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Landsat MSS-derived land-cover map of northern Alaska: extrapolation methods and a comparison with photo-interpreted and AVHRR-derived maps

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Abstract. Vegetation maps of Arctic areas are needed for a variety of tundra ecosystem and climate change studies and for extrapolating from relatively small, well-known sites to broader regions. We made a preliminary land-cover map of northern Alaska by extrapolating a Landsat Multi-Spectral Scanner (MSS)-derived classification of the Kuparuk River Region (KRR) to all of northern Alaska. We used a 26-scene mosaic that was previously made by the EROS Data Center, and a K-means unsupervised classification algorithm to produce eight broad land-cover categories. The northern Alaska-MSS map (NA-MSS) has the following land-cover categories and respective percentage coverage within the 200 000 km^2 Arctic Slope: *Dry Prostrate-shrub Tundra and Barrens*, 8%; *Moist Graminoid, Prostrate-shrub Tundra*, 22%; *Moist Tussock-graminoid, Dwarf-shrub Tundra*, 4%; *Moist Dwarf-shrub, Tussock-graminoid, Tundra*, 28%; *Moist Low-shrub Tundra and other Shrublands*, 19%; *Wet Graminoid Tundra*, 9%; *Water*, 6%; *Clouds and ice*, $<1\%$; *Shadows*, 4%. Ancillary data were used to improve the classification for a region of sandy tundra not encountered in the KRR and to separate shadows in the mountains from water and wetlands elsewhere.

The NA-MSS map helps to define the distribution of a recently described moist nonacidic (calcareous) tundra and areas of shrublands that are of broad interest to the tundra- and climate-change modelling communities. A boundary separating moist acidic tundra from moist nonacidic tundra stretches across all of northern Alaska (about 850 km). Shrub-dominated tundra is prevalent in the southern and western (warmer, wetter) portions of the map. We created difference maps for comparing the northern Alaska-MSS (NA-MSS) map to the Major Ecosystems of Alaska (MEA) map and a map derived from a time series of Advanced Very High Resolution Radiometer images (NA-AVHRR). Compared to the other maps, the NA-MSS map provides more detailed information for moist tundra areas and shows more shrub-dominated vegetation with different spatial distributions than the other two maps. An accuracy assessment of the map will be performed in 1999.

1. Introduction

1.1. *Need for a new map*

We made a preliminary land-cover map of northern Alaska from a mosaic of Landsat Multi-Spectral Scanner (NA-MSS map) data in response to the needs of

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the US Arctic System Science (ARCSS) Arctic Transitions in the Land—Atmosphere System (ATLAS) project. The project is characterizing and modelling the fluxes of trace-gases, water and energy for the arctic system and how these interact with the larger global system. There is a growing consensus that arctic regions will experience marked changes in precipitation, temperature and the timing of seasonal climate events (Rowntree 1997). During an earlier phase of the ATLAS project entitled the Flux Study (Weller *et al.* 1995), researchers developed a series of models to describe relevant ecosystem processes within the Kuparuk River Region (KRR), Alaska (figure 1). A land-cover map of the 9000 km^2 Kuparuk River watershed and surrounding area was produced from Landsat MSS data (KRR-MSS map; Muller *et al.* 1998). This map was a key element for a variety of geophysical and modelling studies within the basin (Nelson *et al.* 1997, Bockheim *et al.* 1998, Stow *et al.* 1998, Walker *et al.* 1998, Nelson *et al.* in press, Oechel *et al.* in press, Reeburgh *et al.* in press). Scaling the results of the Flux Study from the Kuparuk River basin to northern Alaska, and ultimately to the entire circumpolar arctic region, will require vegetation maps of increasingly larger areas.

1.2. *The Arctic slope and available maps*

Our study focuses on the Arctic Slope of Alaska. This remote 200 000 km^2 area is about the size of South Dakota or England and Scotland combined. It encompasses the drainage basins north of the Brooks Range that empty into the Arctic Ocean, including the Kongakut River west to Point Lisburne (figure 1). We compared our map with two other maps of Alaska that include the Arctic Slope: (1) the Major Ecosystems of Alaska (MEA) map (Joint Federal State Land Use Planning Commission 1973) and (2) an Advanced Very High Resolution Radiometer (AVHRR) interpretation (Markon *et al.* 1995).

The MEA map is currently the primary reference for the distribution of vegetation in northern Alaska (figure 2(*a*)). This map is based on an earlier map made by John Spetzman, who first mapped the diversity of vegetation in northern Alaska (Spetzman 1959, 1963). It portrays four broad categories of tundra (moist tundra, wet tundra, alpine tundra and high brush). The map gives a good impression of vegetation transitions due to the major physiographic provinces, the Arctic Coastal Plain, Arctic Foothills and Brooks Range, but it cannot be used for relating vegetation to finer scale landscape features nor to climatic gradients.

A more recent interpretation of the vegetation of northern Alaska is the Vegetation Greenness Classes image map of Alaska (Markon *et al.* 1995). The map has 77 land-cover classes derived from 1991 NOAA-11 AVHRR data with a 1 km × 1 km pixel size. The classes are based on a time-series of vegetation greenness, as measured by the Normalized Difference Vegetation Index (NDVI; Goward *et al.* 1991). The NDVI data were composited into eleven half-month periods, between 1 May 1991 and 15 October 1991. In the published 1994 version of the map, the classes are given general vegetation names (e.g. *Nonvegetated*, *Shrubland (tall)*, *Shrubland—(dwarf)*, *Dry or moist herbaceous*, *Water*, etc.). A later revision of the map contains 22 classes, 12 of which occur in northern Alaska, with more detailed names (Fleming 1997, unpublished). Figure 2(*b*) is based on a 54-class version of the Greenness-Classes map, of which 33 classes occurred in the northern Alaska tundra region. To create the land-cover categories of the northern Alaska-AVHRR (NA-AVHRR) map, we regrouped the 33 tundra classes into seven classes that corresponded as closely as possible to the units on the KRR-MSS map, based

