay Unit	1:18,000	TC	Excellent	All types of disturbance are visible, but linear features associated with roads (i.e. debris) difficult to map
17/7/80	Prudhoe Bay Unit	1:18,000	TC	Very good—not crisp in some areas	*Idem*
23/7/81	Prudhoe Bay Unit	1:18,000	TC	Very good—not crisp in some areas	*Idem*
?/7/82	NASA	1:60,000	CIR	Excellent	Roads, gravel pads**, major flooding, large areas of debris
4/7/83	Prudhoe Bay Unit	1:18,000	TC	Excellent	All types of disturbance are visible; debris associated with roads may be difficult to map

* Identities indicated in Introduction except for US-IBP = US International Biological Program, and NASA = National Aeronautic and Space Administration.
† Film types: TC = true colour; BW = black and white; CIR = colour infrared.
** Gravel pads are areas where gravel has been laid to depths of 2 m or more and compacted for the purpose of establishing a firm base for construction of oil drilling rigs, airstrips, and other oilfield facilities. These are constructed to prevent subsidence of the terrain in this marshy permafrost region.
‡ *See* footnote to this page. — Ed.

show the region prior to any development. In addition, aerial photographs have been taken of the Prudhoe Bay oilfield by the oil industry almost yearly during its development from 1968 to 1983. This series of photographs displays the rapid transformation of the Prudhoe Bay region from a remote undeveloped wilderness in 1949 to the most-developed area in the North American Arctic by 1983.

Objectives of the Study

This study had two major objectives. The first was to map the general sequence of development of the entire oilfield at a scale of 1:24,000 and to analyse the map data for trends regarding the rate of growth of the road system, gravel placement, and artificial impoundments. The second objective was to select an area of intense development for a more comprehensive analysis at the 1:6,000 scale. This included the production of a map showing geobotanical features as well as the progression of 'historical' anthropogenic and natural disturbances, anthropogenic disturbance being defined as any change to the landscape due to human activity.

This map, termed an Integrated Geobotanical and Historical Disturbance Map (IGHDM), permitted a detailed time-series analysis of areas covered by natural and anthropogenic disturbances. The anthropogenic disturbances included direct impacts—such as roads and gravel pads—and indirect effects, such as dust-covered areas, construction debris, flooding, and thermokarst.* The map was constructed on a geobotanical base that depicted the terrain prior to any anthropogenic disturbance, thus permitting an analysis of the distribution of geobotanical features affected by each type of disturbance. The methods of making

* Defined as 'topographic depressions resulting from thawing of ground-ice' (cf. page 158).—Ed.

an IGHDM were developed during this study. Only one map has been analysed at this point, but others are planned in order to compare development within different parts of the oilfield. Analysis of the map data gives insight regarding the patterns and rates of development, and also yields data on the amount that each geobotanical feature has been affected by the various types of impacts.

METHODS

Map of Cumulative Development of the Prudhoe Bay Oilfield (1:24,000 scale)

A map depicting the 'historical' development of the Prudhoe Bay oilfield was prepared directly on the 1970 USGS orthophoto topographic maps (1:24,000-scale series), namely sheets B-4NE, B-3NW, B-4SE, B-3SW, A-3NW, and A-3NE, of the Beechey Point Quadrangle. (This last is a 1:250,000-scale USGS map defined by the 147° and 150° longitude lines and the 70° and 71° latitude lines [*see* Fig. 1].) Table I gives details of the aerial photographs that were available for mapping the growth of development.

Each photograph was projected onto the orthophoto base-map with an Artograph DB300 projector, and the scale of the photographs was matched exactly to that of the base-map. All roads, airstrips, gravel pads (*see* third footnote to Table I, above), gravel mines, and areas of construction-related flooding, were transferred onto the base-map. The minimum size of a facility or flooded area mapped was 0.60 ha (1.5 acres). All construction appearing in a given year was coded with a colour and an alphabetic code. As photographs were not available for every year, the date given on the map for a constructed facility indicates the first year that it appeared on available photographs—rather than, necessarily, the actual year of its construction.

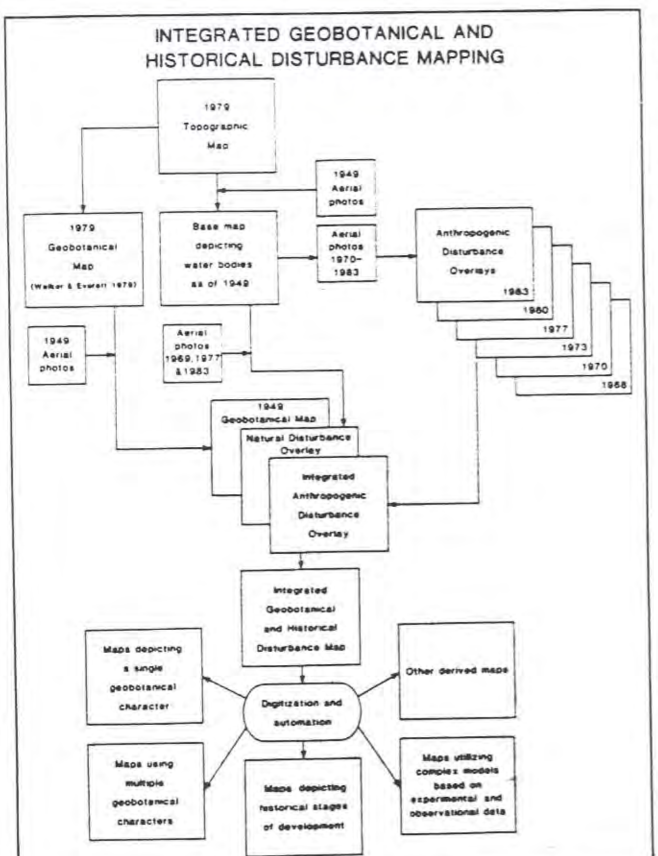

FIG. 2. *Steps involved in production of the 1:6,000-scale integrated geobotanical and historical disturbance map and its derivatives.*

The map was planimetred by hand to obtain areal measurements of gravel pads, airstrips, flooding, and gravel extraction areas, as well as linear measurements of the roads, for each year. Roads were classified as primary roads, secondary roads, Spine Road, and pipeline construction roads. The Spine Road is the major transportation corridor through the oilfield. To determine the total area covered by each type of road, the primary roads and the Spine Road were assumed to have basal widths of 15.2 m (50 ft), and other roads were assumed to be 13.4 m (44 ft) wide. Those are the standard road-widths used within the oilfield. Based on these assumptions, the total area covered by gravel was calculated for each year.

