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Use of Landsat TM Imagery in Determining Important Shorebird Habitat in the Outer Mackenzie Delta, Northwest Territories

C.L. GRATTO-TREVOR[1]

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ABSTRACT. Landsat Thematic Mapper (TM) imagery was examined to determine important habitats for shorebirds in the outer Mackenzie Delta, Northwest Territories. In June and July 1991 and 1992, 89 ground plots (200 × 200 m) in different habitats were censused for breeding shorebirds. Habitat type in ground plots was determined by observation and compared to the type identified at the site by an unsupervised Landsat classification technique.

The most common species of shorebirds breeding in the area were red-necked phalaropes (*Phalaropus lobatus*) and common snipe *(Gallinago gallinago)*, followed by semipalmated sandpipers (*Calidris pusilla*), stilt sandpipers (*C. himantopus*), pectoral sandpipers (*C. melanotos*), whimbrel (*Numenius phaeopus*), Hudsonian godwits (*Limosa haemastica*), lesser golden plovers (*Pluvialis dominica*), and semipalmated plovers (*Charadrius semipalmatus*). Long-billed dowitchers (*Limnodromus scolopaceus*) were rarely seen. Most species were concentrated in areas of low-centre polygons, sedge, and "low terrain" upland tundra (damp and tussocky). However, snipe were most common in dense willow habitat, and semipalmated plovers were found breeding only on sparsely vegetated gravel. Average density of breeding shorebirds in low-centre polygon or "pure" sedge habitat was 82 pairs per km^2 in 1991 (SD = 73.8), and 49 in 1992 (SD = 49.5).

Although the Landsat TM imagery analysis used here correctly identified habitat types near the original, intensively surveyed ("ground-truthed") area, it often misidentified habitats at some sites 10 to 30 km away, probably because of irregular flooding and subtle year-to-year differences in water levels in the active outer delta, and edge habitats too narrow to be distinguished by the satellite imagery. However, the technique can identify potential shorebird habitat roughly, and at least eliminate obviously unsuitable areas in large regions of the Arctic.

Key words: shorebirds, Landsat TM, Mackenzie Delta, habitat

RÉSUMÉ. On a examiné des images prises avec le capteur TM Landsat, afin de déterminer quels sont les habitats importants pour les oiseaux de rivage dans le delta aval du Mackenzie (Territoires du Nord-Ouest). En juin et en juillet 1991 et 1992, on a étudié 89 parcelles de terrain (de 200 m sur 200) dans différents habitats pour y recenser les oiseaux de rivage en train d'y nicher. On a déterminé le type d'habitat des parcelles de terrain par examen visuel et on l'a comparé à celui identifié pour chaque parcelle par une technique de classification non dirigée au Landsat.

Les espèces les plus courantes d'oiseaux de rivage en train de nicher dans la région étaient le phalarope hyperboréen (*Phalaropus lobatus*) et la bécassine des marais (*Gallinago gallinago*), suivies du bécasseau semipalmé (*Calidris pusilla*), du bécasseau à échasses (*C. himantopus*), du bécasseau à poitrine cendrée (*C. melanotos*), du courlis corlieu (*Numenius phaeopus*), de la barge hudsonienne (*Limosa haemastica*), du pluvier doré d'Amérique (*Pluvialis dominica*), et du pluvier semipalmé (*Charadrius semipalmatus*). Le bécasseau à long bec (*Limnodromus scolopaceus*) n'a été observé que de rares fois. La plupart des espèces étaient concentrées dans des zones de polygones concaves, de carex et dans la partie basse de la toundra de hautes-terres (humide et parsemée de buttes). Cependant, la bécassine des marais était plus commune dans un habitat de saules dense, et le pluvier semipalmé ne nichait que sur du gravier, où la végétation était éparse. Dans l'habitat de polygones concaves ou de carex «pur», la densité d'oiseaux de rivage nicheurs était en moyenne de 82 paires par km^2 en 1991 (écart-type = 73,8) et de 49 en 1992 (écart-type = 49,5).

Bien que l'analyse des images prises avec le capteur TM Landsat que l'on a utilisée identifie les types d'habitats proches de la zone originale, qui ont été validés sur le terrain, elle donne souvent une fausse identification des habitats situés sur certains sites qui s'en éloignent de 10 à 30 km, en raison surtout d'inondations irrégulières et de légères variations d'une année à l'autre du niveau de l'eau dans le delta aval actif, et dans des habitats en lisière trop étroits pour être distingués dans l'imagerie par satellite. Cette technique permet d'identifier en gros l'habitat potentiel des oiseaux de rivage, et d'éliminer des zones qui, de toute évidence, ne conviennent pas dans de vastes régions de l'Arctique.

Mots clés: oiseaux de rivage, TM Landsat, delta du Mackenzie, habitat

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[1] Prairie and Northern Wildlife Research Centre, Environment Canada, Canadian Wildlife Service, 115 Perimeter Road, Saskatoon, Saskatchewan S7N 0X4, Canada

INTRODUCTION

The breeding range of most North American shorebirds (Order Charadriiformes, suborder Charadrii) is restricted to arctic Canada and Alaska. Any major impact on habitat in these areas could have severe effects on population levels of entire species. However, our information on shorebird breeding densities and distributions throughout northern Canada is very sparse. Since logistical constraints prevent censusing the entire region, we need an efficient technique to identify important habitat types without extensive ground-truthing. Use of satellite imagery to map habitat types important to nesting shorebirds offers potential for extrapolation from small-scale ground surveys to larger areas. Although this method has been used with varying degrees of success to map and monitor wetlands (Tomlins and Boyd, 1988; Gross et al., 1989; Johnston and Barson, 1993), to classify muskox habitats (Ferguson, 1991), and even to estimate populations of dunlin (*Calidris alpina* L.) breeding in Scotland (Avery and Haines-Young, 1990), no published studies except that of Dickson and Smith (1991) have involved breeding shorebirds in the Canadian Arctic.

A previous study of the outer Mackenzie Delta reported that Landsat Thematic Mapper (TM) imagery could be used to identify and map vegetation types of the area (Jaques, 1987a, b; Dickson et al., 1989; Dickson and Smith, 1991) on the basis of an unsupervised classification procedure. Habitat types were ground-truthed in a small area of the outer delta (Fish Island and vicinity) and related to several types of satellite imagery, including Landsat Multi-Spectral Scanner (MSS) and Landsat TM. It was determined that Landsat TM imagery was superior in identifying potential nesting and staging habitats of migratory shorebirds.

The present study sought to determine whether previous results could be extrapolated to a broader area. Specifically, the objectives were: 1) to test whether the priority shorebird breeding habitat identified by Dickson et al. (1989) was indeed the habitat with highest densities of breeding shorebirds in the entire outer delta; and 2) to examine the accuracy of the Landsat TM analysis habitat classifications in the entire outer delta, using the same Landsat TM imagery and imagery analyses similar to those of the previous study.

STUDY AREA

The study area encompassed approximately 765 000 ha in the outer Mackenzie Delta, Northwest Territories, above the tree line (Fig. 1). High- or low-centre polygons (patterned ground) are common in areas that are poorly drained, with fine-grained materials, in continuous or discontinuous permafrost (Ritchie, 1984). Channel freeze-up begins in late September, and peak discharge into the delta follows breakup in late May or early June. Occasionally discharge is very high after heavy precipitation in late summer (Hirst et al., 1987). Temperature regimes and the amount of ice cover on delta channels determine the extent of spring flooding. In four of five years, thermal breakups occur during warm springs and flooding of the delta is minimal. Conversely, in about one year in five, mechanical breakups occur during cool springs, and up to 90% of the outer delta may be flooded (Blasco, 1991).