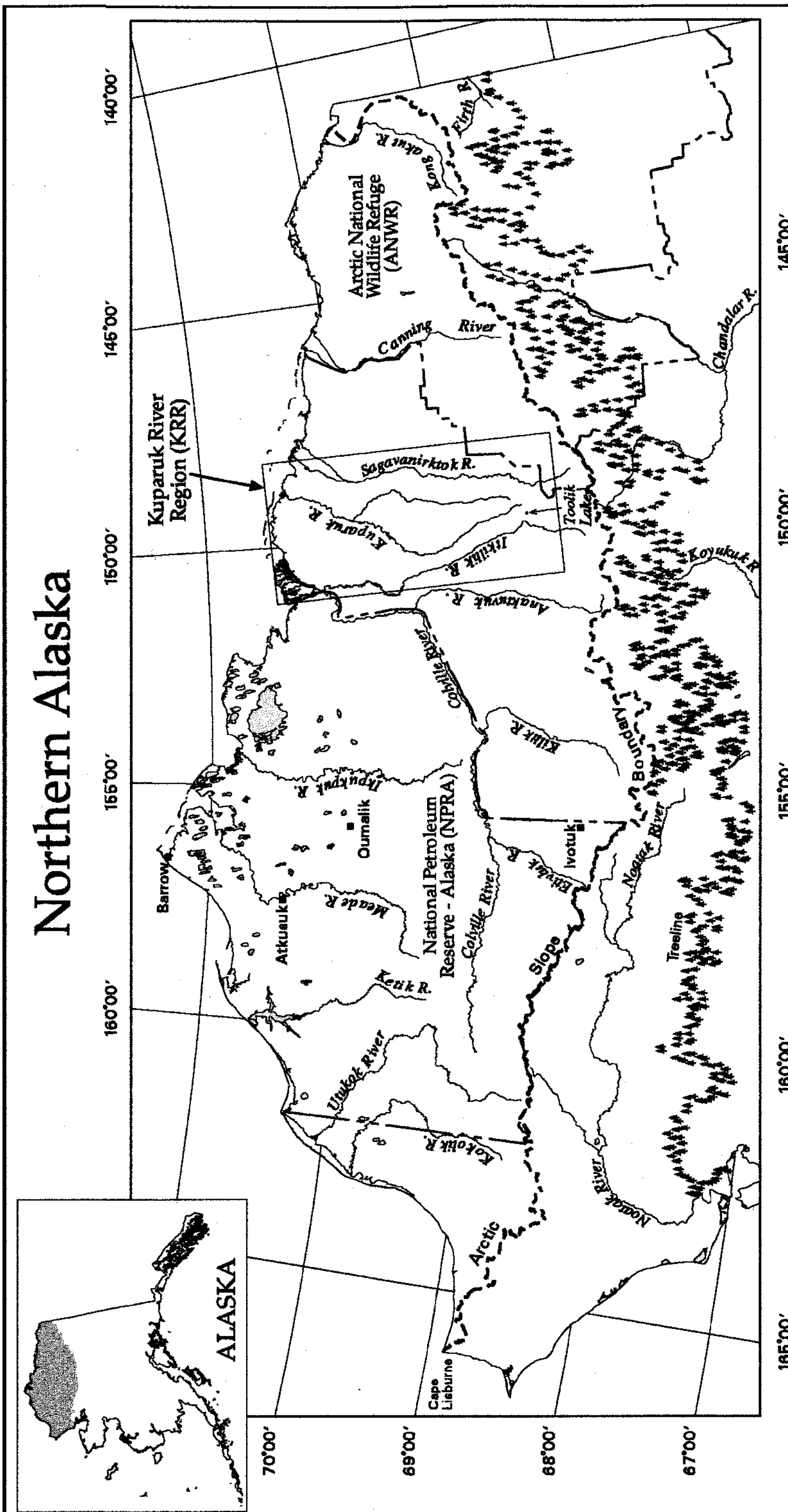
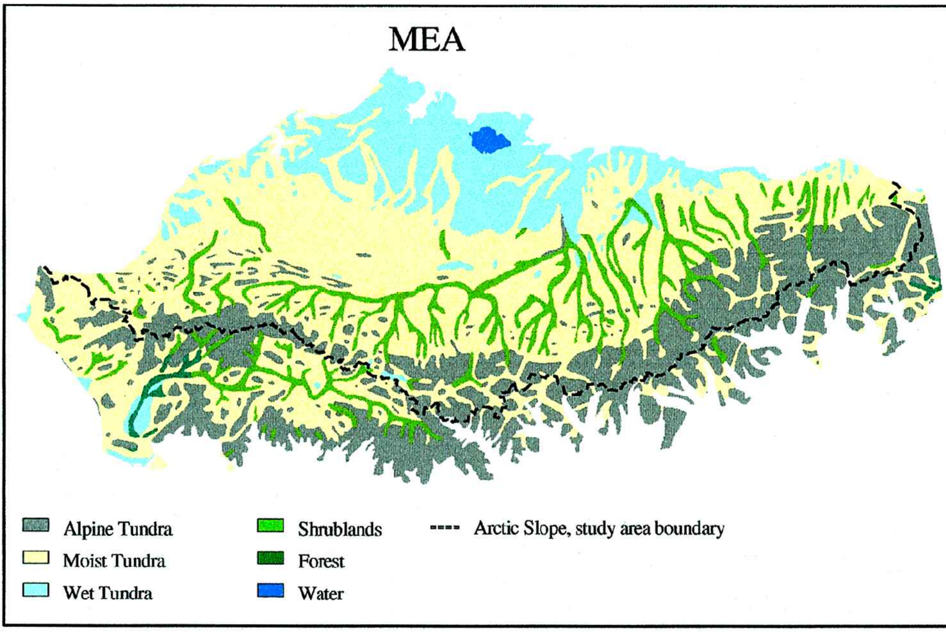
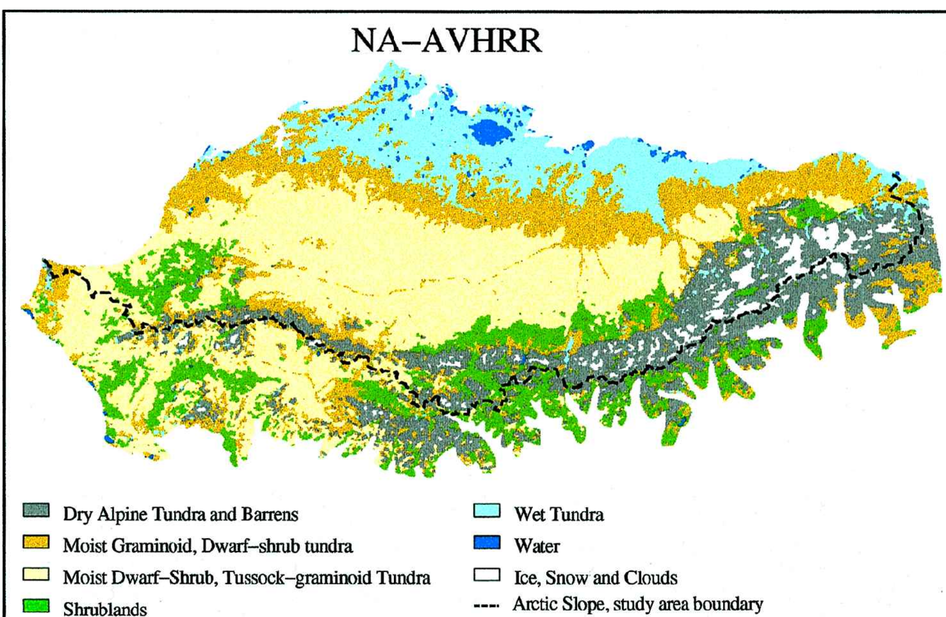


Figure 1. Northern Alaska and location of places mentioned in the text.



(*a*)



(*b*)

Figure 2. (*a*) Major Ecosystems of Alaska (MEA) map, (*b*) Northern Alaska-AVHRR (NA-AVHRR) map. Southern boundary corresponds to the arctic treeline on the MEA (Joint Federal-State Land-Use Planning Commission 1973). The NA-AVHRR map is derived from Markon *et al*. (1995)

primarily on information from the literature and curves provided by the EROS Alaska Data Center (ADC) that portrayed the seasonal trend of NDVI for each class. The NA-AVHRR map has several advantages over the MEA map. In particular, it eliminates the false impression that many-km-broad shrublands occur along the major rivers. It also provides more detail within the moist tundra category and it portrays some broad areas of shrubby vegetation outside of the river systems that are coincident with known areas of shrub tundra.

Other maps of portions of northern Alaska were used extensively as reference information for the NA-MSS map, including maps of the Prudhoe Bay vicinity (Walker 1985, Walker and Acevedo 1987), the Arctic National Wildlife Refuge (Jorgenson *et al*. 1994, Walker *et al*. 1982), the National Petroleum Reserve—Alaska (Morrissey and Ennis 1981, Pacific Meridian Resources 1996), and the Toolik Lake region (Walker and Walker 1996).

2. Methods

2.1. *Data characteristics*

2.1.1. *KRR-MSS dataset and land-cover map*

The KRR-MSS map was derived from an earlier mosaic of 13 Landsat MSS scenes which covered only the eastern half of northern Alaska (the Central Arctic Management Area and the Arctic National Wildlife Refuge or CAMA/ANWR mosaic, table 1). The mosaic was prepared by the US Geological Survey (USGS), EROS Data Center in Sioux Falls, South Dakota, using the Large Area Mosaic Software (LAMS), which is part of the LAS image processing system. The scenes were radiometrically corrected to a reference scene (starred scene in table 1), meaning that the digital numbers of all the other scenes in the mosaic were modified to correspond with the reference scene in terms of brightness values for comparable image bands. The result was a seamless mosaic that had the appearance of a single image. The KRR-MSS land-cover map (not shown; Muller *et al*. 1998) contained eight land-cover categories: (1) *Barrens*, (2) *Moist Nonacidic Tundra (MNT)*, (3) *Moist Acidic Tundra (MAT)*, (4) *Shrublands*, (5) *Wet Tundra*, (6) *Water*, (7) *Clouds and Ice*, and (8) *Shadows*. An accuracy assessment of the map indicated about 87% overall accuracy (Muller *et al*. 1998). The high accuracy was due largely to the simple legend and extensive previous field and mapping experience in the region.

2.1.2. *NA-MSS dataset*

The northern Alaska-MSS (NA-MSS) dataset was derived from CAMA/ANWR mosaic plus a 13-scene mosaic prepared for the National Petroleum Reserve—Alaska (NPR-A; table 1). This mosaic was also prepared by the USGS, EROS Data Center. Both the eastern and western images consisted of three bands of MSS data (green, red and near-infrared) resampled from a nominal 80-m pixel size to a 50-m pixel size using cubic convolution interpolation. However, in order to create a reasonably sized dataset, when the eastern and western mosaics were joined the pixel size was resampled to 100 m, and the green band was eliminated. Individual Landsat MSS images that made-up the NA-MSS dataset were acquired during the snow-free growing seasons of 14 August 1976 to 13 September 1986. Most (22 of 26) of the acquisition dates were during the period of peak high vegetation greenness, from mid-July to late-August (table 1). Visual analysis of the NA-MSS image revealed some striping within the image. This could not be corrected using standard destriping algorithms because the image had already been geo-referenced. However, the

Table 1. Landsat-MSS scenes used in making the Arctic Slope mosaic and dates of acquisition. The first 13 scenes compose the Central Arctic Management Area (CAMA)/Arctic National Wildlife Refuge (ANWR) mosaic, which was used to make the land-cover map of the Kuparuk River Region (Muller *et al.* 1998). The remaining 13 scenes were used for the National Petroleum Reserve in Alaska (NPR-A) mosaic. The two groups of scenes were joined together at the EROS Data Center in Sioux Falls, South Dakota, to form the Arctic Slope mosaic. The starred (*) scene was the radiometric reference scene.

Scene	Date
CAMA/ANWR	
82157020462	14 August 1976
82163320534	13 July 1979
82163320534	14 July 1979
82163420592	14 July 1979
82238620391	4 August 1981
82238720445	5 August 1981
82237221013	21 August 1981
85018121305	29 August 1984
85050321184	17 July 1985
85050821363	22 July 1985
85051921175	2 August 1985
85051921181*	2 August 1985
85092621154	13 September 1986
NPR-A	
82903212425	13 July 1977
82905213525	15 July 1977
82906214015	16 July 1977
82906214105	16 July 1977
82906214135	16 July 1977
82922212755	1 September 1977
82922212825	1 September 1977
82129721153	11 September 1978
83049621573	14 July 1979
82164021333	20 July 1979
82164021335	20 July 1979
85085821422	7 July 1986
85085821424	7 July 1986

relatively simple classification scheme reduced the effect of localized differences in Digital Numbers (DNs) due to striping.

