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ABSTRACT

Qualitative and anecdotal reports indicate the disappearance of vegetation from the outermost part of the Anderson River delta, Northwest Territories, possibly due to increased soil salinity. The delta, part of a federal migratory bird sanctuary, is among the most important areas for breeding and summering birds in the Northwest Territories, and loss or degradation of habitat there is an important conservation issue. Thus, the objective of this study was to quantify the amount of habitat loss at the Anderson River delta and determine when the loss occurred.

We mapped changes in vegetation cover of the Anderson River delta, for the 31-year period 1972–2003, using 13 multispectral images gathered by sensors on the American Landsat satellite series. In any time series analysis such as this, it is important to account for variability in the satellite imagery (e.g., differences in sensor types, aging of the sensors, atmospheric effects, and annual differences in weather or growing season) which could influence results. In order to account for the instrument effects, and to partially correct for atmospheric effects, we attempted to convert the satellite images from 8-bit scaled Radiance at the Sensor data to 32-bit radiance, and then to Top of the Atmosphere reflectance, using calibration constants provided by the data suppliers. However, calibration data were not available for all of the scenes. Therefore, we precisely co-registered all images in the series, and then transferred the calibration from the well-calibrated 1986 image to those scenes with no or questionable calibration data. In an attempt to limit the seasonal effects, we chose images from a limited period each year (30 June to 8 August), matching the peak of summer vegetative growth. Small differences in the "biological" date of the images probably remained after this matching, as the timing of the seasons can vary significantly among years. Therefore, we also considered annual variability in spring weather (June temperatures) when carrying out analyses and evaluating long-term changes in vegetation.

The Normalized Difference Vegetation Index (NDVI), a quantitative index of chlorophyll-containing plant biomass or vegetative cover, was calculated for each image in the time series. Long-term changes in NDVI were assessed in three ways: (1) by measuring the areal extent of habitat change over the 31-year study period; (2) by estimating the change in mean NDVI over time for several Regions of Interest (ROIs)

within the study area; and (3) by creating thematic maps of NDVI change over time using an unsupervised remote-sensing approach.

Results of the three types of analysis showed good agreement. The areal extent of habitat loss in the Outer Islands ROI used by most of the nesting Lesser Snow Geese (*Chen caerulescens caerulescens*) and Black Brant (*Branta bernicla nigricans*) was 45% and the mean NDVI value for the ROI declined by 37.5%. Reductions in areal extent of plant cover (ranging from 7% to 92%) and NDVI (ranging from 7.9% to 78.6%) varied greatly among the seven smaller regions that made up the Outer Islands ROI. In one other large ROI (the Western Delta), the extent of vegetation cover declined by 18%, and the mean NDVI declined by 11.9%. Visual observations of habitat change indicate that dead shrubs and barren mud flats now occupy significant parts of the delta that were apparently well vegetated by willows, grasses and sedges, and other herbaceous plants in the past. Soil samples taken from the areas with degraded habitat are highly saline, implicating salt water flooding by the Beaufort Sea as a potential cause of vegetation loss. NDVI values in the Outer Islands and parts of the Western Delta were variable from year to year and we were unable to attribute NDVI change to catastrophic loss of habitat such as might be caused by large storm surges in one or two years. Rather, it appeared that loss in vegetation has been occurring gradually since at least 1972.

In contrast to the situation in the outer delta, where vegetation loss was prevalent, our analyses showed that the NDVI values for upland tundra near the Anderson River delta increased by 21.1% between 1972 and 2003. There was also a significant correlation between NDVI and spring temperature for the uplands area. These findings were in agreement with other studies carried out since the 1980s in Siberia and Alaska that used Advanced Very High Resolution Radiometer (AVHRR) data to describe a 25-year period of more or less constant increase in NDVI. However, our longer time series showed a period of considerable inter-annual variations in NDVI and both high and low NDVI values early in our time series that were apparently driven by relatively warm (1972, 1982) and cool (1974, 1978) spring weather, respectively. The significant positive relationship between uplands NDVI and year no longer existed when the influence of June weather (mean daily temperature) was "controlled for" statistically.