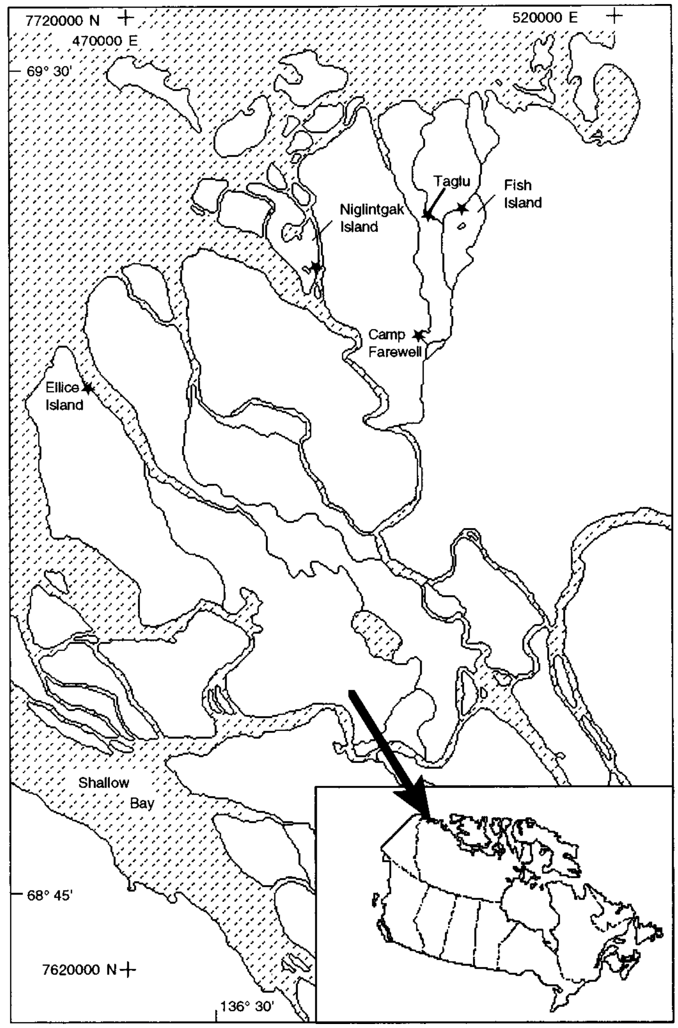

FIG. 1. Study area in the outer Mackenzie Delta, N.W.T. Campsites used in 1991 and 1992 are marked by small stars.

Flooding frequency, duration, rate of sediment deposition, and erosion rates are important in determining local vegetation. *Equisetum*, *Carex* and *Salix* exist in areas where flooding and siltation are most severe, while poplars and spruce are found in areas of infrequent flooding and little sediment deposition. Areas dominated by herbaceous plants flood annually, willow/alder habitats are flooded two to five years out of ten, and areas with spruce and alder flood one to two years out of ten (Hirst et al., 1987). Substrate factors such as soil texture, moisture, and drainage are also important in determining vegetation types present. Sedge, *Arctophila*, and *Equisetum* can survive inundation of more than 50 days per year, and stands of willow up to a month of flooding. Spruce and poplar are usually flooded for only two or three days per year. Silt deposition can be heavy in low areas (*Equisetum* areas averaged 9.2 cm per year), but is much lighter at higher elevations (Hirst et al., 1987). The Beaufort Sea coastline is submerging. Erosion occurs at the rate of 1–2 m per year, with some areas up to 10–20 m per year. Storm surges that result from strong onshore winds are most common in late summer, and can affect water levels as far south as Inuvik (Blasco, 1991). Plant communities in the delta area have been described in detail by Corns (1974), Dickson et al. (1989) and Jaques (1991).

The area was extensively surveyed for oil and gas reserves in the 1970s. Most gravel pads were constructed at this time. Considerable development (including processing plants and onshore and offshore pipelines) is planned when hydrocarbon prices make this economically feasible (R.A. Owens Environmental Services, 1989). This has led to an interest in determining population densities, distributions, and habitat requirements of wildlife, to ensure knowledgeable decisions regarding sustainable development and protection of these species.

STUDY SPECIES

Shorebirds breeding in the outer Mackenzie Delta include (in order of abundance) red-necked phalaropes, common snipe, semipalmated sandpipers, pectoral sandpipers, stilt sandpipers, long-billed dowitchers, semipalmated plovers, lesser golden plovers, Hudsonian godwits, and whimbrel. See Table 1 for scientific names. Another species identified as breeding in the area, at least historically, is the nearly extinct Eskimo curlew (*Numenius borealis* Forster) (Gollop et al., 1986); however, we observed none during this study.

TABLE 1. Breeding shorebirds observed in this study and their letter codes.

Species	Scientific name	Letter code
Lesser golden plover	*Pluvialis dominica* Müller	LGPL
Semipalmated plover	*Charadrius semipalmatus* Bonaparte	SEPL
Hudsonian godwit	*Limosa haemastica* L.	HUGO
Whimbrel	*Numenius phaeopus* L.	WHIM
Common snipe	*Gallinago gallinago* L.	COSN
Long-billed dowitcher	*Limnodromus scolopaceus* Say	LBDO
Semipalmated sandpiper	*Calidris pusilla* L.	SESA
Pectoral sandpiper	*Calidris melanotos* Vieillot	PESA
Stilt sandpiper	*Calidris himantopus* Bonaparte	STSA
Red-necked phalarope	*Phalaropus lobatus* L.	RNPH

These species are all migratory, wintering in South or Central America, or in the southern United States. The birds arrive in the Mackenzie Delta about the time of river ice breakup in the spring, and start to lay eggs by mid June (Dickson et al., 1989; Gratto-Trevor, 1994).

Mating systems are highly variable, and include polyandry (e.g., red-necked phalaropes), monogamy (e.g., semipalmated sandpipers), and polygyny (e.g., pectoral sandpipers). Incubation and/or brood care can be shared by both parents, or carried out by the male or female only, depending on the species. Nest failure is usually due to predation of shorebirds and their eggs. Foxes, weasels, hawks, owls, and jaegers are common predators of shorebird eggs, young, and sometimes adults (Gratto-Trevor, 1992). After about three weeks of incubation, shorebird eggs hatch. Shorebird hatch is fairly synchronous in an area: it is timed for peak insect emergence, particularly of dipterans such as midges and mosquitoes (Holmes and Pitelka, 1968; Nettleship, 1973). Young shorebirds are precocial, able to walk and feed themselves from hatch. They are brooded and guarded for several weeks by their parent(s). Young are fledged in two to three weeks, by which time many adults have migrated south. Juveniles follow several weeks after the adults, in late July and August (MacNeil and Cadieux, 1972; Ashkenazie and Safriel, 1979; Morrison, 1984).

METHODS

Landsat TM Analysis

The Landsat TM analysis was conducted by D. Jaques (Ecosat Geobotanical Surveys Inc., Vancouver), who also provided the analysis for the Dickson et al. (1989) study (Jaques, 1987a, b). Much of the following description of Landsat methodology is adapted from Jaques (1987a, b, 1991).

Four Landsat TM images were analyzed for a 23 July 1986 date: Track 64-Frame 11 Quadrant 3, 64-11 Quadrant 1, 64-12 Quadrant 8, and 64-12 Quadrant 12. Most of the study area, including all ground plot sites, was encompassed by Image #64-11 Quadrant 3, which is the image used by Dickson et al. (1989). The visible red (Channel 3: 0.63–0.69 μm), near-infrared (Channel 4: 0.76–0.90 μm) and mid-infrared (Channel 5: 1.55–1.75 μm) bands were analyzed for each Landsat TM image. For most types of surfaces, reflected radiation varies across different wavelengths in a characteristic pattern. For this reason, Landsat TM satellites contain a number of sensors, each measuring and recording amount of reflectance from a specific ground area (pixel) across a band of wavelengths (Thomas et al., 1987; Richards, 1993). The range of wavelengths in Landsat TM bands 3, 4, and 5 has been variously described as useful in differentiating plant species, land/water boundaries, amount of vegetation cover, and soil and vegetation moisture content (Rees, 1990; Johnston and Barson, 1993).