2.2. *Basis of extrapolation*

We produced the NA-MSS map by extrapolating the results of the KRR-MSS map (the KRR-MSS dataset; Muller *et al.* 1998) to the NA-MSS dataset. A remote sensing approach for extrapolating the KRR-MSS map to the entire Arctic Slope was valid for two primary reasons: (1) The climate, physiography, substrates and vegetation of the larger Arctic Slope are broadly similar to those of the KRR, and (2) the imagery available for making the Arctic Slope map was very similar to that used for making the map of the KRR. There were, however, some differences in the datasets used for making the KRR-MSS and NA-MSS maps that posed potential problems for extrapolation. Our first idea for extrapolating the land-cover classification from the KRR was to use a maximum likelihood classification algorithm with training-site data derived from the KRR map. We speculated that this would give the best and quickest results for matching the classification within the KRR. However, this was not possible due to inexact overlay between the KRR-MSS and NA-MSS datasets. This problem was a result of differing spatial resolutions and spatial offset brought about in the geo-referencing and mosaicking used for the datasets which make each map. Thus, it was not possible to simply expand the classification to encompass the larger region. A new classification was required and our best alternative for replicating and extrapolating the classification was to apply the same unsupervised classification methods used to create the KRR-MSS map. However, the NA-MSS dataset had only two spectral bands (red and infrared), compared with three (green, red and infrared) in the KRR-MSS dataset, and the pixels were 100 m compared with 50 m. Further analysis showed that the loss of the green band was not critical because there was a 98% correlation between the green and red bands. The 50% loss of spatial resolution was compatible with our goal of scaling to a larger region.

Another important consideration was that the scene acquisition dates should be as close to the same date as possible during the period of peak greenness. Although the scenes spanned an 11 year period (1976–1986), nearly all the scenes were in the July–August peak-greenness window (table 1). There were four September scenes, when the vegetation could potentially have been senescing. The 11 years spanning the acquisition dates of the scenes were relatively unimportant because of the high year-to-year similarity of biomass and late-season phenological development in tundra vegetation (Sorensen 1941, Webber 1978, Chapin and Shaver 1985, Walker *et al.* 1995). There were also no large-scale disturbances, such as burned areas, within the study area.

2.3. *Classification techniques*

Since there are no forests on the Arctic Slope, we first cropped the NA-MSS mosaic to include only tundra areas north of the arctic tree line to avoid inclusion of forest cover. We used an IsoData unsupervised classification based on input of the red and infrared spectral data. Due to the large size of the dataset, we opted to use the less complicated and faster processing K-means unsupervised classification algorithm to extract cluster classes (Tou and Gonzalez 1974, Jensen 1996). We used the ENVI (version 3.0) image-processing software package to analyse the data and perform all classification steps. We first specified the formation of 45 cluster classes. The 68% data ellipses for the initial 43 clusters (two clusters had zero pixels) were plotted (figure 3(*a*)). These were compared to the 40-cluster output for the original KRR-MSS map (Auerbach 1996, unpublished data). Based purely on the raw DNs, the clusters derived from the North Slope image did not match well with those of the KRR classification. However, the mosaicking of images required normalization of DNs based on a single image. This normalization process caused a shifting of the range of DNs. When plotted, the distribution of clusters followed a spatial pattern similar to that derived in the KRR classification, giving us confidence in extrapolating the KRR-classification to the larger region.

We used first-hand experience with the area, the KRR land-cover map and other local area maps from the North Slope as supplementary information to interpret and group each cluster into the most appropriate of the eight land-cover categories. Since we had the most familiarity with the Kuparuk River Basin, we gave this information the most weight when grouping cluster classes into land-cover categories.

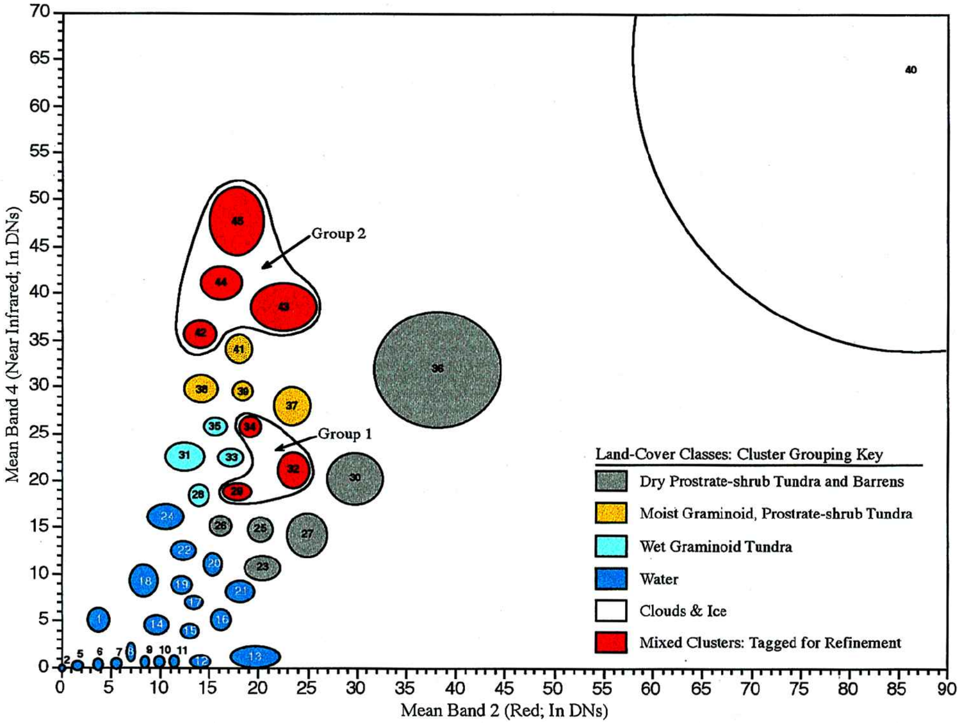
During the process of analysing these 43 cluster classes, we identified seven clusters (29, 32, 34, 42, 43, 44 and 45) that spectrally overlapped two or more land-cover classes (figure 3(*a*)). These clusters were tagged and pooled into two groups of clusters depending on the land-cover categories they overlapped. Group 1 consisted of clusters 29, 32 and 34, which overlapped the *Wet Tundra*, *Barrens* and *MNT* categories; and Group 2 consisted of clusters 42, 43, 44 and 45, which overlapped the *MAT*, *Shrublands* and *Barrens* categories. The K-means algorithm was reapplied to the pixels in the MSS image that fell into each of these two groups and resulted in 31 additional clusters. The spatial distribution of these new clusters was analysed, and each one was grouped into the land-cover categories with the best match on the reference maps. One of the new clusters within Group 2 still overlapped land-cover types. This was further split with the K-means algorithm into three finer clusters and grouped into appropriate land-cover categories. At this point, we concluded that further differentiation of the data would result in significant improvement of the classification. The refinement of clusters resulted in a total of 69 cluster classes (figure 3(*b*)).

We compared the percentage cover of land-cover classes on the original KRR-MSS with those within the KRR on the new NA-MSS (table 2). The small differences in percentage cover between the two maps is partially a function of spectral signal mixing that occurred during resampling to 100-m resolution to create the NA-MSS dataset. For example, the 5.5% decrease in *Shrublands* and 3.2% increase in *MAT* is due to many shrublands occurring along narrow water-tracks interspersed within large swaths of *MAT*. In such areas, mixing of reflectance values for the larger 100-m pixels resulted in DNs more closely similar to those of *MAT*. Similarly, the 2.2% decrease in *Water* and 2.4% increase in *Wet Tundra* was probably the result of the blending of the smaller water bodies with the surrounding wet tundra at the larger pixel size. The close similarity in areal distribution of land-cover categories between the KRR-MSS and NA-MSS classification suggest that our effort to extrapolate the land-cover classification to the North Slope successfully duplicated the patterns seen in the KRR classification.

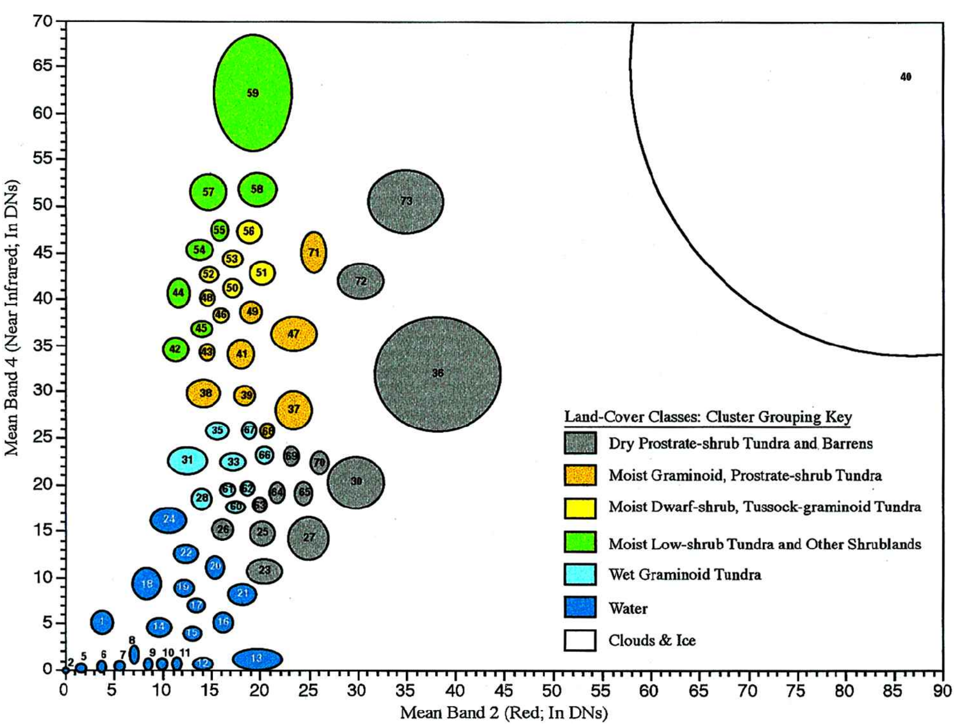
2.4. *Corrections using ancillary datasets*

The first iteration of the classification had two problems that were correctable using ancillary data. First, pixels shadowed by clouds and mountains were classified as *Water* due to their low DNs in both bands. Similarly, for mountainous areas on the edge of shadowed areas, pixels were classified as *Wet Tundra*, a result of spectral mixing of the shadows and adjacent barren tundra areas. These shadow problems were corrected by using a set of boundaries that demarcated the mountains and cloud-shadow areas. These boundaries were digitized directly on the screen using the false colour infrared (CIR) version of the MSS image as a base map. With a contrast stretch applied to the CIR image, it was possible to differentiate between uplands, clouded areas and lowlands. Using the digitized data, all pixels in

Figure 3. (*a*) Initial 68% data ellipses for 43 clusters derived from initial classification of a MSS image of the North Slope of Alaska clustering using a K-means unsupervised algorithm. Mixed clusters are encircled to signify to which group they were assigned. (*b*) Final 68% data ellipses of 69 total clusters derived from initial clustering and subsequent splits of clusters.