Integrated Geobotanical and 'Historical' Disturbance Map (1:6,000 scale)

The area selected for the IGHDM was Map 22 of a series of 47 topographic maps of the Prudhoe Bay Unit (Air Photo Tech 1979). These maps have a scale of 1:6,000 and a 1.52 m (5 ft) contour interval. Map 22 is of one of the more heavily developed areas within the field, and includes the location of the Sohio Base Operations Camp. The production of the IGHDM involved the prior production of three principal overlays: 1) geobotanical features, 2) natural disturbance, and 3) anthropogenic disturbances, which were integrated together to form the IGHDM (Fig. 2).

Geobotanical maps:—A base-map showing the pre-disturbance shapes of water-bodies was prepared from the 1949 photographs and the 1979 topographic map, and located accurately the positions of lakes and streams. Each photograph was projected onto a mylar (frosted plastic drafting film) surface by means of an Artograph DB300 projector. The geobotanical information included vegetation, soils, landforms, surface forms, and percentage of open water. Much of this information came from an earlier geobotanical map (Everett *et al.*, 1981) and was transferred directly onto the new map, the major exceptions being areas which were significantly changed since 1949. These latter areas were mapped from the 1949 and 1968 aerial photographs. The minimum 'polygon' diameter on this map is 3 mm (= 0.15 ha, 0.38 acre). (Map 'polygons' are areas of maps enclosed by line boundaries.) Each such 'polygon' was coded with a nine-parts code in fraction form as follows:

$$\frac{1^{\circ}\text{ vegetation, }2^{\circ}\text{ vegetation, }3^{\circ}\text{ vegetation; percentage of open water}}{\text{landform; }1^{\circ}\text{ surface form, }2^{\circ}\text{ surface form; }1^{\circ}\text{ soil, }2^{\circ}\text{ soil}}$$

In addition to primary (1°) cover types and features, secondary (2°) and tertiary (3°) features were mapped if they covered more than 30% of a given map-polygon. Table II contains the legends for the geobotanical characters. The vegetation legend is a modified version of Level C of the

TABLE II

Geobotanical Codes Used in the Prudhoe Bay Region, Alaska.
(Codes are modified from Walker *et al.* [1980, 1983].)

Code	Description
	VEGETATION
1	Water
2	Aquatic grass tundra
3	Aquatic sedge tundra
5	Wet sedge tundra
6	Wet graminoid tundra (saline areas)
9	Moist sedge, dwarf-shrub tundra
10	Moist tussock-sedge, dwarf-shrub tundra
13	Moist or dry dwarf-shrub, fructicose-lichen tundra (snow beds)
16	Moist shrubland (riparian areas)
19	Dry dwarf-shrub, crustose-lichen tundra
21	Dry dwarf-shrub, forb, grass tundra
22	Dry low-shrub, forb, grass tundra
24	Dry forb tundra
26	Dry grassland (dunes)
	PERCENTAGE OPEN WATER
1	0−5%
2	6−30%
3	31−60%
4	61−90%
5	91−100%
	LANDFORM
1	Distinct drained thaw-lake basin, or developing basins in residual surfaces of the coastal plain
2	Basin associated with hilly terrain often with thermokarst features
3	Residual surface (gently rolling thaw-lake plains)
4	Inter-thaw-lake area (gently rolling and flat thaw-lake plains; may include some very old, indistinct thaw-lake basins)
11	Pingo
12	Active braided floodplain
13	Stabilized braided floodplain
14	Meander floodplain
15	Stream drainage
16	Sand dunes
17	Beach
18	Spit
25	Island
51	Lake or pond
52	River or stream
53	Ocean
54	Artificial impoundment

Code	Description
	SURFACE FORM
1	High-centred polygons*, centre-trough relief greater than 0.5 m
2	High-centred polygons*, centre-trough relief less than 0.5 m
3	Low-centred polygons*, centre-rim relief greater than 0.5 m
4	Low-centred polygons, centre-rim relief less than 0.5 m
5	Mixed high- and low-centred polygons*
6	Frost scars
7	Strangmoor** and/or discontinuous low-centred polygon rims (generally well-defined features visible on 1:6,000-scale photographs)
8	Hummocky terrain associated with steep slopes
9	Pingo, with undefined or varied surface forms
10	Non-patterned ground or with pattern occupying less than 20% (includes some areas with aligned hummocks that are not visible on photographs)
11	Reticulate pattern
12	Active sand-dune
13	Active floodplain alluvium
14	Thermokarst pits (density greater than 4 pits per 1 cm circle on 1:6,000-scale photograph)
21	Water
	SOIL**
1	Pergelic Cryoborolls
2	Pergelic Cryaquolls or Cryosaprists
3	Complex of: *a)* Pergelic Cryohemists or Cryofibrists; *b)* Histic Pergelic Cryaquepts; *c)* Pergelic Cryaquepts
4	Association of: *a)* Pergelic Cryohemists or Cryofibrists or Histic Pergelic Cryaquepts; *b)* Pergelic Cryosaprists or Cryaquolls
5	Association of: *a)* Pergelic Cryaquolls or Cryosaprists; *b)* Pergelic Cryaquepts
6	Pergelic Cryorthents
7	Pergelic Cryopsamments
8	Pergelic Cryaquepts
9	Soil covered by a thin layer of wind-blown sand
10	No soil

* Ice-wedge polygons have two basic forms: high-centred and low-centred polygons. High-centred forms consist of an elevated 'centre', usually about 5–10 m wide surrounded by a 'trough' which delineates the locations of the ice wedges and separates one polygon from the adjacent ones. Low-centered forms consist of a central 'basin' surrounded by an elevated 'rim' and a 'trough'.
** United States Soil Survey nomenclature (7th approximation, Soil Survey Staff, 1975).