For every Instantaneous Field of View (IFOV) on the ground (a 30×30 m pixel), each Landsat TM sensor records a measure of the radiation intensity, called a Digital Number (DN). These DNs must be corrected by removal of radiometric and geometric errors, that is, by calibrating the detected signal and accurately relating the DNs to their position on the surface (Rees, 1990). Therefore, quantitative radiometric calibration was conducted on the raw data following the procedure described by Murphy (1983). Radiometric quality was good, and destriping procedures successful. Stripes, often present in raw Landsat data, are due to the slightly different calibration of each sensor in the satellite.

Calculations were performed on the radiometrically corrected data (in the forms: 3/[3+4+5], 4/[3+4+5], and 5/[3+4+5]) to eliminate most between-scene radiometric variance. Band ratios remove some viewing angle effects and compensate for the decrease in brightness away from the centre of the image (Rees, 1990).

The four images were pieced together and then geometrically corrected after initial classification. If data are geometrically corrected before classification, artificial data distributions and noda can occur, owing to changes in DN values produced by the resampling algorithm (Verdin, 1983; Jaques, 1987a). Classification after fitting together images can, however, lead to inconsistencies between scenes in defining habitat classes. Since all ground plots in this study were contained within one Landsat quadrant, this would not affect interpretation of the ground-truthing results. After the images were pieced together, the full image was geometrically corrected to 1:50 000 National Topographic System topographic map sheets. Forty-eight ground control points (points of known ground and image location) throughout the study area were used to produce the geometric transformation equation. A third-order polynomial relationship was derived from these data, and resampling was conducted to 30 m pixels (IFOV width and height for Landsat TM bands 3, 4, and 5). The geometric correction produced a UTM-corrected image mosaic with average accuracies of 6.3 m north-south and 8.1 m east-west, based on residual errors.

The purpose of a classification procedure is to lump together pixels with similar spectral signatures (similar DN values over the Landsat TM bands examined), which are presumably similar ground surfaces. If sufficient ground-truthing information is available throughout the study area, it can be used to 'train' a supervised classification. If not, an unsupervised classification can be used to produce clusters of points that are later related to ground cover (Richards, 1993). In the initial study (Dickson et al., 1989), an unsupervised classification produced classes that accurately reflected vegetation cover in their study area, including a habitat type used by most nesting shorebirds there. For that reason, and because detailed ground-truth data were available for only part of the entire area, an unsupervised classification algorithm for Maximum Likelihood Decision Rule (Van Trees, 1968) was also used here. This automated process finds clusters of DN values and assigns each pixel to the most likely cluster. The number of classes, level of difference necessary before another cluster is formed, and lower limits of probability before calling a pixel unclassifiable can be factored into the analysis. Here the initial classification produced 64 classes with distinct signatures (with a merge factor of 1.39). These were merged into 25 classes based on multispectral similarities (similar DNs in all three bands), using a decimation factor of 2.0. These 25 classes were then grouped into 16 major Landsat Classification Units (LCUs) based on geographic distribution, spectral signature similarities, and correlation with the ground-truth data and maps (Table 2).

These results were analyzed using detailed ground-truth data from colour aerial photographs taken in 1981, when B.C.

TABLE 2. Radiometric digital number (DN) values of 23 July 1986 Landsat TM classification for the outer Mackenzie Delta, N.W.T. (from Jaques, 1991).

LCU	Original Landsat Classification	Band 3 Mean DN (SD) μm		Band 4 Mean DN (SD) μm		Band 5 Mean DN (SD) μm	
1	1	207.7	(9.5)	152.5	(31.6)	0.02	(0.3)
1	2	197.3	(7.0)	134.4	(33.9)	6.3	(6.9)
1	3	217.3	(21.0)	78.9	(26.5)	12.1	(16.1)
4	4	105.9	(5.7)	180.1	(20.4)	104.0	(11.0)
5	5	93.2	(3.7)	251.3	(6.1)	82.8	(6.7)
2	6	170.7	(14.7)	126.3	(19.9)	42.1	(17.0)
3	7	135.3	(5.2)	111.7	(16.8)	96.5	(10.9)
2	8	170.6	(7.7)	162.0	(12.8)	25.7	(8.1)
6	9	127.7	(9.1)	227.5	(19.0)	51.5	(12.9)
7	10	113.2	(5.8)	116.3	(7.9)	124.2	(6.8)
2	11	166.1	(5.8)	203.3	(22.6)	12.6	(9.4)
3	12	153.2	(6.6)	98.6	(16.2)	78.5	(8.9)
8	13	129.2	(5.6)	63.3	(12.7)	127.1	(9.0)
8	14	142.0	(7.9)	62.5	(13.5)	110.6	(7.0)
9	15	120.6	(3.3)	155.6	(15.0)	95.9	(7.9)
10	16	102.5	(2.0)	155.8	(6.0)	119.9	(2.9)
11	17	131.4	(3.4)	161.0	(14.8)	78.6	(7.5)
11	18	136.7	(2.8)	184.0	(6.7)	61.0	(4.1)
8	19	114.2	(5.0)	86.8	(6.7)	136.7	(5.0)
12	20	111.0	(2.2)	140.2	(6.8)	116.0	(4.0)
13	21	116.0	(2.6)	132.8	(5.2)	112.7	(2.8)
14	22	104.9	(1.9)	137.7	(5.4)	125.3	(3.0)
15	23	99.4	(4.0)	216.5	(8.1)	95.7	(6.2)
16	24	114.5	(3.9)	201.4	(7.6)	82.7	(5.0)
16	25	105.4	(4.4)	230.7	(8.0)	81.2	(3.9)

Hydro flew across the delta from southwest to northeast midway within the outer delta (Pearce and Cordes, 1985). Vegetation mapping of Garry Island was also used (Kerfoot, 1969), as well as the vegetation mapping and habitat descriptions of Reid and Calder (1977). These sets of data were used to identify the vegetation characteristics of the Landsat Classification Units (LCUs) and to control revision of the initial mapping results. The final 16 LCUs were mapped onto colour Applicon maps at both 1:100 000 and 1:50 000 scales. Area computations were conducted via automated pixel count software.

Since the purpose of the present project was to test the results of the Dickson et al. (1989) study by extending the research area, methodology for the Landsat TM analysis was identical to that used by Dickson et al. (1989), including use of the same imagery (23 July 1986). However, with the exception of "priority shorebird habitat" (Landsat Classification Unit 9), habitat types identified in this study are not identical (although they are in most cases similar) to those of Dickson. In the present study habitats were selected more for ease of ground recognition by non-botanists, since the results were intended to provide simple habitat categories for use by ornithologists. For the same reason, as well as for statistical analysis of shorebird densities, I clumped the 16 LCUs into six general habitat types, plus water, also easily recognizable on the ground (Table 3). These were: unvegetated mudflats and gravel pads (Habitat Type I), emergent vegetation (II), wet sedge/willow habitats (III), dense willow (IV), upland tundra (V), and low-centre polygon or pure sedge habitats (VI).

TABLE 3. Landsat classification units (LCUs) and habitat types, excluding open water.