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1. INTRODUCTION

The Anderson River Delta Migratory Bird Sanctuary, in the western Canadian Arctic, is one of the most important breeding and summering areas for waterfowl and other migratory birds in the Northwest Territories (Latour et al. 2008). Several low-lying islands, which cover an area of about 12.5 km^2 in the outer delta of the Anderson River, are a particularly important nesting area for Lesser Snow Geese (*Chen caerulescens caerulescens*) and Black Brant (*Branta bernicla nigricans*). During the 1970s and 1980s, 4000 to 8000 Lesser Snow Geese nested in the outer Anderson River delta (Kerbes 1986; Kerbes et al. 1999). The islands and nearby parts of the delta also provided nesting habitat for up to 2500 Black Brant — nearly 6% of the Canadian population of this subspecies (Latour et al. 2008). Since the 1980s, the numbers of both Lesser Snow Geese and Black Brant have declined markedly (Armstrong 1998; Hines and Wiebe Robertson 2006), possibly due to vegetation changes in the outer delta that were observed as early as 1991 (Armstrong 1995) but which may have been occurring much earlier. Since then, further degradation of the habitat has been observed both by local Inuvialuit, who travel, fish, and hunt in the area, and by Canadian Wildlife Service (CWS) biologists. Highly saline soils occur in areas with dead vegetation (CWS, unpublished data) implicating flooding of the delta by salt water as a possible cause of habitat loss. There are no systematic ground observations in the area over time; however, satellite multispectral imagery from the U.S. Landsat series has been available since 1972 and has been used to quantitatively map environmental changes in all parts of the world, including the Arctic (e.g., Tucker et al. 1985; Ferguson 1991; Gould 1998). Landsat imagery has recently been used to detect qualitative changes in the arctic habitats preferred by nesting geese in the lowlands near Hudson Bay (Jefferies et al. 2006).

The objective of this analysis was to quantify the reports of habitat loss at the Anderson River delta using satellite imagery, identify areas that had been impacted, and determine if the changes were associated with any specific time interval. By so doing, we hoped to determine if habitat loss was gradual (perhaps reflecting slower long-term degradation of the site) or whether it could be associated with any particularly significant environmental event such as an unusually high fall storm surge from the Beaufort Sea or exceptional spring flooding of the Anderson River.

2. THE STUDY AREA

The Anderson River empties into the Beaufort Sea at Wood Bay (69°42′N, 129°00′W) about half way between the communities of Paulatuk and Tuktoyaktuk, Northwest Territories, in the western Canadian Arctic. The river delta and surrounding area is particularly important to migratory birds, leading to its designation as a Migratory Bird Sanctuary in 1961 (Figure 1). As reported by Latour et al. (2008), "the river spans the transition from spruce forest to dwarf shrub tundra and flows through a gradually widening floodplain that is flanked by river terraces. The delta of low alluvial islands, channels, and lakes extends northward into the shallow waters of Wood Bay. The surrounding landscape is generally low and rolling and is dotted with lakes and ponds. The lower river passes through sedimentary rocks of Cretaceous origin. Tundra polygons have developed in poorly drained soils around the river mouth." Levees occur along the shores of islands subject to spring flooding. The outer part of the Anderson River delta, including several low-lying islands, is characterized by mud flats, grass and sedge cover in some low wet areas, and low willows (<1 m tall), as well as a variety of herbaceous plants on levees and other slightly drier ground. As indicated by the presence of lines of driftwood deposited well above normal summer water levels, most of the outer delta is flooded by the spring freshet of the Anderson River or by fall storm surges off the ocean. Tides in Wood Bay have a range of about 0.5 m (Fisheries and Oceans Canada 2007), but much higher or lower water levels can be expected under conditions of strong onshore or offshore winds.

The biological importance of the area to migratory birds has been described by Barry (1967), Alexander et al. (1991), and Latour et al. (2008) and the numerous sources referred to therein. Historically, the islands and nearby parts of the outer delta have been especially important to Lesser Snow Geese (*Chen caerulescens caerulescens*) and Black Brant (*Branta bernicla nigricans*). As noted above, numbers of both species have declined markedly since the 1980s, possibly due to changes in vegetation in the outer delta.

3. METHODS

Acquisition and processing of Landsat data

The first satellite sensors with moderate resolution and multispectral imagery capable of quantitatively mapping vegetation were launched as part of the American Landsat series in 1972 (United States Geological Survey 2005, 2007). This series has provided nearly continuous global coverage since that time, with increases in spatial resolution, reductions in sensor noise, and improvements to many other sensor characteristics over time (Table 1).

We assembled a series of 13 cloud-free summer images for 12 years between 1972 and 2003 (Table 1). Two images from the same date, 18 July 1986, were selected for validation purposes (discussed below) but other scenes were selected to be as equally spaced in time as image availability and quality permitted. We restricted our analyses to images acquired from 30 June to 8 August, a period that included the peak of vegetation growth and was before the first heavy autumn frosts. Similarly, Stow et al. (2004) found that the tundra vegetation near Barrow, Alaska, reached its peak at the end of July and the beginning of August.