Walker (1983) hierarchical vegetation mapping classification system. This system is appropriate for mapping Alaskan tundra ecosystems with either photo-interpretation or Landsat methods. Percentages of water, surface forms, and landforms, were mapped according to the legends used in the North Slope Borough's geographic information system (GIS). Soils were mapped according to K.R. Everett's legend (in Walker *et al.*, 1983).

'Historical' natural disturbance overlay:—The purpose of the natural disturbance overlay is to quantify rates of natural change by mapping observable changes for the years 1968, 1977, and 1983. Examples of natural change are lake-boundary erosion, lake drainage, and stream-channel changes. Each set of photographs was projected onto the map surface, one photo at a time. Areas that had changed were coded with the year of the photograph on which the disturbance was noted and the vegetation type after disturbance.

'Historical' anthropogenic disturbance overlay:—Preparation of the anthropogenic disturbance overlay involved

TABLE III

Disturbance Codes for the Anthropogenic Disturbance Overlay.

Code	Disturbance Type
1	Gravel roads and pipeline construction roads
2	Peat roads
3	Gravel pads
4	Continuous flooding, more than 75% open water
5	Discontinuous flooding, less than 75% open water
6	Construction-induced thermokarst
7	Vehicle tracks—deeply rutted and/or with thermokarst
8	Vehicle tracks—not deeply rutted
9	Winter road
10	Gravel and construction debris (more than 75% cover)
11	Gravel and construction debris (less than 75% cover)
12	Heavy dust or dust-killed tundra
13	Excavations of river gravels or other gravel sources, road-cuts or construction excavations
14	Barren tundra caused by oil-spills, burns, blading, etc.
15	Barren tundra caused by previous flooding

compiling disturbances for the years 1970, 1972, 1973, 1977, 1979, and 1983, onto a single map-sheet. Separate overlays were prepared for each year from the respective photography in the manner employed for the natural disturbance overlay. Table III lists the anthropogenic disturbance codes. The final, anthropogenic disturbance overlay was prepared by registering the overlays for all six years and tracing all the resulting 'polygons' onto a seventh sheet.

Map integration:—The final step prior to automation of the maps was to integrate the geobotanical, natural disturbance, and anthropogenic disturbance, overlays onto a single sheet. This integration process is the same as that developed by the Enviromental Systems Research Institute for making integrated terrain-unit maps (Dangermond *et al.*, 1982). The three overlays were registered and all boundaries were traced onto a fourth sheet of mylar. A final copy of the uncoded IGHDM was drafted with ink, to provide a clean copy for digitization. This version of the IGHDM contained all the 'polygon' boundaries but no codes. The 'polygon' information was contained in an attribute file stored in the computer. There were 30 attributes for each 'polygon', which included geobotanical, natural disturbance, and anthropogenic disturbance, information. A sequential identification number was assigned to each 'polygon'. The sequence numbers were written on formatted coding sheets, and attribute codes for each 'polygon' were recorded by reference to the appropriate overlays. Coded data were recorded and verified on magnetic tape. Copies of the tape, code sheets, and drafted IGHDM, were sent to the North Slope Borough GIS for automation.

Digitization and automation:—The IGHDM was automated, using the ARC/INFO software of the Environmental Systems Research Institute. The ARC/INFO software consists of two primary components. The ARC component manages cartographic (locational) information and is a topologically structured coordinate file made up of 'graphic entities'. The INFO portion of the software is the data-base management system that handles tabular (non-locational)

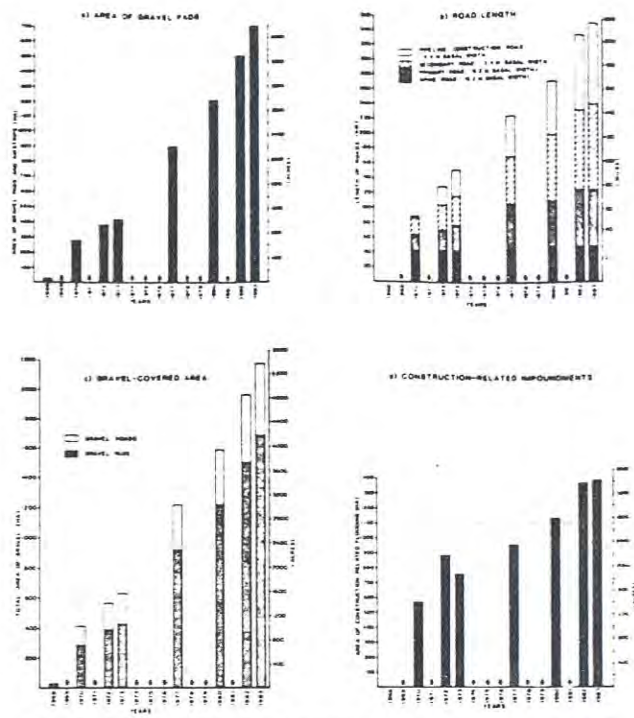

FIG. 3. *Area of anthropogenic disturbances within the Prudhoe Bay oilfield for years of available photo coverage. Starred (*) columns are years of missing or incomplete data. Regression equations for the respective data-sets are as follows: a) Y = 107.9X − 124.8 (r = .99), b) Y = 21.2X + 10.2 (r = .99), c) Y = 132.2X − 51.2 (r = .99), d) Y = 74.5X + 237.9 (r = .93).*

information associated with geographic features. A detailed description of the software is available by writing to the Environmental Systems Research Institute, Inc., 380 New York Street, Redlands, California 92373, USA.

The digital file of coded attribute data contained a unique identifier for each 'polygon' and a list of codes describing the geobotanical and disturbance information for each 'polygon'. This information was used to create an attribute file within ARC/INFO, and was related to the digital geographic data by the unique sequence-number identifier. Final quality review and editing of the data-base were accomplished by producing verification plots and by review of tabular summaries. The INFO software was used to calculate the total area for each attribute, and to generate tabular reports of areas in hectares and percentage of total area.

RESULTS

Cumulative Development of the Prudhoe Bay Oilfield

The map of cumulative development of the oilfield was drawn to a scale of approximately 1:24,000 and was not appropriate for reproduction here. Planimetry data from this map (Table IV and Fig. 3) document the growth of the oilfield—including areas covered by gravel pads, roads, gravel, and flooding.