Habitat Type	LCU	Description
I (mudflats)	2	very wet bare mudflats with little or no vegetation cover; very shallow standing water
	3	moderately wet to dry mud/silt flats with *Equisetum* cover low to medium; gravel pads
II (emergents)	6	very wet emergents
	7	wet emergents (drier than LCU 6 and LCU 13)
	8	emergents/water complex; shoreline sites with low plant cover
III (wet sedge/willow)	11	willow, sedge, *Equisetum*/water complex, very wet
	12	short to medium willow (*Salix lanata*)/sedge (*Eriophorum*); higher plant cover than LCU 13
	13	short to medium willow/sedge (*Eriophorum*); wetter and lower plant cover than LCU 12
	15	moderately wet, medium to tall willow (*Salix richardsonii*)/sedge shrubland
	16	wet, moderately dense medium to tall willow (*Salix richardsonii*)/sedge shrubland
IV (dense willow)	4	high plant cover; willow/sedge uplands and alluvial flats; backslope shrub type
	5	alder and tall willow (*Salix alaskensis, S. lanata*) dense cover
V (upland tundra)	10	Pleistocene uplands dry tundra; dwarf shrub; higher
	14	Pleistocene uplands tundra; dwarf shrub; lower; tussocks
VI (sedge/low-centre polygons)	9	moderately wet, sedge/patterned ground

According to the Landsat analysis (Jaques, 1991), over 40% of the study area was open water. Excluding open water, the outer delta consisted of 11% mudflats, 15% emergent vegetation, 23% wet sedge/willow, 35% dense willow, 7% uplands, and 9% low-centre polygons or pure sedge.

Ground Plots

In 1991 and 1992, eighty-eight 200 × 200 m plots were censused for breeding shorebirds in these areas (Fig. 1): Fish Island (17 to 26 June 1991: 13 plots); Niglintgak Island (2 to 12 July 1991: 14 plots, including 1 gravel pad); Camp Farewell area (15 to 25 June 1991: 25 plots, including 1 gravel pad); northern Ellice Island (28 June to 2 July 1992: 11 plots, including 1 gravel pad); and Taglu (6 to 14 July 1992: 25 plots, including 7 gravel pads). Detailed maps of plots and records of each bird observed on or near a plot can be found in Gratto-Trevor (1994).

Plot locations, chosen to represent the major habitat types identified by Landsat TM analysis of the study area, were marked on detailed aerial photographs. Landsat-identified habitat types of each plot were obtained from the 1:50 000 colour Applicon maps. Observed habitat types were those actually seen on the ground, using the same seven categories described in the Landsat analysis. During each census, we noted habitat type and recorded the location and behaviour of shorebirds in the grid. Surveys were not carried out in snow, heavy rain, or high winds, in an effort to standardize visibility (and behaviour) of birds.

In 1991, each plot was divided into a 50 × 50 m grid, with a 1 m high stake with flagging tape placed every 50 m. Alternating flag colours by row allowed the observer to locate observations of shorebirds and nests accurately within the plot area. Each plot was censused three times by two or three observers walking 50 m apart. Observers walked along grid lines during the first and third censuses of a plot, but halfway between grid lines during the second census. In this way observers could have walked no farther than 12.5 m from a nest if it existed during any two censuses. Surveys of a plot were carried out anywhere from one to six days apart, but most commonly (85% of the time) three to five days apart, depending upon weather conditions. Time from first to third survey varied from four to nine days, averaging eight days (n = 26 plots, SD = 1.4 days). All flagging (except for one corner marker in some cases) was removed during the third survey. Information from the three surveys per plot was combined by overlaying locations of shorebirds in the grid, and obtaining an overall total for each plot.

In 1992, methods were adjusted slightly, in that each plot was censused only once by three observers walking 25 m apart. In this way, observers again approached within at least 12.5 m of any bird in the plot. Plots were not marked with flagging tape, but paced off in specific compass directions.

The number of shorebird pairs in a plot was determined by location and behaviour of shorebirds observed during censuses. Only birds flushed from or landing in the plot were counted. Since only male phalaropes care for eggs or young, female phalaropes were not considered when calculating breeding "pairs." In many cases, and most species, "pairs" were represented by single birds flushed from the plot. Breeding pairs per km^2 were obtained for different (observed) habitat types by multiplying plot means by 25 (each plot being 0.04 km^2). Gravel pads were excluded from analyses unless otherwise noted, as these were man-made habitats that contained only breeding semipalmated plovers.

RESULTS

Importance of Habitat Type to Breeding Shorebirds

Mean numbers of shorebird pairs per plot were greatest in observed Habitat Type VI (polygons or sedge) in both 1991 and 1992 (ANOVA with GT2 family error test for differences between habitat types; 1991 ANOVA $p = 0.02$, GT2 $p < 0.05$: VI > IV; 1992 ANOVA $p = 0.004$, GT2 $p < 0.05$: VI > V, VI > III; Fig. 2). Overall densities in Habitat Type VI were greater in 1991 than in 1992 owing to extremely large numbers of red-necked phalaropes in two 1991 plots.

Although the number of breeding pairs was low for observed Habitat Type V (upland tundra), this result is somewhat misleading. There were two types of uplands defined by Landsat: LCU 10 and LCU 14. LCU 10 was observed to be higher and drier than LCU 14, with a dense shrubby cover of birch and aspen. Any water present was in small, deep depressions. LCU 14, on the other hand, was most often an

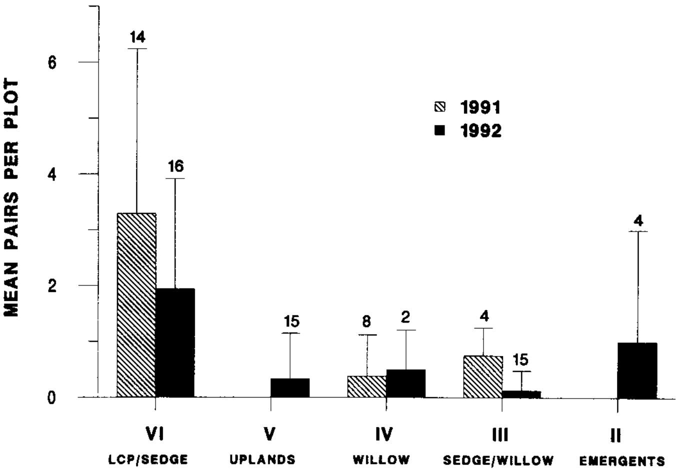

FIG. 2. Mean pairs of breeding shorebirds per plot in different habitat types observed in 1991 and 1992. Numbers above bars represent the number of plots surveyed.

TABLE 4. Estimated densities of shorebird species[1] in different (observed) habitat types; n = number of plots.

	Habitat Type (pairs/km²)								
	VI polygons or sedge		V uplands	IV willow		III&II wet sedge/ willow/ emergents		I gravel	
	1991 n=14	1992 n=16	1992 n=15	1991 n=8	1992 n=2	1991 n=4	1992 n=19	1991 n=2	1992 n=9
COSN	5	5	0	9	0	6	1	0	0
HUGO	4	1	0	0	0	6	0	0	0
LBDO	2	0	0	0	0	0	0	0	0
LGPL	0	2	2	0	0	0	0	0	0
PESA	2	2	0	0	0	0	0	0	0
RNPH	52	30	0	0	12[2]	6	7	0	0
SEPL	0	0	0	0	0	0	0	13	14
SESA	4	5	5	0	0	0	0	0	0
STSA	9	6	2	0	0	0	0	0	0
WHIM	5	2	0	0	0	0	0	0	0

[1] Species codes are listed in Table 1.
[2] One RNPH nest in small patch of wet sedge in dense willow plot.

upland "valley," lower and wetter than LCU 10, with hummocky grassy clumps of vegetation and often small creeks. No shorebirds were found breeding in LCU 10: none were present in any of the 10 plots. However, shorebirds were observed in three of the six LCU 14 plots, with a total of five pairs present (Mean = 0.83 pairs per plot, SD = 1.17). Three of these pairs were semipalmated sandpipers (three different plots, two nests, plus one with chick), one was a lesser golden plover nest, and one was a stilt sandpiper nest.