Group 2
Group 1
Land-Cover Classes: Cluster Grouping Key
Dry Prostrate-shrub Tundra and Barrens
Moist Graminoid, Prostrate-shrub Tundra
Wet Graminoid Tundra
Water
Clouds & Ice
Mixed Clusters: Tagged for Refinement
Mean Band 4 (Near Infrared; In DNs)
Mean Band 2 (Red; In DNs)

(*a*)


Land-Cover Classes: Cluster Grouping Key
Dry Prostrate-shrub Tundra and Barrens
Moist Graminoid, Prostrate-shrub Tundra
Moist Dwarf-shrub, Tussock-graminoid Tundra
Moist Low-shrub Tundra and Other Shrublands
Wet Graminoid Tundra
Water
Clouds & Ice
Mean Band 4 (Near Infrared; In DNs)
Mean Band 2 (Red; In DNs)

(*b*)

Table 2. Land-cover percentages for the Kuparuk River Region on the KRR-MSS map and the NA-MSS map.

Land-cover category	Percentage cover		Difference (%)
	NS-MSS map	KRR-MSS map	
Dry Prostrate-shrub Tundra and Barrens	4.9	3.8	1.0
Moist Graminoid, Prostrate-shrub Tundra	40.1	38.4	1.7
Moist Dwarf-shrub, Tussock-graminoid Tundra	21.7	18.5	3.2
Moist Low-shrub Tundra and Other Shrublands	13.2	18.7	– 5.5
Wet Graminoid Tundra	10.3	7.9	2.4
Water	8.8	11.1	– 2.2
Clouds and Ice	0.2	0.2	0.0
Shadows	0.8	1.5	– 0.6

mountainous and cloudy areas that were originally classified as *Water* and *Wet Tundra* were reclassified as *Shadows* and *Barrens* respectively.

The second problem occurred with the *Moist Nonacidic Tundra* (*MNT*) category. On the KRR-MSS classification, *MNT* covers most moist tundra areas on the coastal plain. A similar, but acidic, tundra type is common west of the Colville River on stabilized sand dunes of a large late-Pleistocene sand sea (Carter 1981). To correct this problem, we identified the sandy *MAT* areas as a separate land-cover class. We used a surficial geology map of NPRA (Williams *et al.* 1985, modified in Gryc 1985) to identify the sand-sea region. The boundary was digitized and then overlain on the classification results. Within this area, any pixel previously defined as *MNT* was reclassified to the new class, *Moist Tussock-graminoid*, *Dwarf-shrub Tundra* (cold, acidic and sandy).

We also changed the names of the original land-cover categories to reflect the dominant plant growth forms and in order to distinguish the new sandy class from typical tussock tundra. To eliminate the pixelated 'salt and pepper' appearance, we smoothed the data by applying a 5-pixel moving window majority algorithm (only for display purposes).

2.5. *Comparison of the NA-MSS map with the MEA and NA-AVHRR maps*

We did both an area-wise and spatial comparison of the NA-MSS map with the MEA and NA-AVHRR maps. Since all three maps covered different areas, these analyses were confined to the area of the Arctic Slope (figure 1), excluding a small 910 km^2 area in the Brooks Range along the southern edge of the map which was missing on the NA-MSS mosaic. The study area boundary encompasses tundra regions north of the Brooks Range, with a climate comparable with that of the KRR. It does not include the Noatak River or Firth River valleys, which appear on all three maps, but are forested and have quite different climates from those of the KRR and Arctic Slope. In addition to confining comparison to a common area, we desired a common resolution. Since the MEA map was a polygon dataset and the NA-MSS had 100-m resolution, we converted them to 1 km × 1 km grids to match the NA-AVHRR map. The NA-MSS was resampled using a majority analysis in each

$1\,km \times 1\,km$ cell existing on the NA-AVHRR map which caused some spatial and areal generalization.

The area-wise comparison had two parts, and the first was performed by generalizing the NA-MSS and NA-AVHRR maps to the legend of the MEA map to include five categories (*Alpine Tundra*, *Moist Tundra*, *Wet Tundra*, *Shrublands* and *Water*; table 3, column 1). The second part generalized the NA-MSS map to the legend of the NA-AVHRR map and included seven categories (*Alpine Tundra and Barrens*; *Moist Graminoid*, *Dwarf-shrub Tundra*; *Moist Dwarf-shrub*, *Tussock-graminoid Tundra*; *Shrublands*; *Wet Tundra*; *Water*; and *Ice*, *Snow and Clouds*; table 3, column 2).

Second, we prepared difference maps to obtain a more detailed picture of the spatial patterns of differences in the three maps. We made two difference maps; the first compared the NA-MSS map with the MEA map, and the second compared the NA-MSS with the NA-AVHRR map. For each comparison (NA-MSS vs. MEA and NA-MSS vs. NA-AVHRR), pixels that were the same on both land-cover maps were portrayed as white. Pixels that were different were portrayed as they were coded on the NA-MSS map. Difference matrices, similar to error matrices used in accuracy assessments (e.g. Muller *et al.* 1998), were used to examine the differences in the maps in more detail.

3. Results

3.1. *Comparison of land-cover area*

Of the 199 973 km^2 on the NA-MSS map within the Arctic Slope (figure 4, table 4), *Dry Prostrate-shrub Tundra and Barrens* covers 8%; *Moist Graminoid*, *Prostrate-shrub Tundra*, 22%; *Moist Tussock-graminoid*, *Dwarf-shrub Tundra*, 4%; *Moist Dwarf-shrub*, *Tussock-graminoid*, *Tundra*, 28%; *Moist Low-shrub Tundra* and

Table 3. Crosswalk for the legends on the Major Ecosystems of Alaska, Northern Alaska-AVHRR, and Northern Alaska-MSS maps.

Major Ecosystems of Alaska	Northern Alaska-AVHRR	Northern Alaska-MSS
Alpine Tundra	Dry Alpine Tundra and Barrens	Dry Prostrate-shrub Tundra and Barrens
	Ice and snow	Ice, snow and clouds
		Shadows
Moist Tundra	Moist Graminoid, Dwarf-shrub Tundra	Moist Graminoid, Prostrate-shrub Tundra (nonacidic)
		Moist Tussock-graminoid Dwarf-shrub Tundra (cold, acidic)
	Moist Dwarf-shrub, Tussock-graminoid Tundra (typical tussock tundra)	Moist Dwarf-shrub, Tussock-graminoid tundra (typical tussock tundra)
Shrublands	Shrublands	Moist Low-shrub Tundra and other Shrublands
Wet Tundra	Wet Tundra	Wet Graminoid Tundra
Water	Water	Water

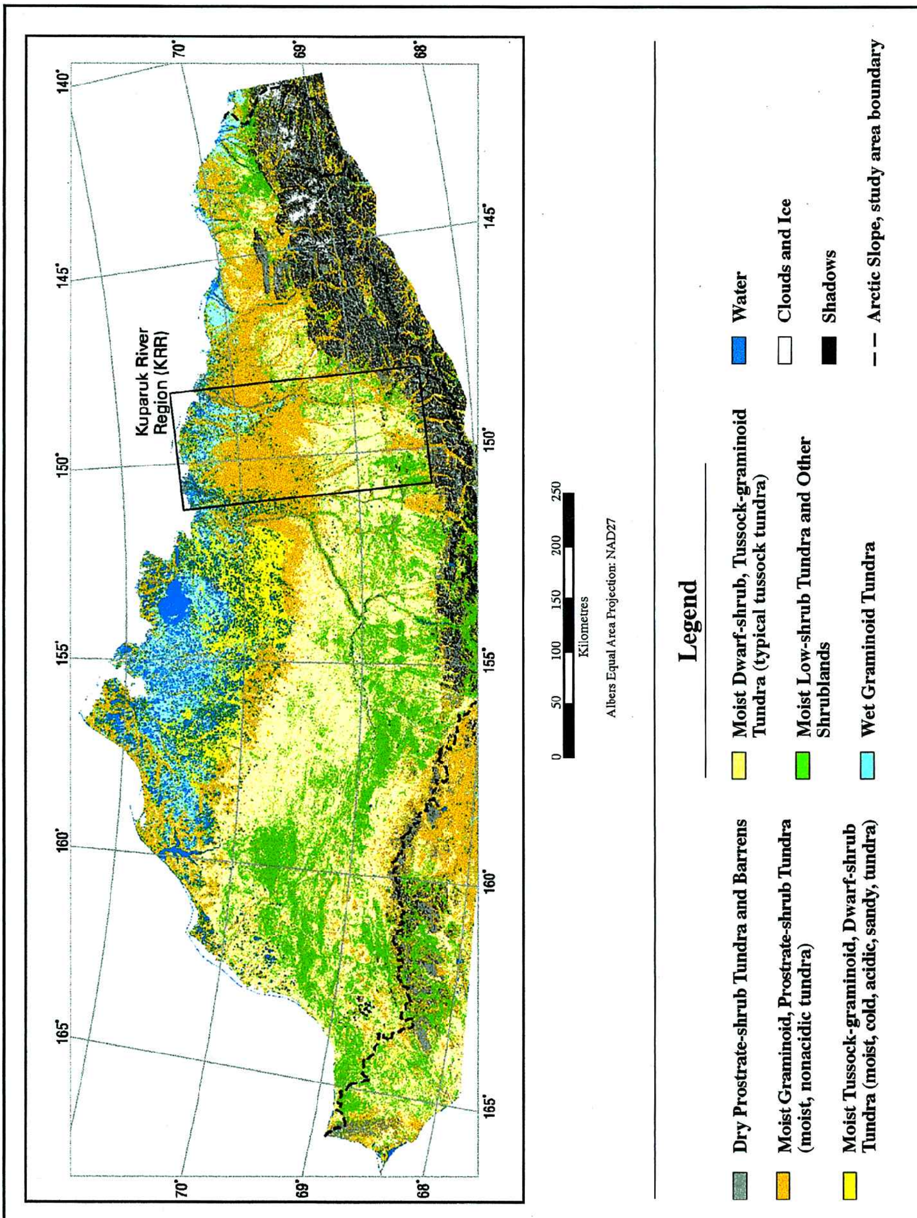


Figure 4. Final land-cover map of North Slope resulting from the extrapolation of the land-cover classification of the Kuparuk River Region (KRR) and subsequent corrections using ancillary data.