Integrated Geobotanical and 'Historical' Disturbance Map (IGHDM)

The basic uncoded IGHDM (Fig. 4) was used to make all other derived maps, such as the maps of surface-water

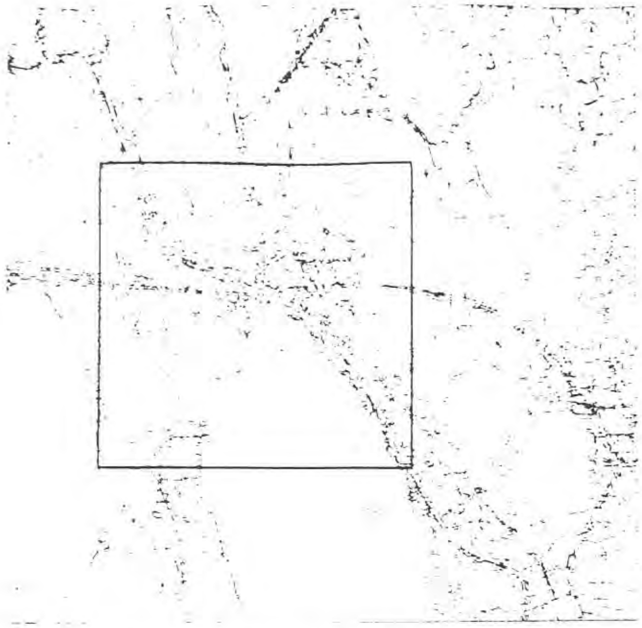

FIG. 4. *'Polygon' map for the integrated geobotanical and historical disturbance map. The map 'polygons' are small areas of the map enclosed by line boundaries. Large square is the portion of the map depicted in Fig. 7.*