Species Densities in Different Habitats

Densities of each shorebird species in each observed habitat type were generally very similar in 1991 and 1992 (Table 4). In Habitat Type VI (low-centre polygons or sedge), red-necked phalaropes were the most common shorebirds, followed by stilt sandpipers and common snipe. Whimbrel, semipalmated sandpipers, Hudsonian godwits, lesser golden plovers and pectoral sandpipers were sometimes present, and rarely, long-billed dowitchers. This agrees with incidental observations in non-plot sites.

Most Type IV (dense willow) plots were censused in 1991, when only common snipe were observed in these plots. In 1992, one red-necked phalarope male and day-old chicks were found in a small patch of pure sedge in one of the two observed Type IV plots. Aside from such small patches of other habitat, no shorebirds other than snipe were ever found in dense willow, even during extensive travel in non-plot areas. In fact, even snipe were not common in the dense willow plots, although males were often seen and heard winnowing overhead.

All Type V (upland tundra) plots were censused in 1992. As noted earlier, "high-terrain" bushy uplands held no breeding shorebirds during the surveys. However, "low-terrain" wetter uplands held semipalmated sandpipers and lesser golden plovers as often as did Type VI habitat.

Shorebirds were not common in Type III (wet sedge/ willow) or Type II (emergents) plots, except in small patches of habitat with a reasonable understory (not too wet or too bare), where red-necked phalaropes were sometimes found. One snipe was also flushed from this habitat.

The only shorebirds found breeding on gravel areas were semipalmated plovers. Ten gravel pads or beaches were examined. A single pair of semipalmated plovers was observed on one pad, and two pairs on each of three other sites.

Combining the data from 1991 and 1992 plots, species densities in Type VI plots (low-centre polygons or pure sedge) ranged from red-necked phalaropes, at 40.0 pairs/ km², to lesser golden plovers and long-billed dowitchers at 0.8 pairs/km². The most common species in the uplands (Type V) was semipalmated sandpiper, at 5.0 pairs/km², and in dense willow (Type IV), common snipe at 7.5 pairs/ km². Red-necked phalaropes were again the most common species in Habitat Types II and III (emergents, wet sedge/ willow), at 6.5 pairs/km².

Accuracy of Landsat TM Habitat Type Identification

Plots were located in five general areas in 1991 and 1992, at varying distances from the original (Dickson and Smith, 1991) study area (Fig. 1, Table 5). The 11 gravel pads surveyed in 1991 or 1992 were all correctly identified by the Landsat analysis. The Fish Island and Niglintgak areas surveyed in 1991 were both low-lying and primarily damp to wet. They included no upland plots. Excluding gravel pads, habitat types of all 13 plots in the Fish Island area were correctly identified by the Landsat analysis (Table 5). Two of the 13 plots on Niglintgak Island were misidentified: one plot observed as Type VI (sedge) and another seen as Type IV (dense willow) were both defined by Landsat analysis as Type III (wet sedge/willow; Table 5).

In 1992, the 61 plots were scattered around three campsites: Taglu area (25 plots), Camp Farewell area (25 plots), and northern Ellice Island (11 plots). Excluding gravel pads, the remaining plots included Habitat Types III, IV and VI as in 1991, plus Types II (emergent vegetation) and V (upland tundra).

In the Taglu area, which was very near the Fish Island site, only 3 of 18 plots were misidentified (Table 5). Many plots were low-lying habitats, but uplands were also surveyed. One plot identified by the analysis as Type I (mudflats or gravel pads), and one identified as Type II (emergents) were observed as Type VI (polygons or sedge). One plot observed as Type VI was identified by Landsat as type III (wet sedge/willow).

TABLE 5. Percent accuracy of habitat types[1] defined by Landsat TM analysis versus observed habitat types, 1991 and 1992.

Location[2]	Year	% Correctly identified by Landsat (N)	Distance from Fish Island area (km)
Fish Island	1991	100 (13/13)	0
Taglu area	1992	83 (15/18)	0
Camp Farewell area	1992	54 (13/24)	10
Niglintgak Island	1991	85 (11/13)	15
North Ellice Island	1992	20 (2/10)	30

[1] Habitat types are defined in Table 3.
[2] Locations of camps are shown in Figure 1.

The Camp Farewell area was the farthest inland, and this region contained the greatest proportion of upland tundra of any area examined. Here 11 of 24 plots were misidentified by the Landsat analysis (Table 5). Three plots observed as Type V (upland tundra), one plot seen as Type III (wet sedge/willow), and one Type VI (polygons or sedge) were all identified by Landsat as Type IV (dense willow). Two plots observed as Type III were identified as Type VI, and two of Type VI, around pond margins, were described by Landsat analysis as Type V. Two other plots of Type VI were misidentified, one as Type II and the other as Type III.

Northern Ellice Island was the most coastal of all areas censused, and consisted entirely of low-lying sites, with no upland tundra. Eight of 10 plots were misidentified as to observed habitat type. Three plots of Type III and two of Type II were described by Landsat as Type VI. Two plots observed as Type III and one as Type II were defined as Type IV.

A chi-square goodness-of-fit test was used to determine whether significant differences in accuracy of Landsat-defined habitat types existed among the five sampling areas. Although the overall chi-square was not significant (chi-square = 7.03, df = 4, $p = 0.10$), calculation of Bonferroni 95% confidence intervals indicated that fewer plots than expected were correctly identified to habitat type for the Ellice Island area. Significance of Bonferroni confidence intervals is not dependent upon significance of the overall chi-square (Neu et al., 1974; Byers et al., 1984; White and Garrot, 1990).

Not surprisingly, given the disparities between ground-truthing and Landsat identification of habitat, there were no significant differences in mean pairs per plot among Landsat-identified habitat types in 1991. In 1992 the Landsat result was opposite to that for observed habitat type, with more breeding shorebirds in Habitat Types I and II (bare ground, emergents), than in Type VI (polygons and sedge) (1991 ANOVA $p = 0.12$; 1992 ANOVA $p = 0.053$, GT2 $p < 0.05$: II & I > VI).

DISCUSSION

Importance of Habitat Type to Breeding Shorebirds

The priority habitat type of Dickson et al. (1989), which here included both low-centre polygonal ground and pure sedge areas, contained by far the highest densities of breeding shorebird pairs (65/km^2), compared to dense willow (10/km^2), emergents and wet sedge/willow (10/km^2), and upland tundra (8/km^2). Most of these were red-necked phalaropes. Excluding phalaropes, the “priority” habitat still contained the highest densities of birds (25/km^2), with lower densities in upland tundra (8/km^2), dense willow (7/km^2), and emergents and wet sedge/willow (3/km^2). Excluding snipe, the next most common species, densities were still highest in polygon/sedge (20/km^2) and upland tundra (8/km^2), and lowest in dense willow (0/km^2) and emergents and wet sedge/willow (1/km^2). However, if only low-terrain upland tundra is considered, densities are similar (21/km^2) to those in priority habitat, when phalaropes and snipe are excluded. No birds were observed in high-terrain upland tundra plots.

The densities of birds in priority habitat appear comparable to results of Dickson et al. (1989) in primarily priority habitat on Fish Island (43 to 91 birds/km^2), although Dickson et al. calculated total birds, rather than pairs, per area. Since “pairs” does not necessarily mean that two birds were seen, numbers are not directly comparable. In wet sedge/patterned ground and wet sedge habitats at Stokes Point and Phillips Bay, Yukon, a far greater density of shorebirds was seen (176 birds/km^2) during ground transects, due mostly to high numbers of pectoral and semipalmated sandpipers (Dickson et al., 1988).