Image data from the Multispectral Scanner (MSS) on Landsats 1, 2, and 3, the Thematic Mapper (TM) on Landsat 5, and the Enhanced Thematic Mapper (ETM) on Landsat 7 were obtained from three suppliers:

(1) Global Land Cover Facility (GLCF) at the University of Maryland — an online global archive of selected Landsat and other data at www.landcover.org (University of Maryland 2008);
(2) MacDonald, Dettwiler and Associates Ltd. (MDA), a commercial vendor providing access to Canadian government archives; and
(3) the United States Geological Survey (USGS) EROS Data Center (EDC), Sioux Falls, South Dakota, which holds one of the largest collections of aerial and satellite images of the Earth surface.

All image processing was carried out with the commercial image-processing program ENVI™ version 4.3 (Research Systems 2004). Each 180 km × 180 km Landsat scene was first converted to UTM Zone 9 WGS84, and then cropped to include only the region immediate to the Anderson River delta to reduce processing times. The imagery was obtained in a variety of formats and geometries. Therefore, we manually co-registered all of the images after cropping to include only the area of interest. The 80-m MSS data were resampled to 30 m so that they could be analyzed together with the 30-m TM data.

We were concerned that calculated products from the MSS and TM sensors might differ because their spectral bands were not identical. Other authorities (reviewed in Coppin et al. 2004) have reported no differences in estimates made using the two different sensors, but their studies were for lower latitude environments, and might not be directly applicable to the Arctic. Our comparison of an MSS and a TM scene for the same day in 1986 also showed very small differences in the Normalized Difference Vegetation Index. Since the MSS and TM sensors were responding similarly to the amount of green vegetation present, we used the two types of imagery in our time series analysis. For 1986, we used the TM scene.

Many studies (reviewed in Coppin et al. 2004) emphasize the importance of calibrating Landsat imagery from raw digital numbers to reflectance or performing some type of normalization to remove calibration and sensor differences among images. This was particularly important for our study, as there were large between-scene differences in image brightness that made interpretation of the raw data difficult. The differences in brightness were primarily related to the way the imagery had been "pre-processed" by the data providers and were also influenced by differences in gain calibration of different sensors over time. Reflectance is the ratio of the radiant light energy reflected from a target to the amount of light energy striking the target. Top of Atmosphere (TOA) reflectance units take into account variation in solar radiation due to the earth–sun distance and seasonal and diurnal changes in solar elevation (Olsson 1995; Chander and Markham 2003), but can be calculated only where reliable calibration data exist. Absorption and scattering within the atmosphere are not included in TOA reflectance.

We calculated at-sensor TOA reflectance for every scene, using ENVI™ to first convert digital data from scaled 8-bit digital numbers back to 32-bit at-sensor radiance (a measure of radiant intensity arriving at the sensor per unit area, solid angle, and over a given wavelength range) based on the calibration coefficients supplied with each scene or, for one scene with no metadata, the closest scene in time. We then converted the at-sensor radiance values to TOA reflectance using a model that predicted illumination from latitude, longitude, date, and time. However, calibration constants were not available for every scene, and some (including the scene for which we assigned calibration constants) were highly suspect.

We have taken two approaches to calibrate the imagery. For the period 1985 to 2003, we relied on the *absolute calibration* of Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper imagery using the metadata provided to calculate TOA reflectance. In order to extend the MSS imagery from the 1972–1982 period, and for the 1988 and 1992 TM scenes from the Global Land Cover Facility that appeared to have different pre-processing, we circumvented the lack of reliable calibration data via a *relative calibration* using the pseudo-invariant target technique (Hall et al. 1991). Each scene requiring a relative calibration was compared to the 1986 TM scene. Pairs of reflectance values were chosen from the two scenes for between 15 and 30 locations assumed to have constant reflectance over time (e.g., deep dark ocean water and unvegetated areas). An adjustment gain and offset (relative to the 1986 scene) for each scene to be normalized was derived from a regression of these paired reflectance values (Table 1). R^2 values for these regressions exceeded 0.95, indicating the reliability of making such adjustments.

The Normalized Difference Vegetation Index

In order to evaluate changes in plant cover among years, we employed a commonly used index of photosynthetic green biomass, the Normalized Difference Vegetation Index (NDVI) (e.g., Tucker et al. 1985). NDVI is the ratio of the measured intensities in the red and near-infrared spectral bands. The principle behind NDVI is that chlorophyll causes considerable absorption of incoming sunlight in the red region of the electromagnetic spectrum, whereas the spongy mesophyll of a plant leaf creates considerable reflectance in the near-infrared region of the spectrum. As a result, vigorously growing healthy vegetation has low red reflectance and high infrared reflectance, with resulting high NDVI values. NDVI is directly and quantitatively related to chlorophyll-containing green vegetative biomass, and is easier to interpret than false colour imagery that is intended to mimic infrared aerial photographs. Non-vegetated features such as barren rock and soil, water, and clouds exhibit NDVI values near or less than zero.