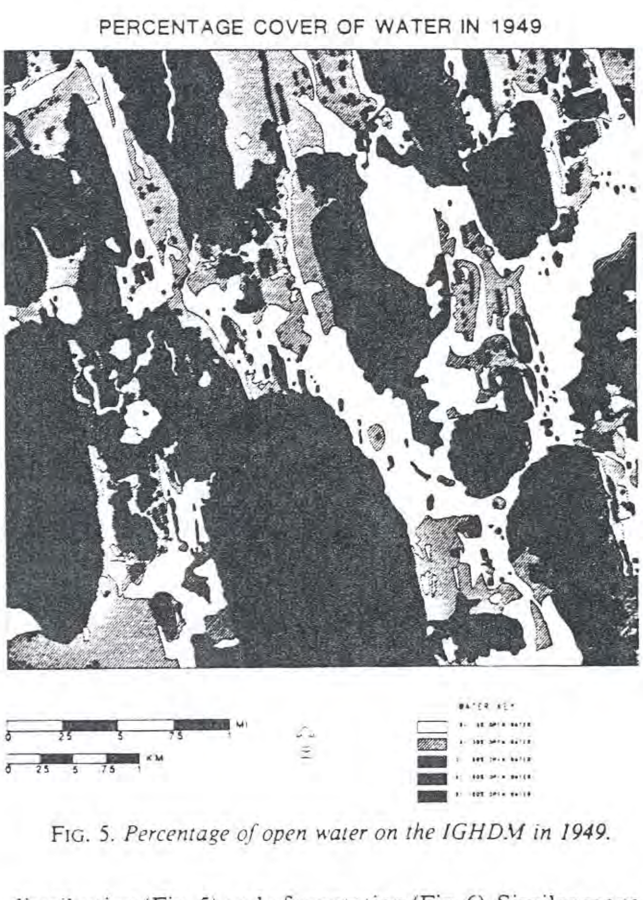

FIG. 5. *Percentage of open water on the IGHDM in 1949.*

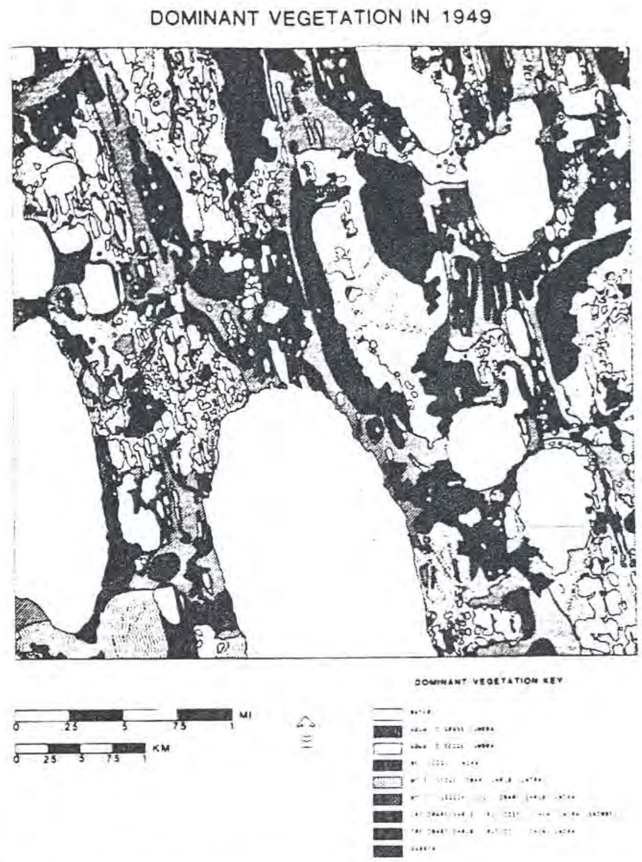

FIG. 6. *Dominant vegetation on the IGHDM in 1949.*

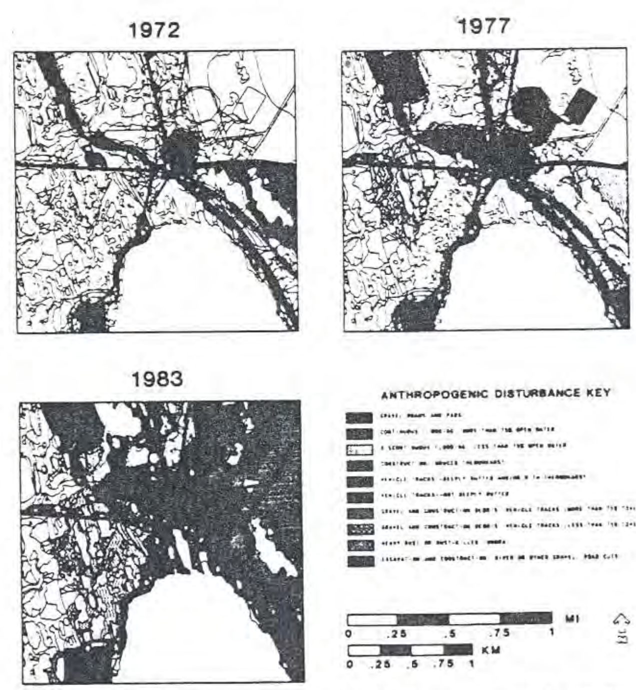

FIG. 7. *Anthropogenic disturbance for three years of the study on a portion of the IGHDM.* See *Fig. 4 for location of this map's area.*

distribution (Fig. 5) and of vegetation (Fig. 6). Similar maps were made for soils, landforms, and surface forms. The progression of anthropogenic change was also mapped (Fig. 7). The anthropogenic disturbances affect the vegetation types differentially, and are not distributed randomly across the landscape; instead they are concentrated within

TABLE IV

Additions to the Major Disturbance Types for the Years of Record in the Prudhoe Bay Oilfield.

Year	Gravel Pads Area (ha)	Spine Road Length (km)	Spine Road Area (ha)	Primary Roads Length (km)	Primary Roads Area (ha)	Secondary Roads Length (km)	Secondary Roads Area (ha)	Pipeline Construction Roads Length (km)	Pipeline Construction Roads Area (ha)	Total Roads Length (km)	Total Roads Area (ha)	Total Gravel-covered Area (ha)	Construction-related Flooding Area (ha)
1968	28.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.6	0.0
1970	253.0	40.8	62.3	24.1	36.7	22.1	29.6	2.8	3.8	89.8	132.4	385.4	568.9
1972	103.0	0.0	0.0	6.4	9.7	12.2	10.2	21.3	28.6	39.9	48.5	151.5	309.1
1973	36.1	0.0	0.0	5.9	9.0	5.4	7.2	11.6	15.6	22.9	31.8	67.9	−122.5
1974*	91.0	0.0	0.0	9.2	14.0	2.0	2.6	6.7	9.0	17.9	25.6	116.6	74.4
1975*	31.5	0.0	0.0	11.4	17.4	2.2	2.9	4.3	5.7	17.9	26.0	57.5	23.5
1976*	59.5	0.0	0.0	0.4	0.6	4.4	6.0	3.7	4.9	8.5	11.5	71.0	0.0
1977	312.5	3.3	5.1	3.6	5.5	14.8	19.9	4.0	5.3	25.7	35.8	348.3	105.3
1978*	57.8	0.0	0.0	0.0	0.0	11.1	14.9	6.4	8.6	17.5	23.5	81.3	0.0
1979*	115.0	2.8	4.3	0.4	0.7	2.4	3.3	4.3	5.8	9.9	14.1	129.1	56.1
1980	128.8	0.0	0.0	0.0	0.0	11.3	15.2	5.8	7.8	17.1	23.0	151.8	121.3
1981*	106.5	0.0	0.0	4.2	6.4	7.1	9.5	22.6	30.4	33.9	46.3	152.8	1.1
1982	183.7	0.0	0.0	9.5	14.4	11.8	15.8	8.5	11.5	29.8	41.7	225.4	232.9
1983	186.0	0.0	0.0	0.0	0.0	7.8	10.5	9.4	12.6	17.2	23.1	209.1	10.9
Total	1,693.0	46.9	71.7	75.1	114.4	114.6	147.6	111.4	149.6	348.0	483.3	2,176.3	1,381.0

* Years with incomplete or missing aerial photographic coverage.
Available information from unpublished draft map by T. Rothe.

TABLE V

Distribution of Disturbance Types Within the Various Vegetation Units on the IGHDM.

Disturbance types for 1983	Water ha	Water % Area	Aquatic Grass Tundra ha	Aquatic Grass Tundra % Area	Aquatic Sedge Tundra ha	Aquatic Sedge Tundra % Area	Wet Sedge Tundra ha	Wet Sedge Tundra % Area	Moist Sedge, Dwarf-shrub Tundra ha	Moist Sedge, Dwarf-shrub Tundra % Area	Moist Tussock-sedge, Dwarf-shrub Tundra ha	Moist Tussock-sedge, Dwarf-shrub Tundra % Area	Dry Dwarf-shrub Fruticose-lichen Tundra ha	Dry Dwarf-shrub Fruticose-lichen Tundra % Area	Dry Dwarf-shrub, Crustose-lichen Tundra ha	Dry Dwarf-shrub, Crustose-lichen Tundra % Area	Barren ha	Barren % Area	Total ha	Total % Area
Gravel roads	3.77	0.18	0.16	0.01	15.14	0.73	19.55	0.94	14.15	0.67	0	0	0	0	0.73	0.03	0	0	53.50	2.56
Gravel pads	16.16	0.77	0.62	0.03	23.01	1.10	67.43	3.23	57.14	2.74	0.03	0.00	0	0	5.04	0.24	0	0	169.43	8.11
Continuous flooding (>75% open water)	0.13	0.01	0.83	0.04	163.91	7.85	104.89	5.02	18.54	0.89	0.18	0.01	0	0	1.20	0.06	0	0	289.68	13.88
Discontinuous flooding (<75% open water)	0.01	0.00	0.11	0.00	67.08	3.22	43.69	2.09	10.34	0.48	0	0	0	0	0	0	0	0	121.23	5.79
Construction-induced thermokarst	0.14	0.01	0	0	3.26	0.16	29.77	1.43	24.02	1.16	0	0	0	0	2.10	0.10	0	0	59.29	2.86
Vehicle tracks, deeply rutted	0	0	0	0	0.25	0.01	1.42	0.07	1.00	0.04	0	0	0	0	0	0	0	0	2.67	0.12
Vehicle tracks, not deeply rutted	0	0	0	0	2.12	0.10	0.25	0.01	1.21	0.06	0	0	0	0	0	0	0	0	3.58	0.17
Gravel and debris (>75% cover)	0.22	0.01	0	0	2.66	0.13	7.28	0.35	6.52	0.30	0.50	0.02	0	0	0	0	0	0	17.18	0.81
Gravel and debris (<75% cover)	0	0	0	0	5.23	0.26	6.73	0.32	9.08	0.44	0	0	0	0	0	0	0	0	21.04	1.02
Heavy dust or dust-killed tundra	0	0	0	0	1.82	0.09	1.31	0.06	1.18	0.05	0	0	0	0	0	0	0	0	4.31	0.20
Previously-flooded areas with dead vegetation	0	0	0	0	2.91	0.14	1.53	0.07	0	0	0	0	0	0	0	0	0	0	4.44	0.21
No mapped disturbance	770.59	36.90	29.53	1.42	183.23	8.78	212.45	10.17	133.89	6.42	4.35	0.21	0.34	0.02	6.53	0.31	0.78	0.04	1,341.69	64.27
TOTAL	791.02	37.88	31.25	1.50	470.62	22.57	496.30	23.76	277.07	13.25	5.06	0.24	0.34	0.02	15.60	0.74	0.78	0.04	2,088.04	100.00