Species Densities in Different Habitats

Overall, red-necked phalaropes were the most common breeding shorebird, followed by common snipe. Stilt sandpipers and semipalmated sandpipers were also abundant. Hudsonian godwits and whimbrel were less common, and lesser golden plovers, pectoral sandpipers, and long-billed dowitchers even less so. Other studies in the area generally concur with these species-abundance rankings, but disagree in several respects. Martell et al. (1984) list common snipe as uncommon to rare above the tree line. This statement presumably comes from Porsild’s (1943) report, which also lists stilt sandpipers as very uncommon. Hudsonian godwits are not listed at all, but Barry and Spencer (1976) note that Porsild missed some species because he did not spend much time in the outer delta. Common snipe were most obvious during flight displays, but were flushed from plots on numerous occasions, particularly in 1991 when more willow sites were censused. Höhn (1959) noted changes in the bird composition of the Anderson River Delta in 1955 compared to a previous study there in the 1860s. He related this to a northward movement of the tree line and to loss of high-arctic shorebird species in the area. Perhaps snipe have moved north as well, even above the tree line.

In the western portion of the Mackenzie Delta, on the arctic coastal plain, semipalmated sandpipers, pectoral sandpipers, red-necked phalaropes, and lesser golden plovers were considered abundant in the early to mid-1970s, with common snipe and Baird's sandpipers (*Calidris bairdii* Coues) fairly common, and red phalaropes (*Phalaropus fulicarius* L.), buff-breasted sandpipers (*Tryngites subruficollis* Vieillot), long-billed dowitchers, whimbrels and stilt sandpipers uncommon (Salter et al., 1980). Also in the western part of the delta (Yukon), Hawkings (1986) listed red-necked phalaropes and semipalmated sandpipers as common, and pectoral sandpipers and common snipe as uncommon breeders. The remaining species observed in the present study were considered uncommon summer visitants. The western delta is apparently much drier than the central delta studied here.

Densities of individual species in Dickson's main study area on Fish Island ranged from a high of 46 birds/km^2 for red-necked phalaropes to a low of 1 lesser golden plover/km^2 (Dickson et al., 1989). These results agree reasonably well with densities obtained during the present study (Table 4). Those working primarily on the Yukon coast have tended to observe higher densities of most species overall, although results vary widely. Densities of lesser golden plovers, semipalmated sandpipers, pectoral sandpipers and long-billed dowitchers in particular seem higher in the west (in Hawkings, 1987).

Accuracy of Landsat TM Habitat Type Identification

The Landsat TM imagery analysis used here accurately identified habitat types in the vicinity of Dickson's original study area, Fish Island, so any differences in habitat categories between studies did not affect accuracy of the results. Even some distance away, at Niglintgak Island, priority shorebird habitat was correctly mapped. There it was observed as pure sedge, rather than the low-centre polygon habitat that Dickson et al. (1989) appeared solely to consider important shorebird nesting habitat (they did not study phalaropes). However, farther inland, in areas with a higher proportion of upland habitat, Landsat identification of habitat type was considerably less accurate, and at an exposed coastal location, very few plots were correctly mapped as to habitat type.

Some of the misidentifications can be explained by differences in water levels from year to year. The imagery used was from 1986, while fieldwork of the present study was carried out in 1991 and 1992. Since flooding regimes can differ greatly from year to year, areas suitable for shorebird nesting in one year may not be useful in other years. This would be particularly significant in regions most prone to flooding, such as low-lying sites adjacent to the coast. It seems unlikely that large portions of northern Ellice Island would have changed from sedge to bare ground/*Equisetum* in six years, although the coast is submerging and coastal erosion can be significant (Blasco, 1991). Results of this study suggest that areas on the coast defined as priority shorebird nesting habitat by the Landsat analysis, namely northern Ellice Island and the islands near the mouth of Shallow Bay, are currently very unlikely to provide sufficient cover for shorebird nesting.

Reasons for misidentification of habitat types in the inland area (Camp Farewell) are less clear. Sedge habitat along the margins of ponds within tundra uplands was often identified as uplands, presumably because the strip of habitat was too narrow to be recognized by the imagery. Upland sites were not common in Dickson's original study, so these habitats may have been less readily separated out by the analysis. Both upland tundra and dense willow consist of rather dense vegetation, and since not all dense willow was in wet areas, this may have led to signature overlap.

A number of factors can result in overlap of spectral signatures. Since the smallest area of measure in Landsat TM imagery is 30×30 m, any ground surface smaller than this will be measured as a mixture of reflectances from that surface and the others making up the remainder of the pixel. Many arctic vegetation units are smaller than 30×30 m, including individual polygons, or sedge habitat around the edges of ponds. While reflectance from low-centre polygon habitat is greatly influenced by the high soil moisture content, that of pond edges appears to be masked by the nearby upland habitat (and if edge enhancements are used to better differentiate water/land boundaries, narrow sedge edges are even more likely to be lost).

A combination of the visible and near-infrared spectral bands allows discrimination of bare soil or bodies of water from vegetation (De Jong, 1994), since the spectral reflectance of most chlorophyll-containing surfaces is similar (Thomas et al., 1987). Differentiation of specific types of vegetation can be more difficult. In visible wavelengths, pigmentation primarily controls the reflectance of vegetation. A decrease in chlorophyll production due to stress, disease, or senescence will lead to a corresponding decrease in reflectance in the chlorophyll absorption wavelengths. In the near-infrared, the interaction of incident radiation with the structure of leaves is more important in affecting reflectance. For example, mature plants, those with thick leaves, a dense covering of hair, or a thick waxy cuticle will have a higher reflectance than immature plants, or those with thin leaves. Reflectance over many wavelengths decreases with an increase in the moisture content of vegetation. Vegetation canopy degree of cover, geometry and configuration of ground cover, shadow, and salt or silt accumulation on plants also affect reflectance of vegetation (Gross et al., 1989). Wind or wilting may change the orientation of leaves from horizontal to vertical, and so result in increases in visible reflectance and decreases in near-infrared (reviewed in Thomas et al., 1987). These factors can be useful in separating various cover types, determining the condition of vegetation, or estimating biomass. However, because reflectance can vary with age of the plant, moisture content, and so on, these factors may result in the same species of plant having different reflectances over a single satellite image, or different species overlapping in spectral signature.

The soil background in areas of partial vegetation cover may also have a significant effect on reflectance (Huete, 1989). Particularly in areas of significant spatial soil-surface variations (due to dry matter accumulation, decomposition, topographic influences, irregular drying patterns, or variable wetting or drying cycles), reflectances of specific vegetation covers could vary widely. The soil-surface contribution to reflectance of vegetation cover varies with such factors as the amount of soil exposed, surface-moisture content, organic matter content (decomposed and undecomposed), particle size distribution, soil mineralogy, soil structure, surface roughness, and shadow.

Various atmospheric factors may also affect reflectance of a vegetation type (Kaufman, 1989). For example, clouds smaller than pixel size can generate changes in the apparent surface reflectance, as can dust or salt particles. If atmospheric effects vary over the satellite image, they may mask differences among vegetation types. The adjacency effect can also lead to misclassification, as it results in increased radiance detection above dark surfaces surrounded by adjacent bright areas (and vice versa).

Even if conditions for a particular vegetation cover (moisture, soil-surface, topography, atmospheric effects, etc.) are consistent across the entire study area, some habitat types may not be separable with Landsat imagery, no matter what combination of bands or analyses are used. Each Landsat sensor measures reflectance over a range of wavelengths. Therefore, if vegetation 'A' has a high reflectance at 0.77 μm, and vegetation 'B' is equally high at 0.89 μm (and this is their only major reflectance difference), these cover types would not be separable under Landsat TM imagery, since both 0.77 and 0.89 μm are contained within band 4, and so are not differentiated. Differences residing outside wavelengths measured would also be missed by TM sensors (Gross et al., 1989).