Table 4. Area and percentage-cover of land-cover classes on the entire NA-MSS map and the Arctic Slope portion.

Land-cover category	Entire NA-MSS map		Arctic Slope portion of NA-MSS map	
	Area cover (km^2)	Percentage cover	Area cover (km^2)	Percentage cover
Dry Prostrate-shrub Tundra and Barrens	25 434	10.6	16 863	8.4
Moist Graminoid, Prostrate-shrub Tundra	55 100	22.9	43 587	21.8
Moist Tussock-graminoid, Dwarf-shrub Tundra	7495	3.1	7495	3.7
Moist Dwarf-shrub, Tussock-graminoid Tundra	63 829	26.5	55 480	27.7
Moist Low-shrub Tundra and Other Shrublands	43 920	18.3	37 202	18.6
Wet Graminoid Tundra	19 096	7.9	18 007	9.0
Water	13 553	5.6	12 990	6.5
Clouds and Ice	1688	0.7	1364	0.7
Shadows	10 381	4.3	6986	3.5
Total	240 497	100.00	199 973	100.0

other *Shrublands*, 19%; *Wet Graminoid Tundra*, 9%; *Water*, 6%; *Clouds and Ice*, < 1%; *Shadows*, 4% (table 4). Typical habitats and plant communities within each land-cover unit are shown in table 5. Readers should refer to cited references for more details regarding species composition of the dominant plant communities. If these categories are grouped into the larger categories of the MEA map, about 12% is *Alpine Tundra*, 59% is *Moist Tundra*, 16% is *Shrublands*, 8% is *Wet Tundra*, and 5% is *Water* (figure 5(*a*)). Compared with the MEA and NA-AVHRR maps, the NA-MSS map has less *Alpine Tundra* (12% vs. 17% on the MEA and 15% on the AVHRR map), more *Moist Tundra* than the MEA map (59% vs. 54%), more *Shrublands* (16% vs. 11% and 8%), less *Wet Tundra* (8% vs. 19% and 17%) and more *Water* (5% vs. 0% and 1%; figure 5(*a*)).

When the NA-MSS map is compared with the NA-AVHRR seven unit legend (figure 5(*b*)), the NA-MSS map has the same amount of *Alpine Tundra and Barrens* (12%); less *Moist Graminoid*, *Dwarf-shrub Tundra* (32% vs. 36%), *Wet Tundra* (8% vs. 17%), *Ice*, *Snow*, *and Clouds* (1% vs. 3%); and more *Moist Dwarf-shrub*, *Tussock-graminoid Tundra* (27% vs. 23%), *Shrublands* (16% vs. 8%) and *Water* (5% vs. 1%).

3.2. *Comparison of the map patterns*

3.2.1. *NA-MSS versus MEA*

Overall, there is a 56.5% agreement between the NA-MSS and MEA maps (table 6(*a*), figure 6(*a*)). The highest levels of agreement are within the *Alpine Tundra* and *Moist Tundra* categories, and the lowest levels of agreement are in the *Shrublands*, *Water* and *Wet Tundra* categories. Of the *Alpine Tundra* areas on the NA-MSS map, 78.3% are shown as the same unit on the MEA map (horizontal comparison in table 6(*a*)), whereas 59.2% of the *Alpine Tundra* on the MEA map is shown as the same unit on the NA-MSS map (vertical comparison in table 6(*a*)). The lower agreement in the latter comparison is due to greater resolution and more mountain valleys

Table 5. Common habitats and plant communities within each land-cover category.

Land-cover classes: common habitats	Dominant plant communities
Dry Prostrate-Shrub Tundra and Barrens:	
1. Lichen-covered, and partially vegetated siliceous rocks in foothills and mountains	1. *Cetraria nigricans-Rhizocarpon geographicum*[1]
2. Dry partially-vegetated alpine tundra	2. *Selaginello sibiricae-Dryadetum octopetalae*[2]
3. Limestone bedrock	3. *Saxifraga oppositifolia-Saxifraga eschscholtzii*[3]
4. Barren and partially vegetated river alluvium	4. *Epilobium latifolium-Castilleja caudata*[3]
5. Barren coastal mud flats	5. *Carex subspathacea-Puccinellia phryganodes*[4]
6. Dunes	6. *Elymus arenarius-Artemisia borealis*[4]
7. Roads and gravel pads	7. Unvegetated
Moist Graminoid, Prostrate-shrub Tundra (nonacidic):	
1. Moist nonacidic hillslopes and moderately well-drained surfaces with pH$\geq$5.5	1. *Dryado integrifolia-Caricetum bigelowii*[2,7], *Astragalus umbellatus-Dryas integrifolia*[3]
2. Dry nonacidic river terraces and gravelly well-drained slopes	2. *Oxytropis bryophila-Dryas integrifolia*[4]
3. Dry acidic tundra on hill crests, moraines and kames	3. *Selaginello sibiricae-Dryadetum octopetalae*[2], *Salici phlybophyllae-Arctoetum alpinae*[2]
4. Nonsorted-circle and -stripe complexes on the coastal plain and in the foothills	4. *Juncus biglumis-Saxifraga oppositifolia*[4], *Astragalus umbellatus-Dryas integrifolia*[3]
5. Moist/wet patterned-ground complexes (e.g. low-centred polygon complexes), especially on the coastal plain, with more than 50% moist nonacidic tundra	5. *Dryado integrifolia-Caricetum bigelowii*[2], *Carex aquatilis-Eriophorum angustifolium*[4], *Carex aquatilis-C. chordorrhiza*[1]
6. Moist coastal tundra	6. *Saxifraga cernua-Carex aquatilis*[5,8], *Sphaerophorus globosus-Luzula confusa*[5,8], *Dryas integrifolia-Carex aquatilis*[5,8]
Moist Tussock-graminoid, Dwarf-shrub Tundra (cold acidic):	
1. Moist tussock tundra in the sand region with pH$<$5.5	1. *Eriophorum vaginatum-Ledum decumbens*[6]
2. Moist/wet patterned-ground complexes in sand region (e.g. low-centred polygon complexes), especially on the coastal plain, with more than 50% moist nonacidic tundra	2. *Eriophorum vaginatum-Ledum decumbens*[6], *Carex aquatilis-Eriophorum angustifolium*[6], *Carex aquatilis-C. chordorrhiza*[6]
Moist Dwarf-shrub, Tussock-graminoid Tundra (typical tussock tundra):	
1. Moist acidic hillslopes and moderately drained terrain with pH$<$5.5	1. *Sphagno-Eriophoretum vaginati*[2]
Moist Low-Shrub Tundra and other Shrublands:	
1. Riparian shrublands along rivers	1. *Salix alaxensis-S. lanata*[2], *Sphagno-Eriophoretum vaginati betuletosum nanae*[2], *Salix pulchra-Calamagrostis canadensis*[2]
2. Watertracks and shrublands in basins in foothills	2. *Eriophorum angustifolium-Salix pulchra*[1]
3. Tussock tundra dominated by low shrubs	3. *Sphagno-Eriophoretum vaginati*[2]
4. Shrublands on south-facing slopes	4. *Salix glauca-Alnus crispa*[3]
5. True shrub tundra on flat or gently rolling surfaces	5. Willow dominated uplands

Table 5. (*Continued*).