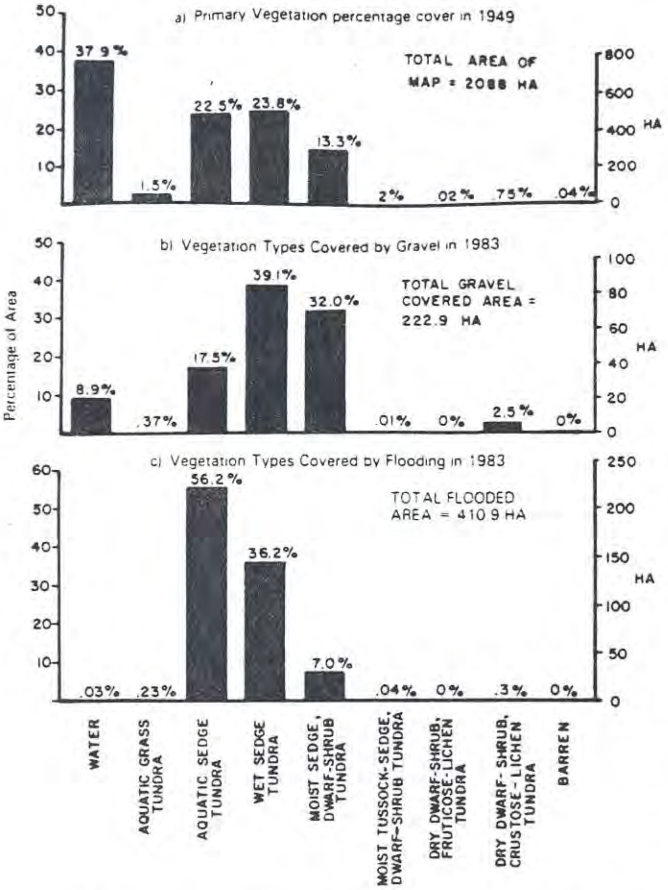

FIG. 8. a) *Percentage distribution of primary vegetation types as of 1949 on the IGHDM (Fig. 4);* b) *distribution of vegetation types impacted as of 1983 by gravel placement, and* c) *by impoundments. Note: if the water areas are subtracted from the total area available for gravel placement, the percentages in* a) *are as follows: water, 0%; aquatic grass tundra, 2.4%; aquatic sedge tundra, 36.2%; wet sedge tundra, 38.3%; moist sedge, dwarf-shrub tundra, 21.4%; moist tussock-sedge, dwarf-shrub tundra, 0.3%; dry dwarf-shrub, fruticose-lichen tundra, 0.03%; dry dwarf-shrub, crustose-lichen tundra, 1.2%; barren, 0.06%.*

particular vegetation-types (Fig. 8). For example, 'moist sedge, dwarf-shrub tundra' occupied 13.3% of the undisturbed landscape in 1949. Even if the water areas are subtracted as areas unavailable for gravel replacement (*see* caption of Fig. 8), only 21.4% of the remaining area is of this 'moist sedge, dwarf-shrub tundra'. However, 32% of the area covered by gravel roads and pads occurs on this type. A similar pattern exists for 'dry dwarf-shrub, crustose-lichen tundra'. The distribution of gravel and impoundments on the various vegetation-types is significantly different from the distribution of undisturbed vegetation ($\chi^2 = 43.33$, $p < .01$ for gravel; $\chi^2 = 97.85$, $p < .01$ for flooding). The chi-square values were adjusted to exclude water, as roads and pads are generally built to avoid lakes. Also, flooding as defined cannot occur in an area that has already been coded as water on the geobotanical overlay. Table V gives a summary of the impact of all mapped anthropogenic disturbances as they affect the primary vegetation-types. Natural disturbances are clearly minor when compared with areas affected by anthropogenic disturbances (Tables V and VI).

TABLE VI

Summary of Natural Disturbances for the Period 1968 to 1983 on the IGHDM.

Year	Disturbance type	Cumulative area disturbed since 1949 ha	%
1968	Lake erosion	4.43	0.21
1977	Lake erosion	6.47	0.31
	Drained pond	0.13	0.01
1983	Lake erosion	7.91	0.38
	Drained pond	0.13	0.01

DISCUSSION

The 1:24,000-scale map contains data regarding the whole field, whereas the IGHDM (Fig. 4) covers a smaller area but yields more detailed information regarding the effects of indirect impacts, such as roadside disturbances and thermokarst, which could not be mapped at the 1:24,000 scale. Also, the effects on the geobotany which are important for wildlife considerations can only be determined from the IGHDM.

The Entire Oilfield

Regression analysis of the yearly additions for four major disturbance types—length of roads, area of gravel pads, total gravel-covered areas, and areas of flooding—shows that there has been a linear increase in all these factors during the first 15 years of development (Fig. 3). Information such as this is beneficial for determining the accumulated impacts for the oilfield as a whole, or for small subareas such as individual drill-sites. Comparison with other oilfields can help us to determine whether there are general patterns of development that are repeated in other large oilfields. For example, the rate of growth of the road network within the Prudhoe Bay oilfield is very similar to that in the nearby Kuparuk oilfield (Fig. 9). This is somewhat surprising considering the number of variables that could conceivably affect those rates.