It is possible that fewer misclassifications would have occurred if a supervised, rather than unsupervised, classification had been used. Since a supervised classification uses areas of known habitat to train the computer to recognize spectral signatures of these habitat types, the habitat classes produced are recognizable ones. However, spectral signatures may overlap greatly among classes, making a great many pixels unclassifiable. On the other hand, an unsupervised classification produces statistically identifiable clusters of pixels. These clusters, or classes, then must be related to habitat type by ground-truthing. Since classes are based solely on spectral similarity rather than field data, it may be difficult to relate the classes to actual habitat types (Rees, 1990). Here detailed ground-truthing was available only for the Fish Island area. Dependence on a "training area" that may be unrepresentative of the classes existing in the study area as a whole can produce less useful results than an unsupervised classification that uses pixels from the entire area (Alföldi, 1978). For that reason, and because the unsupervised classification correctly identified habitat classes (particularly "priority" shorebird habitat) in the original study (Dickson et al., 1989), an unsupervised classification was used here.

Normally the accuracy of the classification increases with a decrease in the number of classes used (Rees, 1990). However, the final lumping of habitat classes here was made on the basis of ecological recognition, not spectral similarity (see Tables 2 and 3); this may have masked reasons for misclassifications of habitat types that appear visually different but may be very similar spectrally.

In a study examining the use of Landsat TM data for mapping and monitoring wetlands in British Columbia, Tomlins and Boyd (1988) determined that a supervised classification produced superior results to an unsupervised analysis. However, although large and homogenous plant communities and ponds and lakes were accurately classified (70–97% correct) using a supervised classification, small or heterogenous plant communities, and those in complex transition zones (particularly edges of small wetland polygons) were poorly classified. The authors concluded that in small and complex plant communities, Landsat TM imagery will not provide sufficient resolution for accurate examination of wetland communities. A more recent, but similar study of wetlands in Australia (Johnston and Barson, 1993), found that cluster-classes identified by an unsupervised Landsat TM classification represented variability in vegetation density, productivity and soil moisture, rather than different plant species. They concluded that preliminary mapping units could be identified from this technique. When they performed a supervised classification, no simple correlation was found between vegetation classes identified on the ground and the spectral data. The authors suggested that a greater number of classes identified by ground-truthing might have improved the supervised classification, but that some vegetation types are not sufficiently different spectrally to be separated reliably. They noted the importance of matching the data resolution to the task.

In the current study, part of the difficulty in accurately relating habitat type to classes produced by the Landsat analysis may have been that the difference between good and poor shorebird habitat often depends on subtle differences in water levels and "understory" vegetation. In much of the active outer delta, as noted, these factors can change considerably from year to year. In addition, most arctic nesting shorebirds are small, and do not breed colonially. Therefore, they can nest in very small patches of appropriate habitat that the Landsat TM imagery cannot distinguish. Specific habitat associations for breeding shorebirds were not tested, but all 'priority' habitat was associated with ponds or wet areas.

CONCLUSIONS

The priority shorebird nesting habitat identified by Dickson et al. (1989) certainly contained the highest densities of breeding shorebirds. However, in this study it included sedge meadows, in addition to well-developed low-centre polygonal ground. Densities of shorebirds breeding in the outer delta were not extremely high, except for some dense patches of red-necked phalaropes. Fish Island and vicinity, including the area just east of Big Horn Point, are among the most significant breeding areas for shorebirds in the delta. However, areas defined by the Landsat TM analysis as priority shorebird nesting habitat that are directly on the Beaufort Sea coast, including northern Ellice Island and many of the islands near the mouth of Shallow Bay, are unlikely to be useful to nesting shorebirds because extensive and prolonged flooding has resulted in a lack of ground cover vegetation. As these areas were not ground-truthed until 1992, it is not known whether this reflects misidentification by the Landsat analysis used here or actual changes in vegetation since the satellite imagery was taken in 1986.

This Landsat TM analysis, while correctly identifying priority shorebird habitat in areas that were intensively ground-truthed, may not always be readily extrapolated to surrounding areas, particularly those subject to rapid habitat change (e.g., irregular flooding of the delta). This limits its use in estimating shorebird breeding densities in large regions of the Arctic. However, an unsupervised classification of Landsat TM imagery may be useful in roughly identifying potential shorebird habitat, and at least in eliminating obviously unsuitable areas. Even with a supervised classification using many detailed training areas, as noted by Rees (1990), perfect multispectral classification of homogeneous ground surfaces will not exist unless every possible surface material has a unique, known, and constant spectral signature, and until an errorless sensor measuring reflectance over the entire spectrum of wavelengths is created. In agreement with Johnston and Barson (1993), I conclude that the primary savings in using satellite imagery may be in reducing field costs and time by allowing a better targeting of field survey sites.

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REFERENCES

ALFÖLDI, T.T. 1978. Introduction to digital images and digital analysis techniques: A basic course for the appreciation of digital analysis of remotely sensed multispectral data. Canadian Centre for Remote Sensing Technical Note 78-1. Ottawa: Energy, Mines and Resources Canada.

ASHKENAZIE, S., and SAFRIEL, U.N. 1979. Breeding cycle and behaviour of the semipalmated sandpiper at Barrow, Alaska. Auk 96:56–67.

AVERY, M.I., and HAINES-YOUNG, R.H. 1990. Population estimates for the dunlin (*Calidris alpina*) derived from remotely sensed satellite imagery of the Flow Country of northern Scotland. Nature 344:860–862.

BARRY, T.W., and SPENCER, R. 1976. Wildlife response to oil well drilling. Canadian Wildlife Service Progress Notes No. 67. Ottawa: Environment Canada.

BLASCO, S.M. 1991. Regional sea-level changes and coastal retreat in the Canadian Beaufort-Mackenzie region (Abstract). In: Marsh, P., and Ommanney, C.S.L., eds. Mackenzie Delta: Environmental interactions and implications of development. NHRI Symposium No. 4. Saskatoon, Saskatchewan: National Hydrology Research Institute, Environment Canada. 173.

BYERS, C.R., STEINHORST, R.K., and KRAUSMAN, P.R. 1984. Clarification of a technique for analysis of utilization-availability data. Journal of Wildlife Management 48:1050–1053.

CORNS, I.G. 1974. Arctic plant communities east of the Mackenzie Delta. Canadian Journal of Botany 52:1731–1745.

DE JONG, S.M. 1994. Derivation of vegetative variables from a Landsat TM image for modelling soil erosion. Earth Processes and Landforms 19:165–178.

DICKSON, D.L., DICKSON, H.L., and AIUDI, G.M. 1988. Bird surveys at Stokes Point and Phillips Bay, Yukon in 1983. Canadian Wildlife Service Technical Report No. 40. Edmonton, Alberta: Canadian Wildlife Service, Environment Canada.

DICKSON, H.L., and SMITH, A.R. 1991. Use of Landsat Thematic Mapper and multi-spectral scanning imagery to identify habitats and shorebird nesting areas on the outer Mackenzie River Delta, NWT. In: Marsh, P., and Ommanney, C.S.L., eds. Mackenzie Delta: Environmental interactions and implications of development. NHRI Symposium No. 4. Saskatoon, Saskatchewan: National Hydrology Research Institute, Environment Canada. 91–106.

DICKSON, H.L., JAQUES, D., BARRY, S., TELFER, E.L., and SMITH, A.R. 1989. Identification of nesting and staging shorebird areas in the Mackenzie River delta and Richards Island area, Northwest Territories, using Landsat Thematic Mapper Imagery, 1985–1987. NOGAP Project C7.3. Unpubl. report. Available at Canadian Wildlife Service, 4999 – 98 Avenue, Edmonton, Alberta T6B 2X3, Canada.

FERGUSON, R.S. 1991. Detection and classification of muskox habitat on Banks Island, Northwest Territories, Canada, using Landsat Thematic Mapper data. Arctic 44(Supp. 1):66–74.

GOLLOP, J.B., BARRY, T.W., and IVERSON, E.H. 1986. Eskimo curlew: A vanishing species? Special Publication 17. Regina: Saskatchewan Natural History Society. 160 p.