We calculated the NDVI for each pixel of each image using the following formula:

$$\text{NDVI} = (\text{Infrared} - \text{Red}) / (\text{Infrared} + \text{Red})$$

where Red is the reflectance in the 650 nm MSS band or the 660 nm TM and ETM bands, and Infrared is the reflectance in the 950 nm MSS band or 830 nm TM and ETM bands, normalized as described above.

Figure 2 illustrates reflectance values in each spectral band and the resulting NDVI for 8 sample points in the July 1986 TM image. NDVI increases as the infrared band centred at 840 nm increases and the red band centred near 650 nm decreases. Figure 3 illustrates the entire NDVI time series for the study area.

Analysis of temporal trends in terrestrial plant cover

Examination of the imagery indicated obvious variation in water levels throughout the study period. NDVI values for water are negative, and the NDVI for vegetation occurring in flooded areas will tend to be underestimated. Therefore, we excluded from our analysis areas that were under water in any year, and conservatively masked out areas of water from all images to a distance of at least 3 pixels (about 100 m) inland from the shoreline.

In the absence of an obvious single best way to conduct analyses or communicate results, we evaluated vegetation change in three ways: (1) by measuring the areal extent of habitat change over the 31-year study period; (2) by estimating the change in mean NDVI over time for several Regions of Interest (ROIs) within the study area; and (3) by creating thematic maps of NDVI change over time using an unsupervised classification approach.

The areal extent of NDVI change throughout the terrestrial portions of the study area was determined by carrying out a linear regression of NDVI versus year on a pixel-by-pixel basis. The images of R^2 and slope thus created allowed us to map the rate and direction of change and its significance. Vegetation change was deemed to have occurred in an individual pixel when the R^2 value for the regression line was statistically significant (P <0.05). Slope coefficients (b) for each significant regression indicated the average negative or positive change in NDVI per annum. Using the slope for each pixel as an indicator of change, we mapped and measured the area of statistically significant habitat change within several ROIs.

As the second method of quantifying vegetation change, we used the slope of a simple linear regression of NDVI (averaged over all of a given ROI) versus year. The slope of the regression line indicated the average change in NDVI per annum for the ROI. In addition, for each ROI, the total percent change in NDVI over the 1972–2003 time period was calculated as

$$100 \times (NDVI_{2003} - NDVI_{1972}) / NDVI_{1972}$$

where $NDVI_{2003}$ and $NDVI_{1972}$ were estimated from the regression equation.

Inspection of the data indicated NDVI values for some particularly cool springs were lower than expected. To evaluate the potential effect that annual spring weather might have had on our results, the NDVI time series was examined with reference to mean June temperature. This evaluation was carried out with a partial correlation analysis of NDVI on year that statistically "controlled for" the effect of June weather on NDVI. Weather data were obtained for Tuktoyaktuk (160 km west of the study area), the location of the nearest continuously operating weather station (Environment Canada 2007).

In the analyses described above, we recognized four major ROIs (Uplands, Outer Islands, Western Delta, and Inner Delta) as well as seven smaller ROIs within the Outer Islands ROI (Figure 1). The larger ROIs were identified on the basis of physiographic features and the degree of use by geese. The Outer Islands ROI is the principal nesting area for Lesser Snow Geese and Black Brant and the area most apt to be impacted by flooding. The Western Delta is used primarily by brood-rearing and moulting geese and, like the Outer Islands, is subject to flooding. The Inner Delta is less subject to annual flooding, more continuously vegetated with shrubs, forbs, and graminoid plants, and not as heavily used by geese. The well-vegetated Uplands ROI is situated above flood levels. It was regarded as a control or reference area for tracking background levels of change under circumstances where neither flooding nor heavy use by geese occurred.

It became obvious that some of these Regions of Interest (which reflect somewhat artificial geographic or management units) were quite heterogeneous and included areas of both increasing and decreasing NDVIs. Therefore a third approach to detecting long-term changes in vegetation at Anderson River delta was developed by creating a multi-temporal classification of NDVI values in the same way one undertakes a multispectral classification. This technique allowed us to map groups of pixels based on the similarity of their temporal histories, thereby providing broad maps of habitat change over the entire area, not just in the ROIs. In this approach, the NDVI images for each year were reassembled into a single multi-temporal file containing all 12 years of NDVI data, and a simple unsupervised classification technique (ISODATA in ENVI™) was used to group pixels with a similar NDVI history. Fifteen temporal classes were initially created, but some similar classes were manually grouped to simplify the resulting map and subsequent regression analyses of average NDVI on year.