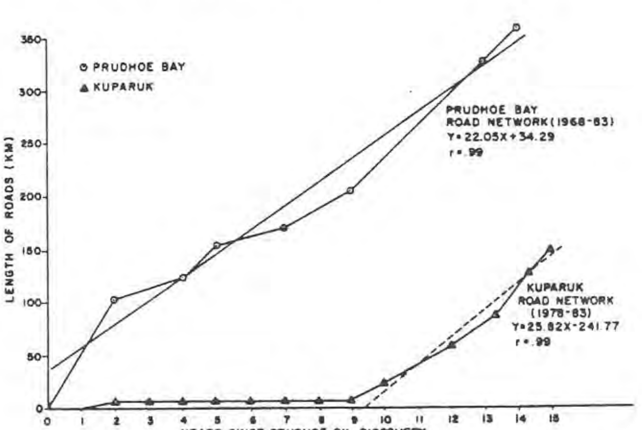

FIG. 9. *Comparison of growth of the Prudhoe Bay and Kuparuk oilfield road networks. Top straight fine line is the regression for the Prudhoe Bay road network since the discovery of oil in 1968. Bottom dashed regression line shows the growth of the Kuparuk road network since 1978 when development began to expand. Kuparuk data are unpublished data of the Authors.*

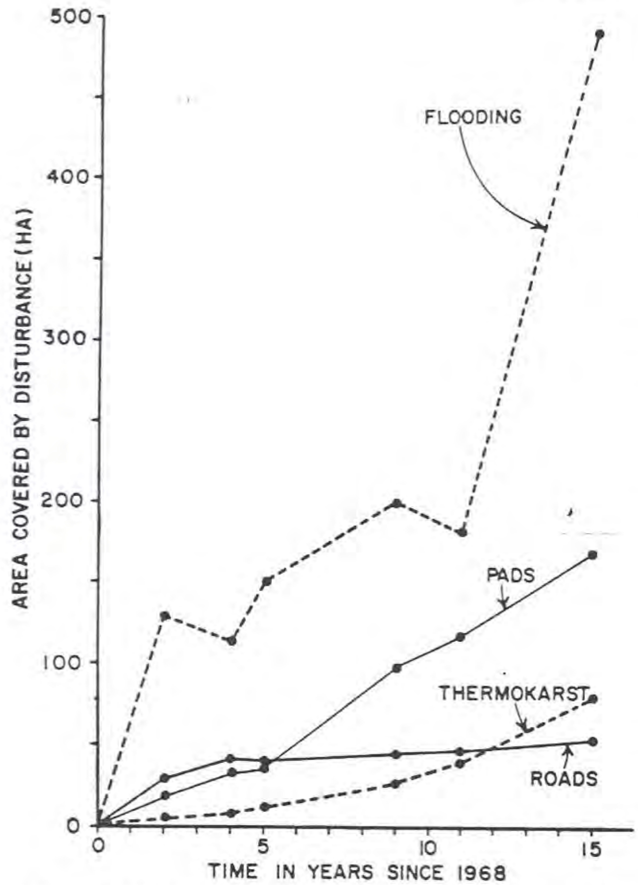

FIG. 10. *The progression of the direct impacts of gravel road and pad placement (continuous lines) and of indirect and induced impacts (dashed lines) for the area of the IGHDM. Data are for the small area blacked in Fig. 1 which is about 22 km² in extent.*

Heavily-developed Portion of the Oilfield (1: 6,000-scale map)

Within the area of the large-scale map we examined the 15-years' history for two direct impacts, roads and total gravel-covered area, and two indirect impacts, flooding and thermokarst (Fig. 10). The area covered by roads levelled off within five years, while the area covered by gravel showed a linear increase throughout the period. This indicates that all the roads which were found necessary for full development of the area were built fairly soon, but that gravel pads continued to increase in size and number as development proceeded. In contrast, roads in the entire oilfield increased linearly for a much longer period of time (*see* Fig. 3), due to expansion of the oilfield perimeter and increased road access within the field.

The total area affected by indirect impacts, particularly flooding, now far exceeds that of direct impacts (Fig. 10). This is partially due to a dramatic rise in flooding in 1983. Whether or not this rise was due to the somewhat earlier-in-the-year photographs taken in 1983 (early July in 1983 as opposed to mid-July in other years), which would be likely to show larger areas flooded from the spring runoff, is unknown to us. Also, 1983 was a generally wetter year with a later-than-usual breakup. However, the rest of the oilfield as a whole did not show a similar dramatic increase in flooding in 1983, even though the photographs for the whole field were also from early July. The sudden rise could be unique to this particular area—possibly the result of a few new areas of gravel placement that resulted in large new areas of flooding.

Also unknown is whether this pattern has been repeated in other areas of the flat coastal plain with very high densities of roads and gravel pads. IGHDM mapping in other similar areas will help to determine the extent and causes of this phenomenon. The Prudhoe Bay field is located in an extraordinarily flat and wet portion of the Alaskan Arctic Coastal Plain. Oilfields developed in somewhat more hilly portions of the coastal plain are not likely to have such severe flooding problems.

The rate of increase of the area covered by thermokarst appears to be accelerating with time (Fig. 10). Thermokarst is defined as topographic depressions resulting from thawing of ground-ice (Webber & Ives, 1978; Washburn, 1980). We might expect that the area of anthropogenic thermokarst would increase exponentially as the number of roads and the thermal effects of dust, impoundments, and other oilfield activities, combined synergistically to melt the subsurface ice.

The IGHDM is also useful for determining how specific types of impact are distributed among the various geobotanical units (Fig. 8). For example, the relatively dry vegetation-types are being selected for road and gravel-pad construction because they offer firmer substrates and present less of a flooding problem than do moister ones. In contrast, flooding is generally restricted to wetter areas, for example in aquatic sedge tundra or wet sedge tundra.