GRATTO-TREVOR, C.L. 1992. Semipalmated sandpiper. In: Poole, A., Stettenheim, P., and Gill, F., eds. The birds of North America, No. 6. Philadelphia: Academy of Natural Sciences and Washington, D.C.: American Ornithologists' Union. 20 p.

———. 1994. Use of Landsat TM Imagery in determining priority shorebird habitat in the outer Mackenzie Delta, NWT (NOGAP subproject C.24). Unpubl. report. Available at Canadian Wildlife Service, Environment Canada, Prairie and Northern Wildlife Research Centre, 115 Perimeter Road, Saskatoon, Saskatchewan S7N 0X4, Canada. 217 p.

GROSS, M.F., HARDISKY, M.A., and KLEMAS, V. 1989. Applications to coastal wetlands vegetation. In: Asrar, G., ed. Theory and applications of optical remote sensing. New York: John Wiley and Sons. 474–490.

HAWKINGS, J. 1986. Breeding bird survey of the Whitefish Station area, Mackenzie Delta, 1985. Canadian Wildlife Service Technical Report Series No. 4. Delta, British Columbia: Canadian Wildlife Service, Environment Canada.

———. 1987. Population status of migratory waterbirds on the Yukon coastal plain and adjacent Mackenzie Delta. Canadian Wildlife Service Technical Report Series No. 28. Delta, British Columbia: Canadian Wildlife Service, Environment Canada.

HIRST, S.M., MILES, M., BLACHUT, S.P., GOULET, L.A., and TAYLOR, R.E. 1987. Quantitative Synthesis of the Mackenzie Delta Ecosystem. Unpubl. report for Inland Waters Directorate, Western and Northern Region, Environment Canada, Edmonton, by Applied Ecology Ltd, North Vancouver. Available from Inland Waters Directorate, Environment Canada, 200 Twin Atria Building, 4999 – 98 Avenue, Edmonton, Alberta T6B 2X3, Canada.

HÖHN, E.O. 1959. Birds of the mouth of the Anderson River and Liverpool Bay, N.W.T. Canadian Field-Naturalist 73:93–114.

HOLMES, R.T., and PITELKA, F.A. 1968. Food overlap among coexisting sandpipers on northern Alaska tundra. Systematic Zoology 17:305–318.

HUETE, A.R. 1989. Soil influences in remotely sensed vegetation-canopy spectra. In: Asrar, G., ed. Theory and applications of optical remote sensing. New York: John Wiley and Sons. 107–129.

JAQUES, D. 1987a. Landsat Imagery for identification and mapping of shorebird habitat in the Mackenzie Delta, Northwest Territories, Canada. Unpubl. report prepared for Canadian Wildlife Service, 4999 – 98 Avenue, Edmonton, Alberta T6B 2X3, by Ecosat Geobotanical Surveys, Inc., North Vancouver.

———. 1987b. Identification of potential shorebird nesting and staging habitat sites using Landsat Thematic Mapper Imagery in the outer Mackenzie Delta, NWT, Canada. Unpubl. report prepared for Canadian Wildlife Service, 4999 - 98 Avenue, Edmonton, Alberta T6B 2X3, by Ecosat Geobotanical Surveys, Inc., North Vancouver.

———. 1991. Landsat Thematic Mapper Imagery for mapping vegetation of the outer Mackenzie Delta, Northwest Territories, Canada. Unpubl. report prepared for Canadian Wildlife Service, 4999 - 98 Avenue, Edmonton, Alberta T6B 2X3, by Ecosat Geobotanical Surveys, Inc., North Vancouver.

JOHNSTON, R.M., and BARSON, M.M. 1993. Remote sensing of Australian wetlands: An evaluation of Landsat TM data for inventory and classification. Australian Journal of Marine and Freshwater Research 44:235–252.

KAUFMAN, Y.J. 1989. The atmospheric effect on remote sensing and its correction. In: Asrar, G., ed. Theory and applications of optical remote sensing. New York: John Wiley and Sons. 336–389.

KERFOOT, D.E. 1969. The geomorphology and permafrost conditions of Garry Island, NWT. Unpublished Ph.D. dissertation, University of British Columbia, Vancouver.

MacNEIL, R., and CADIEUX, F. 1972. Fat content and flight-range capabilities of some adult spring and fall migrant North American shorebirds in relation to migration routes on the Atlantic coast. Naturaliste Canadien 99:589–605.

MARTELL, A.M., DICKINSON, D.M., and CASSELMAN, L.M. 1984. Wildlife of the Mackenzie Delta Region. Boreal Institute for Northern Studies, Occasional Publication No. 15. Edmonton, Alberta.

MORRISON, R.I.G. 1984. Migration systems of some New World shorebirds. In: Burger, J., and Olla, B.L., eds. Behavior of Marine Animals, Vol. 6. New York: Plenum Press. 125–202.

MURPHY, J.M. 1983. Revised radiometric calibration technique for Landsat 4 Thematic Mapper data. Proceedings of the Third Landsat Imagery Directed Questions and Answers (LIDQA) Workshop, Ottawa.

NETTLESHIP, D.N. 1973. Breeding ecology of turnstones *Arenaria interpres* at Hazen Camp, Ellesmere Island, Northwest Territories. Ibis 115:202–217.

NEU, C.W., BYERS, C.R., PEEK, J.M., and BOY, V. 1974. A technique for analysis of utilization-availability data. Journal of Wildlife Management 38:541–545.

PEARCE, C.M., and CORDES, L.D. 1985. Vegetation colonization on the Mackenzie Delta, 1981–1983. Unpubl. report. Available at B.C. Hydro and Power Authority, 333 Dunsmuir, Vancouver, British Columbia V6B 5R3, Canada.

PORSILD, A.E. 1943. Birds of the Mackenzie Delta. Canadian Field-Naturalist 57:19–35.

R.A. OWENS ENVIRONMENTAL SERVICES LTD. 1989. Land-use requirements for anticipated hydrocarbon developments in the Mackenzie Delta-Beaufort Sea Land Use Planning Region. Unpubl. report. Available at Canadian Association of Petroleum Producers, 2100, 350 – 7 Avenue SW, Calgary, Alberta T2P 3N9, Canada.

REES, W.G. 1990. Physical principles of remote sensing. Cambridge: Cambridge University Press.

REID, D.E., and CALDER, G.M., eds. 1977. Vegetation survey and disturbance studies along the proposed Arctic Gas Route. Arctic Gas Biological Report Series, Vol. 37, Chapter 4. Calgary: Canadian Arctic Gas Study Ltd.

RICHARDS, J.A. 1993. Remote sensing digital image analysis. New York: Springer Verlag.

RITCHIE, J.C. 1984. Past and present vegetation of the far Northwest of Canada. Toronto: University of Toronto Press.

SALTER, R.E., GOLLOP, M.A., JOHNSON, S.R., KOSKI, W.R., and TULL, C.E. 1980. Distribution and abundance of birds on the Arctic Coastal Plain of northern Yukon and adjacent Northwest Territories, 1971–1976. Canadian Field-Naturalist 94:219–238.

THOMAS, I.L., BENNING, V.M., and CHING, N.P. 1987. Classification of remotely sensed images. Bristol, U.K.: IOP Publications Ltd.

TOMLINS, G.F., and BOYD, W.S. 1988. An assessment of Landsat-5 Thematic Mapper data for mapping and monitoring wetlands: Summary report. Canadian Wildlife Service Technical Report Series No. 46. Delta, British Columbia: Canadian Wildlife Service, Environment Canada.

VAN TREES, H.L. 1968. Detection, estimation, and modulation theory, Part 1. New York: John Wiley and Sons.

VERDIN, J. 1983. Corrected *versus* uncorrected Landsat 4 MSS data. NOAA Landsat Data Users Notes 27:4–8.

WHITE, G.C., and GARROT, R.A. 1990. Analysis of wildlife radio-tracking data. New York: Academic Press.