4. RESULTS

Temporal changes in area of vegetation cover

NDVI values for each of the 12 images are depicted in Figure 3. NDVI values are highest for the upland areas surrounding the Anderson River and lowest for areas near the outer delta (Figure 3; Table 2). Based on our familiarity with the study area, we expect that large areas with an NDVI of 0.25 or less are barren or very sparsely vegetated. Areas with NDVIs of 0.25–0.30 have some vegetation, and areas with an NDVI of 0.30 or more are relatively well vegetated (see photographs in Figure 4). The highest NDVI values (0.40 or greater) are typically associated with lush lowland areas or dwarf shrub tundra with abundant ground cover.

Figure 5 identifies areas with statistically significant positive or negative trends in habitat area over the 31-year study period. Vegetation loss was most noticeable in the Outer Islands ROI, where we estimated 45% of the habitat had been impacted or lost (Table 3). Although impacts were widely spread throughout the ROI, much of the degraded or lost habitat occurred on Fox Den Island and the neighbouring Flat/Jaeger/Brant group of islands (Tables 2 and 3; Figure 5). Substantial reductions in vegetation cover were noted also for the Western Delta ROI (18%), particularly in the area near Snow Goose Creek. Trends in NDVI for the southern or more inland part of the delta were neutral or positive in most places, although there was evidence of habitat loss or degradation in 1% of the area. Most parts of the Uplands ROI showed positive changes in NDVI over time, and almost none of this ROI showed negative trends. Overall, we estimated that 878 ha of habitat at Anderson River delta has been degraded or lost (Table 3; Figure 5) with most of the lost/degraded area occurring in the Outer Islands (567 ha or 65% of total) and the Western Delta (256 ha or 29% of total) ROIs.

Trends in average NDVI in different Regions of Interest

Regression of the average NDVI versus time for each ROI revealed broad patterns similar to the surface area analysis described previously. NDVI values declined significantly for the Outer Islands ROI as a whole and for most of its constituent smaller ROIs as well (Table 3; Figure 5). Our initial analysis suggested there were no significant long-term trends in average NDVIs for either the Western Delta or Inner Delta ROIs and a significantly increasing trend in NDVI for the Uplands ROI. There was a significant correlation between Uplands NDVI and temperature ($R = 0.680$, $P = 0.015$), but when the effect of June temperature was controlled statistically using partial correlation, this significant positive relationship was no longer evident (partial $R = 0.382$, $P = 0.246$). The partial correlation analysis now indicated a negative change in NDVI of borderline statistical significance for the Western Delta ROI (partial $R = -0.597$, $P = 0.052$, vs. $R = -0.292$, $P = 0.358$ for original analysis), and a stronger negative correlation in NDVI than previously indicated for the Outer Islands ROI (partial $R = -0.818$, $P = 0.002$, vs. $R = -0.684$, $P = 0.014$ for the original analysis). No significant change in average NDVI over time was detected for the Inner Delta ROI by either correlation approach (partial $R = 0.104$, $P = 0.761$, vs. $R = 0.508$, $P = 0.091$).

Unsupervised classification of NDVI change

Five temporal NDVI history classes were recognized on the basis of the unsupervised classification and our subsequent pooling of similar classes (Figure 6). Following is a brief description of the classes based on trends in the NDVI and our understanding of the prevailing environmental conditions and ground cover in the different areas.

Class I (light blue in Figure 6) is located in the lowest and outermost part of the Anderson River delta. Overall vegetation cover in the area mapped by this class has declined greatly since 1972. Estimated NDVI values were 47% lower in 2003 than they had been in 1972 (Table 4). Land cover now consists primarily of mud flats or barren levees with sparse or patchily distributed low grass and sedge cover. Dead willows are abundant in some places.

Class II (dark blue in Figure 6) is found in the Outer Islands and Western Delta ROIs, somewhat inland from the previous class, and on slightly higher ground. It has relatively higher average NDVI values but a similar rate of decline in NDVI as Class I (−48% change) over the 31-year period (Table 4). Dead willows are very abundant in some areas of this thematic class. Based on Figure 3, it is apparent that at the start of the time series, plant cover was more complete and mud flats were far less extensive in Class II compared to Class I areas.

Class III (green in Figure 6) is located further inland in the delta and on slightly higher land than the previous classes. There has been substantial annual variability but no significant long-term trend in NDVI for this class over the study period (Table 4; Figure 6). Plant cover is a mixture of willows and other low shrubs, graminoid plants, and forbs. Extensive mud flats are not present.

Class IV (orange in Figure 6) occurs most abundantly in parts of the inner delta as well as in some upland areas. It is has noticeably more shrub cover than the previously described classes and has abundant herbaceous cover as well. There has been no significant long-term change in NDVI for this thematic class although there has been considerable annual variability. As noted previously in describing changes within ROIs, NDVI values were relatively low during cooler springs (possibly reflecting delayed growth of new green vegetation). Cooler-than-average June temperatures probably accounted for the relatively low values of NDVI witnessed in 1974 and 1978 in this and other thematic classes (Table 4).