Land-cover classes: common habitats	Dominant plant communities
Wet Graminoid Tundra:	
1. Rich fens on coastal plain, along rivers and foothill basins	1. *Carex aquatilis-Eriophorum angustifolium*[4], *C. aquatilis-C. chordorrhiza*[1]
2. Poor fens in foothills	2. *Sphagnum orientale-Eriophorum scheuchzeri*[1], *Carex aquatilis-Sphagnum lenense*[1], *Sphagnum lenense-Salix fuscescens*[1]
3. Wet/moist patterned-ground complexes (e.g. ice-wedge polygon complexes) with > 50% wet tundra	3. *Carex aquatilis-Eriophorum angustifolium*[4], *C. aquatilis-C. chordorrhiza*[3], *Dryado integrifolia -Caricetum bigelowii*[2]
Water:	
1. Water	1. Unvegetated
2. Marshes and aquatic vegetation with more than 50% standing water	2. *Carex aquatilis*[4], *Hippuris vulgaris-Arctophila fulva*[1], unvegetated
Clouds and ice:	
1. Aufeis along braided rivers	1. Unvegetated
2. Clouds mainly at high elevations	2. Mostly alpine vegetation types, barrens
Shadows:	
1. Mostly steep terrain in the mountains	1. Primarily barrens, also snowbeds *Carici microchaetae-Cassiopetum tetragonae*[2] and *Dryas integrifolia-Cassiopetum tetragona*[2]
2. Some cloud shadows	

[1] Walker *et al.* 1996.
[2] Walker *et al.* 1994.
[3] D. A. Walker unpublished data.
[4] Walker 1985.
[5] Elias *et al.* 1996 unpublished.
[6] Komárková and Webber 1980.
[7] Jorgenson *et al.* 1994.
[8] Webber 1978.

on NA-MSS map. *Moist Tundra* shows a similar degree of agreement in both directions of the comparison (64.6% in the horizontal comparison and 70.6% in the vertical comparison). Only 30% of the MEA *Wetlands* are mapped as *Wetlands* on the NA-MSS map (vertical comparison), but 73.8% of the NA-MSS *Wetlands* are mapped identically on the MEA map. Over half (68%) of the areas mapped as *Wetlands* on the MEA map were mapped as either *Moist Tundra* or *Water* on the NA-MSS map, which points to the heterogeneity of wetland complexes. *Shrublands* show little agreement in either the horizontal or vertical comparison of table 6(*a*) (17.8% and 27.1%, respectively). The MEA map shows broad swaths of *Shrublands* along the major river corridors that do not appear on the NA-MSS map, whereas the NA-MSS map shows large areas of upland tundra *Shrublands* in the western and southern foothills. Of the areas mapped as *Shrublands* on the NA-MSS map, 70% are mapped as *Moist Tundra* on the MEA map, and similarly, 65% of the areas mapped as *Shrublands* on the MEA map were mapped as *Moist Tundra* on the NA-MSS map.

3.2.2. *NA-MSS versus NA-AVHRR*

There is 55.4% agreement between the NA_MSS and NA-AVHRR maps (table 6(*b*); figure 6(*b*)). Alpine areas and *Moist Dwarf-shrub*, *Tussock-graminoid*

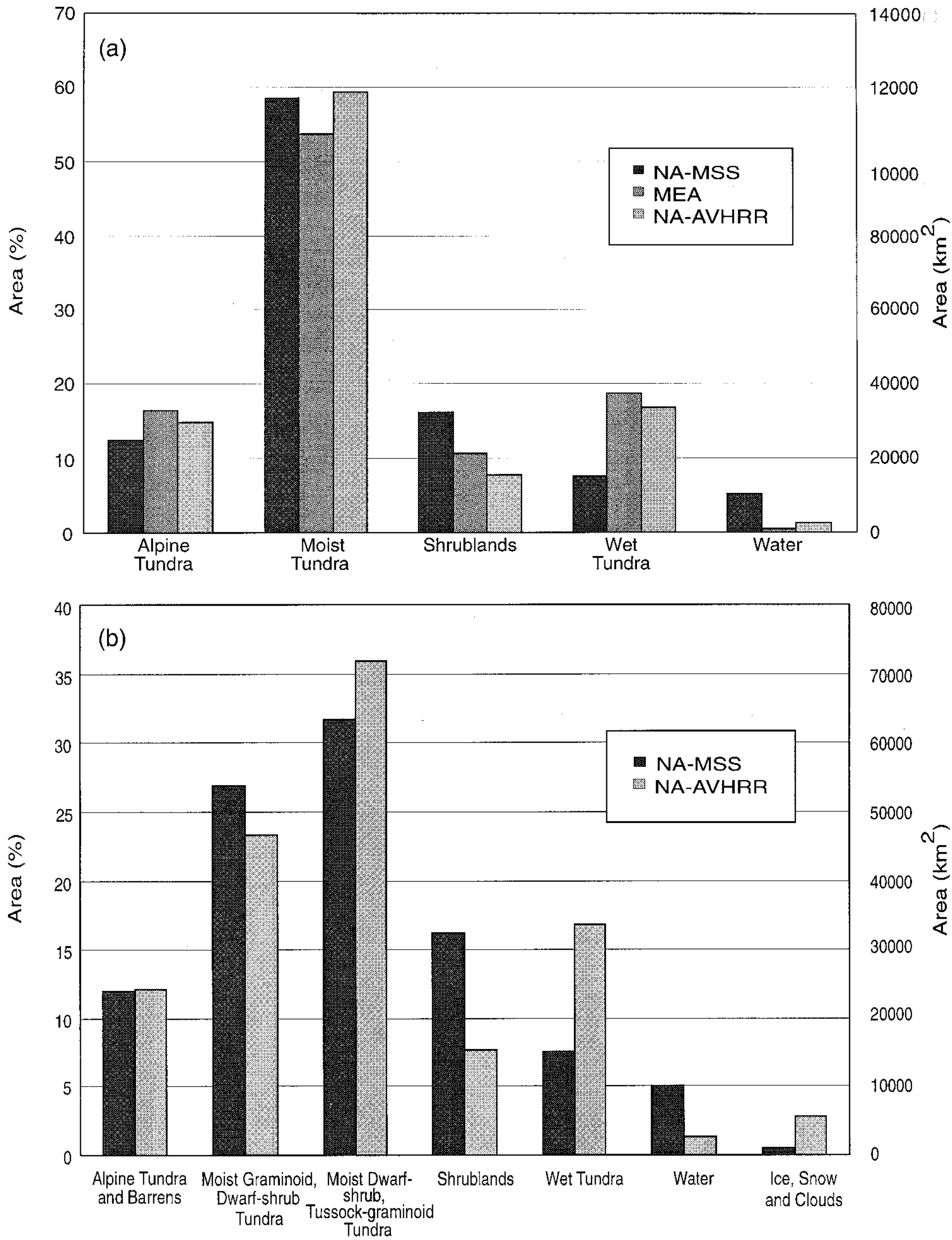


Figure 5. Areas of the land-cover units. (*a*) Comparison of the NA-MSS, NA-AVHRR and MEA maps, with land-cover units grouped according the five units on the MEA map. (*b*) Comparison of the NA-MSS and NA-AVHRR, with land-cover units grouped according the seven units on the NA-AVHRR map.

Tundra (classic tussock tundra) shows a moderately high degree of correspondence between the maps (67% for *Alpine Tundra* in both the horizontal and vertical comparisons, and tussock tundra has 71% agreement in the horizontal comparison and 63% in the vertical comparison). On the NA-AVHRR map, many areas mapped

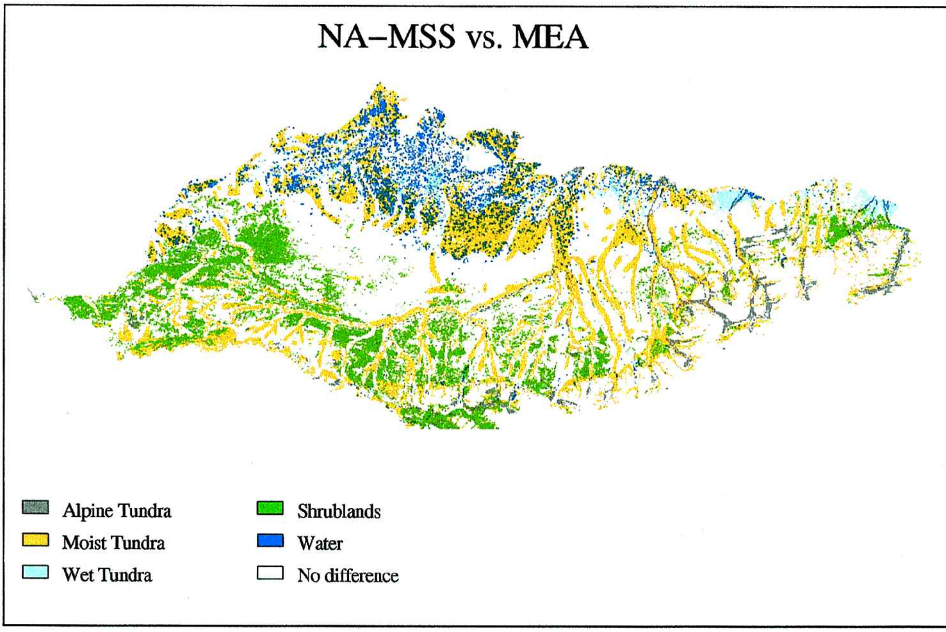
Table 6. Difference matrices (*a*) NA-MSS versus MEA map, (*b*) NA-MSS versus NA-AVHRR map. Values are number of pixels.