The amount and type of habitat that is impacted and lost can be determined from the IGHDM and compared with the original habitat composition for species with specific habitat preferences, provided that the habitat classification can be related to the geobotanical classification. For example, Troy *et al.* (1982) derived a waterbird habitat classification from the geobotanical classification (Table VII); it was based on combinations of vegetation, surface forms, and demonstrated habitat preferences of the common waterfowl and shorebirds. The most common shorebird species preferred moist tundra classes, which are disproportionately covered by gravel (Fig. 8). Gravel cover can be considered a complete habitat loss but some impacts (e.g. flooding) are similar to natural features and may be utilized

TABLE VII

Waterbird Habitat Types Used by Troy et al. *(1982).*

Habitat
Moist tundra/high-centred polygon
Moist tundra/frost-scar
Moist tundra/low relief high-centred polygons
Wet tundra/low relief low-centred polygons
Wet tundra/strangmoor
Wet tundra/non-patterned ground
Aquatic, moist tundra/strangmoor
Aquatic sedge/strangmoor
Water/pond with emergent plants
Water/pond without emergent plants
Impoundments (flooded)

by some species. The full effect of the various impacts on bird-use is beyond the scope of this paper, other than emphasizing the point that maps of this nature can be a major tool for assessing cumulative impacts on wildlife habitat as they show losses of, and changes to, habitats which may be distinguished by the geobotanical classification.

The value of the geobotanical mapping method for habitat evaluations is currently being studied in the Prudhoe Bay region by the Environmental Protection Agency and the US Fish and Wildlife Service. These studies will lead to a comprehensive method for evaluating and mitigating oil development impacts on the coastal tundra of northern Alaska, and, it is hoped, comparable areas elsewhere.

Conclusions

This report demonstrates some of the flexibility of the automated geobotanical map data-base. The data-base has obvious potential for day-to-day planning and record-keeping within the oilfield. It also has many scientific applications. Bird habitat, ground-ice, plant distribution patterns, and many other features, can all be related to the basic data-set. The data-set can also be readily expanded to include other factors such as geology and habitat attributes. It must be emphasized, however, that derived maps and models produced from the base-data are only as good as the understanding of the processes involved. They will remain 'blunt tools' for land-use planning until there are thorough studies of tundra response to disturbance that are specifically related to the various geobotanical units.

Maps can only depict relatively major physical changes to the terrain. They cannot depict total cumulative impact, which includes other factors such as the actual effects on wildlife populations (although the effects on wildlife habitat can be displayed on a map). They do, however, depict the accumulated sum of development and the associated visual impacts. In this regard it should be recognized that, in spite of the clear need to examine cumulative impact in the face of massive development occurring on the North Slope, there exists very little theory or methodology regarding cumulative impact.

The method presented here for depicting complex 'historical' change is a necessary first step towards a comprehensive methodology for evaluating cumulative impact. Although there is uncertainty as to whether site-specific 'histories' and dynamics can be extrapolated to other areas, 'historical' studies can point out the flaws of past practices and help in the development of more effective regulatory methods.

The automation of the geobotany and historical development of the Prudhoe Bay region allows for the quick analysis of the historical changes, and permits the display of the data in a wide variety of map formats. Within this study there are several specific conclusions regarding the historical development of the Prudhoe Bay oilfield:

1. The growth of the Prudhoe Bay road network increased in a linear manner during the period 1968–83. The area covered by gravel pads and flooding also increased linearly.

2. The Kuparuk oilfield road network is showing a growth-rate similar to that in the Prudhoe Bay field.

3. The growth of the road network within a small, heavily developed portion of the field levelled-off within five years, while the area covered by gravel continued to expand linearly for the length of the study.

4. The total area covered by the indirect impacts of flooding and thermokarst was more than double that of the primary impacts. The rate of growth of the area covered by flooding fluctuated from year to year, and was partially controlled by the date of the photograph and yearly precipitation. There was, however, clearly a steady increase in flooding during the period of study. There appears to be an accelerating rate of increase of thermokarst.

5. The anthropogenic impacts within this area from 1968 to 1983 were two orders of magnitude greater than the natural disturbances within the same area from 1949 to 1983 (746 *versus* 8 ha).

6. Disturbance types affect the geobotanical units differentially. On flat and wet thaw-lake plains, moist and dry sites tend to be selected for gravel placement, whereas artificial impoundments occur primarily in the naturally wet or aquatic tundra types. Both of these disturbance distribution patterns have important implications regarding waterfowl and shorebird habitat.

7. A robust link between the cumulative effects of oilfield development and the effects on wildlife habitat still requires much additional research. The creation of habitat models for a wide variety of species, and their integration with appropriate geobotanical map data, will require close cooperation between landscape-oriented ecologists and wildlife specialists.

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Summary

A comprehensive approach to the problem of examining impacts on tundra landscapes is presented, using the Prudhoe Bay oilfield as a model. Development of the oilfield is

documented, utilizing a series of 'historical' disturbance maps for the period 1949–83. Cumulative development of the entire field was mapped at a scale of 1:24,000, and an intensely developed portion of the field was mapped at 1:6,000, using an integrated geobotanical and historical disturbance map (IGHDM). The IGHDM data were automated, and a series of maps was made which depict a variety of information—including geobotany of the area as of 1949, and the historical sequence of development from 1968 to 1983.

The region is ideal for the application of automated GIS technology for studying cumulative impacts because of (1) a commitment by the local government to build a GIS, (2) an existing excellent geobotanical data-base, and (3) an aerial photographic record of the complete history of development from the wilderness state to the present-day industrial complex.

The map data show numerous aspects of the growth of the oilfield, including rates of growth of the road network, total gravel-covered area, and areas covered by flooded impoundments. Within the heavily-developed region (1:6,000-scale map), 0.39% of the area was affected by natural disturbances from 1949 to 1983, whereas 35.74% of the area was affected by anthropogenic physical disturbances from 1968 to 1983. The area covered by indirect impacts of flooding and thermokarst shows an exponential rate of growth, and the total area covered by these indirect impacts is more than double the area affected by the direct impacts of roads and gravel pads. The exponential increase in thermokarst is an example of a synergistically increasing impact within the oilfield. Disturbances are not distributed randomly within the various geobotanical units; they tend to occur within specific moisture-regime categories depending on the type of disturbance.

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