Class V (brown in Figure 6) predominates in upland areas situated well above the Anderson River delta as well as in parts of the inner delta. Characteristic of this class is widespread low shrub cover interspersed with open areas supporting graminoid plants and forbs. This thematic class has shown a statistically significant 21% increase in NDVI since 1972 (Table 4). As discussed above, it is not clear if this trend is real and more permanent in nature or merely an artefact of the cold June weather (and associated effects on plant phenology) during a few years early in the study.

5. DISCUSSION

Comments on data and methodology

One of the purported strengths of the remote sensing approach taken in this study is the potentially long time series available with Landsat data. There are large collections of historical Landsat data in various archives around the world. However, we found that in practice many of the early data archived for our study area were not readily useable. The early Landsat Multispectral Scanners lacked on-board calibration, and therefore there are substantial radiometric differences in data from different sensors (Elvidge et al. 1998). There was also variable degradation of each of the bands on the sensors over time, and the ground processing routines and published calibration functions have changed several times (Chander and Markham 2003; Chander et al. 2007). Some of the MSS data we acquired came with little or no metadata, or with unrecognizable units, and some data had various distortions that required extra attention. We used a modification of the pseudo-invariant target method (Hall et al. 1991) to normalize the reflectance of the 5 images from the MSS sensor and the images from the Global Land Cover Facility TM sensor with questionable or missing calibration data (Table 1) to the reliably calibrated 1986 TM sensor.

The problems noted above probably explain why few authors have attempted to quantify long-term change using the early MSS data, and why there are many reports of methods for relative calibration of early Landsat data (Song et al. 2001; Du et al. 2002; Janzen et al. 2006; Schroeder et al. 2006). There is presently an effort to improve the calibration and long-term consistency of the Landsat Thematic Mapper data record, but no attempt has yet been made to address the problems associated with MSS data (Ad hoc Landsat TM Calibration Working Group 2006; P. Teillet, pers. comm.). Our experience suggests that one should not attempt to use historical Landsat data from a variety of archive sources, but rather obtain only recently processed data from the USGS.

There are several recent studies of arctic NDVI, but most use the Global Inventory Monitoring and Modeling Studies (GIMMS) Advanced Very High Resolution Radiometer (AVHRR) dataset that begins in the early 1980s (Tucker et al. 2001). Our Landsat-derived tundra NDVI values correlated well ($R^2 = 0.69$, $P = 0.01$) with a 1982–2000 time series of the peak NDVI for the Siberian tundra calculated using AVHRR (Fetterer and Savoie 2007). As well, our tundra NDVIs for the period 1985–2003 are strongly correlated ($R^2 = 0.77$, $P = 0.01$) with those reported for tundra on the Alaskan North Slope (Jia et al. 2003). It should be pointed out that all of the reports based on the GIMMS data show only the increase in NDVI since 1982, corresponding to a period when temperatures were steadily increasing. Our extension of the time series back to 1972 shows that the studies conducted so far may have missed a period of both relatively high and relatively low NDVIs that occurred during the 1970s. Thus, existing studies may have underestimated the importance of inter-annual variability in arctic weather in influencing NDVI. We detected no long-term trend in NDVI for the upland tundra area near the Anderson River delta when we controlled statistically for year-to-year variability in June weather.

Ecological changes

The primary ecological or management objectives of this study were to quantify reports of habitat loss at the Anderson River delta and identify areas that had been impacted. We also hoped to determine if the loss of vegetation noted could be attributed to any specific time interval or potentially explanatory environmental event (such as inundation by salt water during a storm surge).

As expected, our results show there were substantial reductions in vegetation cover in the outer islands of the Anderson River delta between 1972 and 2003. (Less expectedly, our results also show there was considerable inter-annual variation in NDVIs that was unrelated to long-term habitat change and probably reflected year-to-year differences in spring weather.) Plant cover decreased over at least 45% of the area of the Outer Islands ROI, and the average NDVI for the ROI declined by 37.5% during the study period. Impacted areas corresponded primarily to the lower-lying parts of the delta, which are the areas most heavily used by nesting Lesser Snow Geese and Black Brant (Armstrong 1995, Kerbes et al. 1999).

The other major ROI where significant changes to NDVI values were noted was the Western Delta. We estimated that 18% of the ROI had been impacted and that the average NDVI for the ROI had declined by 11.9% over the study period. The spatial variability in vegetation change in this area was captured in the unsupervised classification of NDVI time histories (Figure 6).