(*a*)

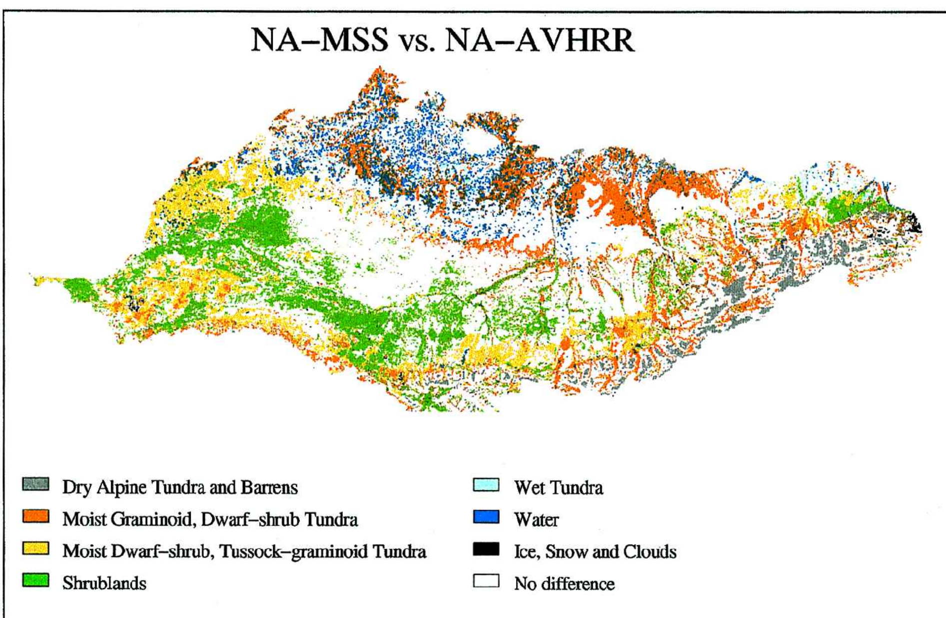
NA-MSS	MEA: Alpine tundra	Moist tundra	Shrublands	Wet tundra	Water	Total	Agreement (%)
Alpine tundra	**19 254**	3594	1186	544	1	24 579	78.3
Moist tundra	9363	**74 519**	13 768	17 734	8	115 392	64.6
Shrublands	3767	22 309	**5700**	159	—	31 935	17.8
Wet tundra	63	3570	243	**11 081**	50	15 007	73.8
Water	85	1578	150	7413	**812**	10 038	8.7
Total	32 532	105 570	21 047	36 931	871	**196 951**	
Agreement (%)	59.2	70.6	27.1	30.0	93.2		
						Total Agreement:	**56.5**

(*b*)

NA-MSS	NA-AVHRR: Alpine Tundra and Barrens	Moist Grami-noid Dwarf-shrub Tundra	Moist Dwarf-shrub Tussock-grami-noid Tundra	Shrub-lands	Wet Tundra	Water	Ice, Snow and Clouds	Total	Agreement (%)
Alpine Tundra and Barrens	**15 929**	830	228	500	1198	201	4761	23 637	67.4
Moist Graminoid, Dwarf-shrub Tundra	5666	**27 783**	3959	2206	12 999	264	12	52 889	52.5
Moist Dwarf-shrub, Tussock-graminoid Tundra	910	10 447	**44 546**	6501	68	31	—	62 503	71.3
Shrublands	866	3221	21 894	**5893**	54	7	—	31 935	18.5
Wet Tundra	77	1934	13	45	**12 574**	344	20	15 007	83.8
Water	102	1674	168	63	6190	**1784**	57	10 038	17.8
Ice, Snow and Clouds	234	21	26	25	6	15	**615**	942	65.3
Total	23 784	45 910	70 834	15 233	33 089	2646	5455	**19 6951**	
Agreement (%)	67.0	60.5	62.9	38.7	38.0	67.4	11.3		
								Total Agreement:	**55.4**



(*a*)



(*b*)

Figure 6. Difference images: (*a*) NA-MSS versus MEA, (*b*) NA-MSS versus NA-AVHRR. Pixels that were the same on both land-cover maps of a comparison are portrayed as white. Pixels that were different are shown as they were coded on the NA-MSS map.

as *Ice and Snow* and *Clouds* in the Brooks Range are not in glacier areas, but were snow or cloud covered during all times of data acquisition in 1991. The other land-cover categories show much lower agreement. On the coastal plain, the NA-MSS map shows more areas of *Moist Tundra*, and reflects a different break between *Wetlands* and *Moist Tundra* in wetland complexes. This is largely a function of the smaller pixel size on the MSS classification, mixing that occurs in the larger AVHRR pixels, and probably a lower threshold of *Wet Tundra* at the break between the *Moist* and *Wet Tundra* categories on the NA-MSS map.

There is little correspondence between *Shrublands* on the two maps. The NA-AVHRR map shows *Shrublands* in the Southern Arctic Foothills of the Arctic National Wildlife Refuge, the southern foothills and mountains between the Itkillik and Etivluk rivers, and in the hills west of the Utukok River, whereas *Shrublands* occur much more broadly across the NA-MSS map and cover about twice the area as *Shrublands* on the NA-AVHRR map. Similarly, the large areas of *Shrublands* in the south and west portions of the NA-MSS map and in the Arctic National Wildlife Refuge, which are mapped as *Moist Dwarf-shrub*, *Tussock-graminoid Tundra* on the NA-AVHRR, suggest that the *Moist Tundra* category is broader on the AVHRR map and contains large areas of shrub-rich tundra. On the other hand, there are also areas mapped as *Shrublands* on the NA-AVHRR map, which are mapped as *Moist Dwarf-shrub*, *Tussock-graminoid Tundra* on the NA-MSS map. Some of these shrubland areas may be defined more on the basis of an early snow melt and relatively high NDVI early in the season. Evidence for this is the band of *Shrublands* portrayed along the northern boundary of the Brooks Range between the Itkillik and Etivluk rivers. This area experienced early snow melt and early green up in 1991, the year of the AVHRR time series data.

4. Discussion

4.1. *Evaluation of the major categories*

4.1.1. *Alpine tundra*

Alpine areas include barren and lichen-covered rocky areas in the mountains, and slopes dominated by *Dryas* communities (e.g. *Selaginello sibiricae-Dryadetum octopetalae*; Walker *et al.* 1994). Shadowed areas generally occur on north-facing mountain slopes with many of the same communities listed above or with snowbed communities (e.g. *Carici microchaetae-Cassiopetum tetragonae* or *Dryas inegrifolia-Cassiopetum tetragona*; Walker *et al.* 1994). *Barrens* that occur along rivers, coastal mudflats, dunes and road networks are estimated to contribute less than 1% to the total within the Arctic Slope. The alpine areas also include glaciers in the higher mountains.

Overall, the general distribution of *Alpine Tundra* is similar on the MEA, NA-AVHRR, and NA-MSS maps; however, at the most general level, the NA-MSS map shows considerably less total area of *Alpine Tundra* (including shadows and glaciers) than the MEA or the AVHRR maps because it provides more detail regarding the mountain valley systems, where extensive *Shrublands* and *Moist Tundra* are common. With respect to glacier distribution, the MEA map does not show any glaciers; the NA-MSS map shows glaciers in Franklin and Romanzov Mountains of the eastern Brooks Range that are close to the glacier distribution on topographic maps of the US Geological Survey, whereas the AVHRR map portrays much larger snow and ice-covered areas, presumably due to the presence of snow or ice in some high glacier-free areas during all the acquisition dates of the 1991 AVHRR database.

4.1.2. *Moist tundra*

The MEA map portrays a single category of *Moist Tundra* that was previously thought to be overwhelmingly dominated by the tussock-tundra plant community (*Sphagno-Eriophoretum vaginati*; Walker *et al*. 1994). The NA-MSS delineates three types of *Moist Tundra* that cover large areas of the Arctic Slope. Two of these are considerably less shrubby than the classic tussock tundra and are most common in the northern, colder, portions of the map area.

Moist Graminoid, *Prostrate-shrub Tundra* (also called moist nonacidic tundra in previous publications; Walker *et al*. in press, Walker *et al*. 1998) is predominantly a calcium-rich nonacidic type that occurs on moderately drained silt deposits in northern Arctic Foothills and Arctic Coastal Plain, along major rivers and near the northern front of the Brooks Range on surfaces glaciated in the late Pleistocene (Walker *et al*. 1998). The dominant plant community in these areas is *Dryado integrifolia-Caricetum bigelowii* (Walker *et al*. 1994). The dominant shrubs in this land-cover unit are mostly prostrate species, such as *Dryas integrifolia*, *Salix arctica* and *S. reticulata*, although erect species of minerotrophic willows such as *Salix lanata* and *S. glauca* are locally abundant in warmer areas. Mosses are mostly minerotrophic species, such as *Tomentypnum nitens*, *Ditrichum flexicaule*, *Distichium capillaceum* and *Hypnum bambergeri*. There is also a conspicuous absence of many key acidophilous tussock tundra species such as *Betula nana*, *Ledum decumbens* and *Sphagnum* spp. The *Moist Graminoid*, *Prostrate-shrub Tundra* unit also includes moist coastal tundra types (e.g. *Saxifraga cernua-Carex aquatilis*, *Sphaerophorus globosus-Luzula confusa*; and *Dryas integrifolia-Carex aquatilis*; Webber 1978, Elias *et al*. 1996). Some of these plant communities occur on acidic soils, but cannot be separated on the basis of the spectral data.

Moist Tussock-graminoid, *Dwarf-shrub Tundra* occurs on moist sandy soils of the sand sea on the Arctic Coastal Plain. The dominant plant community on old, stable, upland surfaces in these areas is *Eriophorum vaginatum-Ledum decumbens* (Komárková and Webber 1980). This vegetation type is spectrally similar to *MNT*, but compositionally similar to typical tussock tundra, except the tussocks of *Eriophorum vaginatum* are very small ($<$ 15 cm tall), dwarf shrubs (e.g. *Ledum palustre* ssp. *decumbens*, *Vaccinium vitis-idaea*, *Betula nana*) are not abundant, and the moss understorey is less developed. These characteristics are probably due to a combination of cold summer temperatures on the coastal plain and the leached sandy, nutrient-poor soils. They give this tundra a less-bright spectral signature than the more typical *MAT* found further south.

Moist Dwarf-shrub, *Tussock-graminoid Tundra* is the classic tussock tundra described in the literature of northern Alaska, northwestern Canada and Chukotka (Hanson 1953, Bliss 1956, Bliss and Cantlon 1957, Spetzman 1959, Lambert 1968, Alexandrova 1980). It was also referred to as moist acidic tundra in recent publications (Walker *et al*. in press, Walker *et al*. 1998). The dominant plant community in northern Alaska is *Sphagno-Eriophoretum vaginati typicum* (Walker *et al*. 1994). Dwarf shrubs ($<$ 20 cm tall), including *Betula nana*, *Ledum decumbens*, *Vaccinium vitis-idaea*, *V. uliginosum* and *Salix planifolia* ssp. *pulchra*, are often dominant, and the tussock cottongrass *Eriophorum vaginatum*, also has high cover.