Farther inland within the Inner Delta ROI and in the nearby Uplands area, there was very little vegetation loss. In fact, for the Uplands ROI, there was a statistically significant increase in NDVI over time in our Landsat dataset that agreed well with results from other studies in Alaska and Siberia (Jia et al. 2003; Fetterer and Savoie 2007). The latter studies used the 1982–2004 GIMMS data to estimate changes in tundra NDVIs. Our longer time series, specifically the significant variability in NDVI, suggested that changes in NDVI in the Uplands ROI of our study area reflected to a large extent random year-to-year variability in weather rather than long-term climate change. Trends for NDVI in the Uplands area were no longer evident when we controlled statistically for effects of June temperature. Thus, the statistically significant increase in NDVI in the Uplands over time might be explained, at least in part, by very cold springs witnessed during the earlier years of the time series (e.g., 1974 and 1978), which delayed green-up.

While there are no historical quantitative field data to compare to present-day conditions at the Anderson River delta, the changes seen in the satellite time series are confirmed by qualitative reports. In the 1960s, Barry (1967) reported that Brant Island, located in the Outer Islands ROI, was an important nesting area for Black Brant and described the habitat there as an "interspersion of mud flats, grassy clumps or hummocks, small shallow sloughs and puddles and a turf of brant grass *(Carex subspathacea)* and *Puccinellia phryganodes.*" In 1991, Armstrong (1995) reported a shift in habitat and nesting area, describing Brant Island as "mostly mud flats with sparse stands of *Carex* and *Puccinellia* on the north and west sides." Armstrong also noted: "much of Flat Island and the north end of Fox Den Island formerly supported stands of low willow (*Salix* spp.), but by 1991 only their dead stems remained." Recent field studies carried out by CWS staff from 2003 to 2007 indicate that the area of sparse plant cover and dead willow (Figure 4: sites 1a and 1b) habitat in the Outer Islands ROI has continued to expand inland, now corresponding closely to the red area delineated in Figure 5. The only continuous shrub communities remaining in the Outer Islands (Figure 4: site 3) are on the southern part of Fox Den Island and nearby Bluff Island (Figures 5 and 6). NDVI values in those areas remain high (>0.4). Other remaining "green areas" are primarily turf communities dominated by salt-tolerant species of grasses and sedges (Figure 4: site 2) or other graminoids growing near freshwater channels. This has created the somewhat linear pattern of plant distribution seen in some of the later NDVI images (Figure 3).

Overall, our results suggest that although NDVI values in the Outer Islands ROI and parts of the Western Delta ROI were highly variable from year to year, there has been a gradual loss in vegetation over time that has been ongoing since at least 1972. This leads us to believe that the observed changes in habitat were not caused by storm surges that inundated the delta with salt water in one or two years.

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Table 1. Landsat data used in the remote sensing analysis of vegetation change at Anderson River Delta Migratory Bird Sanctuary, Northwest Territories, 1972–2003

Year	Julian Day	Month/ Day	Landsat (Sensor)	Archive[a]	Track, Frame	Red band[b]		Near-infrared band[b]	
						Slope	Offset	Slope	Offset
1972	208	Jul 26	1 (MSS)	USGS	Tr65Fr11	***1.235***	***−0.0006***	***0.795***	***0.0217***
1974	197	Jul 16	1 (MSS)	USGS	Tr65Fr11	***1.342***	***−0.0034***	***1.686***	***0.0283***
1978	184	Jul 03	2 (MSS)	GLCF	Tr67Fr11	***2.280***	***0.0091***	***3.417***	***−0.0175***
1982	192	Jul 11	3 (MSS)	MDA	Tr66Fr11	***1.685***	***0.0294***	***1.478***	***0.0158***
1985	219	Aug 7	5 (TM)	MDA	Tr62Fr11	1.040	−1.1700	0.873	−1.510
1986	199	Jul 18	5 (MSS)	USGS	Tr60Fr11	1.386	3.0000	0.945	3.0000
1986	199	Jul 18	5 (TM)	MDA	Tr60Fr11	1.040	−1.1700	0.873	−1.5100
1988	182	Jun 30	5 (TM)	GLCF	Tr60Fr11	***1.362***	***−0.0068***	***1.167***	***−0.0076***
1992	200	Jul 18	5 (TM)	GLCF	Tr61Fr11	***1.082***	***0.0084***	***0.937***	***0.0285***
1995	185	Jul 4	5 (TM)	MDA	Tr60Fr11	1.040	−1.1700	0.873	−1.5100
1997	206	Jul 25	5 (TM)	MDA	Tr60Fr11	1.040	−1.1700	0.873	−1.5100
2000	205	Jul 23	7 (ETM)	MDA	Tr62Fr11	0.619	−5.0000	0.637	−5.1000
2003	214	Aug 02	5 (TM)	MDA	Tr61Fr11	1.040	−1.1700	0.873	−1.5100

[a] Data archives: United States Geological Survey EROS Data Center (USGS), Global Land Cover Facility of the University of Maryland (GLCF), MacDonald, Dettwiler and Associates Ltd. (MDA).