4.1.3. *Shrublands*

The NA-MSS map gives a new impression of the abundance and distribution of shrub-dominated ecosystems in northern Alaska. The map shows a gradient of increasing shrub stature along the coast-inland temperature gradient. Prostrate (< 0.05 m tall or creeping) shrubs are dominant near the coast, dwarf shrubs (0.05–0.2 m tall) are dominant in the northern Arctic Foothills, and low-shrubs (0.2–2.0 m) are dominant in many areas of the southern Arctic Foothills and toward the western part of the map. Currently, we have little information outside of the KRR to confirm if the NA-MSS accurately portrays low-shrubland areas, but it is logical that warmer and moister climates toward the south and west. (Selkregg 1975) would be conducive to more and taller shrub cover (Walker 1987, Chapin *et al.* 1995). Also, during an aerial reconnaissance in 1998, we noted extensive areas of shrub tundra dominated by low willows in the vicinity of the Utukok and Ketik rivers (figure 1). This area is mapped as a vast *Shrublands* on the NA-MSS map but as *Moist Dwarf-shrub*, *Tussock-graminoid Tundra* on the MEA and NA-AVHRR maps.

The most common shrublands in northern Alaska are: (a) tussock tundra dominated by low shrubs (=shrubby variants of *Sphagno-Eriophoretum vaginati*; Walker *et al.* 1994), (b) riparian shrublands, including many shrublands along small foothill water tracks and taller shrublands along the streams and rivers (Walker and Walker 1996); and (c) true shrub tundra with few graminoid plants. The dominant plant communities in each of these habitats are quite different (see table 5), and it would be highly desirable to make finer breaks in the *Shrublands* category.

The distribution of *Shrublands* on the NA-MSS map is very different from that portrayed on either the MEA or NA-AVHRR maps. The MEA map shows broad bands of *Shrublands* along the major rivers. Although *Shrublands* do occur along most rivers, these areas are usually quite narrow and not apparent at the map scale shown in figure 3 (about 1:4 million). The different patterns of *Shrublands* on the NA-MSS and NA-AVHRR are due to a combination of finer spatial resolution on the MSS, and to fundamentally different approaches used to define the land-cover categories. The AVHRR map used a time series of images, and there were classes based on the seasonal progression of NDVI (Markon *et al.* 1995). The classification covered all of Alaska and included many non-tundra vegetation types. For the NA-AVHRR map, we attempted to group the AVHRR categories defined by Markon *et al.* (1995) into categories that matched those of the KRR-MSS map (Muller *et al.* 1998). This effort was not totally successful. For example, our AVHRR *Moist Dwarf-shrub*, *Tussock-graminoid Tundra* category was overly broad and did not separate many areas dominated by low shrubs. Another problem was that some classes may have been strongly determined by the timing of snow melt. However, if the breaks between categories could be refined, the AVHRR time-series data have much promise for circumpolar extrapolations because of their frequent global coverage.

Examination of the other phenological maps in the Markon *et al.* (1995) paper suggests that the map portraying Maximum NDVI better matches the *Shrubland* patterns on the NA-MSS. Also, the definition of *Shrublands* has not been consistent across classification systems. For example, the Alaska Statewide Classification (Viereck *et al.* 1992) defines dwarf shrubs (< 0.2 m), low shrubs (0.2–1.5 m) and tall shrubs (> 1.5 m), and an international classification (UNESCO 1973) separates dwarf shrubs (0.5 m) from other shrubs (> 0.5 m). We break shrubs into the following growth-form categories: prostrate shrubs (very short < 0.05 m tall or with a decumbent (creeping) growth form); dwarf shrubs (0.05–0.5 m); low-shrubs (0.5–2 m); and tall shrubs (> 2 m). For the NA-MSS classification, we consider *Shrublands* to be any vegetation type with a dominance of low shrubs > 0.5 m tall. There has not, however, been an objective evaluation to determine the accuracy of these breaks on our land-cover maps.

4.1.4. *Wet tundra and water*

Wet Tundra is composed of a wide variety of mire plant communities (table 5). *Carex aquatilis*, and *Eriophorum angustifolium* are the overwhelmingly dominant species in most of the plant communities, but other graminoids such as *C. chrodorrhiza* , *C. rotundata*, *E. scheuchzeri* , and *Dupontia fisheri* are locally abundant.

The great majority of *Wet Tundra* on the Arctic Slope is interspersed with thaw lakes on the Arctic Coastal Plain. All three maps give the same general impression of wetland distribution, but the NA-MSS map has more detail and better portrays the distribution of lakes and wetland complexes where the wet tundra is mixed with moist uplands. Compared to the NA-AVHRR map, the NA-MSS shows five times more water, and about half as much *Wet Tundra*. A recent map by the Bureau of Land Management provides much more detail regarding wetland types within the NPR-A (Pacific Meridian Resources 1996).

4.2. *Implications for future research*

The NA-MSS map will be useful for a wide variety of modelling efforts relating vegetation to climate and other geophysical parameters. The various tundra types mapped here have distinctly different regimes of energy and trace-gas fluxes, and the map will be useful for calculating regional energy and trace-gas budgets (McFadden *et al.* in press, Oechel *et al.* in press, Reeburgh *et al.* in press, Vourlitis and Oechel 1997, Walker *et al.* 1998). The map will also be useful for defining regional relationships between arctic plant functional types and climate (Chapin *et al.* 1996, Shaver *et al.* 1997), and could help better define zoanal transitions in vegetation for circumpolar mapping efforts (Alexandrova 1980, Yurtsev 1994, Walker 1995). Hydrology and geomorphology studies can also key in on the vegetation patterns. For example, one of the most interesting patterns is that the northern limit of water-track shrublands is nearly coincident with the northern limit of tussock tundra (*Moist Dwarf-shrub, Tussock-graminoid Tundra*). This is related to the vegetation growing in hillslope water tracks, or horsetail drainages (Cantlon 1961, Walker and Walker 1996), which are uncommon north of the tussock tundra boundary, but the causes of this limit are not presently understood. Geocryological studies relating patterns of cryoturbation to vegetation and climate will also benefit from the map (Hinzman *et al.* 1996, Nelson *et al.* 1997, Bockheim *et al.* 1998, Nelson *et al.* in press).

The contrast between moist acidic and moist nonacidic tundra is of special interest to wildlife biologists. These tundra types have large differences in plant diversity, water budgets, soil temperatures, plant nutrients and levels of toxic secondary plant compounds (Walker *et al.* 1998, Walker *et al.* in press). A previous study identified a conspicuous boundary between acidic and nonacidic tundras near the northern edge of the Arctic Foothills (Walker *et al.* 1998), and the NA-MSS map shows that the boundary extends 850 km across the entire Arctic Slope. Other significant areas of calcium-rich tundra occur on glacial deposits on the northern front of the Brooks Range and in the rugged foothills north of the DeLong Mountains (i.e. region around the headwaters of the Kokolik, Utokok and Colville Rivers).

5. Conclusions

1. A remote sensing approach of extrapolating vegetation information from the well known but relatively small KRR to the much larger Arctic Slope was appropriate especially given the broad similarities of topography, climate and vegetation across the region and the availability of imagery very similar to that used for the KRR map.

2. The map portrays the tundra of the Arctic Slope as a much more complex mosaic than previous maps. Over half (59%) of the Arctic Slope is *Moist Tundra*, which is divided between three categories: *Moist Dwarf-shrub*, *Tussock-graminoid Tundra* (classic tussock tundra) 28%; *Moist Graminoid*, *Prostrate-shrub Tundra* (predominantly moist nonacidic tundra) 22%; and *Moist Tussock-graminoid*, *Dwarf-shrub Tundra* (moist acidic sandy tundra) 4%. *Shrublands* of various types cover about 19% of the Arctic Slope, *Wetlands and Water* cover about 15%, and *Alpine* areas cover about 12%.

3. Substantial areas of calcium-rich tundra occur particularly in the northern portion of the map. The map shows that the transition between moist acidic and nonacidic tundras stretches across all of the northern Arctic Foothills.

4. The pattern of *Shrublands* on the NA-MSS map, particularly in the southern and western portion of the Arctic Slope, is not seen on the other maps, but limited observations suggest that these shrublands do occur. If confirmed these patterns will be useful for relating shrub cover to present climate and terrain factors. The breaks between several of the land-cover categories are based on the abundance and/or stature of shrubs, and an objective evaluation of the accuracy of the portrayal of these breaks on the map is needed.

5. Overall, the level of agreement between the maps is not impressive (56.5% agreement with the MEA and 55.4% with the NA-AVHRR). The poor agreement with the MEA map could be expected because of the age and very general nature of the map. The poor agreement with the AVHRR data is due to a variety of factors including the very different methods for defining the land-cover categories and the lack of consistent criteria for the breaks between land-cover categories. The lack of correspondence within the KRR map area, where we have high confidence in the NA-MSS map, suggests that the AVHRR needs the most refinement. It would be highly beneficial to establish close agreement between the AVHRR map and the MSS-derived map so that circumpolar-scale extrapolations using AVHRR data could be attempted. AVHRR-derived maps of maximum NDVI may show stronger correspondence to the MSS-derived classes.

6. This NA-MSS map is a first approximation of the land cover of northern Alaska. Area measurements of land-cover types within the KRR compare favourably with the KRR-MSS classification, but a full evaluation of the success of the extrapolation to the remainder of the Arctic Slope will have to await an accuracy assessment planned for 1999.

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