[b] The gains and offsets used for calibration to radiance (where available) are indicated in normal font. Where gain and offset data were not available or incorrect, the slopes and offsets were normalized to the 1986 Thematic Mapper scene by the amounts indicated in bold italics.

Table 2. Mean Normalized Difference Vegetation Index (NDVI) for different Regions of Interest at Anderson River Delta Migratory Bird Sanctuary and mean June temperatures at Tuktoyaktuk, Northwest Territories, 1972–2003

		Normalized Difference Vegetation Index and Temperature by Year											
Region of Interest	Area (km^2)	1972	1974	1978	1982	1985	1986	1988	1992	1995	1997	2000	2003
Uplands	60.46	0.570	0.474	0.449	0.570	0.525	0.555	0.535	0.557	0.605	0.595	0.614	0.583
Outer Islands	12.52	0.369	0.259	0.212	0.277	0.286	0.262	0.231	0.185	0.259	0.246	0.187	0.174
Western Delta	14.37	0.418	0.326	0.266	0.377	0.349	0.348	0.312	0.281	0.372	0.347	0.355	0.263
Inner Delta	38.62	0.540	0.453	0.382	0.528	0.525	0.543	0.507	0.498	0.557	0.553	0.538	0.539
Canoe Island	0.14	0.388	0.273	0.247	0.348	0.360	0.353	0.291	0.193	0.270	0.261	0.183	0.178
Bluff Island	0.31	0.386	0.302	0.270	0.378	0.402	0.402	0.328	0.292	0.346	0.354	0.291	0.317
Flat, Jaeger, and Brant Islands	3.01	0.304	0.200	0.170	0.199	0.217	0.183	0.161	0.121	0.201	0.182	0.106	0.120
Oil Drum Island and Gull Islets	0.72	0.211	0.087	0.055	0.127	0.150	0.141	0.141	0.072	0.156	0.137	0.089	0.073
Fox Den Island	6.41	0.426	0.317	0.256	0.338	0.343	0.322	0.282	0.236	0.303	0.291	0.248	0.218
Triangle Island	1.71	0.328	0.202	0.170	0.222	0.225	0.199	0.185	0.151	0.230	0.225	0.135	0.130
Grassy Point	0.15	0.499	0.408	0.276	0.361	0.310	0.262	0.239	0.091	0.214	0.181	0.142	0.116
Mean June temperature (°C) at Tuktoyaktuk, NT	--	4.7	1.9	2.6	5.4	6.0	4.5	7.9	6.3	8.0	8.6	6.6	5.2

Table 3. Temporal changes in Normalized Difference Vegetation Indices (NDVI) for each of the Regions of Interest at Anderson River Delta Migratory Bird Sanctuary, 1972–2003

Region of Interest	Regression of NDVI on year (x)[a]	R^2	P[b]	Total % change in NDVI, 1972–2003	Percent of area showing: Significant positive change	Significant negative change	No significant change	Amount of habitat (ha) lost or degraded[c]
Large Regions of Interest								
Uplands	0.0034x + 0.4994	0.463	**0.015**	21.1	64	0	36	0.9
Outer Islands	−0.0037x + 0.3031	0.467	**0.014**	−37.5	3	45	52	567.2
Western Delta	−0.0014x + 0.3559	0.085	0.358	−11.9	9	18	73	256.3
Inner Delta	0.0025x + 0.4738	0.259	0.091	16.6	30	1	69	53.3
Small Regions of Interest (within Outer Islands)								
Canoe Island	−0.0048x + 0.3544	0.455	**0.016**	−42.2	0	52	48	7.6
Bluff Island	−0.0009x + 0.3531	0.039	0.536	−7.9	3	7	90	2.2
Flat, Jaeger, and Brant Islands	−0.0038x + 0.2401	0.524	**0.008**	−49.3	0	50	50	151.5
Oil Drum Island and Gull Islets	−0.0012x + 0.1394	0.077	0.3835	−27.6	2	12	86	8.6
Fox Den Island	−0.0039x + 0.3601	0.483	**0.0121**	−33.9	6	50	44	322.6
Triangle Island	−0.0032x + 0.2504	0.361	**0.0387**	−39.6	0	35	64	60.4
Grassy Point	−0.0109x + 0.4284	0.803	**<0.0001**	−78.6	0	92	8	13.6

[a] The intercept of the regression equation indicates the estimated NDVI value at the start of the study (1972) and the slope value (b) indicates the expected change in NDVI per annum. Estimates of total % change in NDVI are based on the regression equations.

[b] Statistically significant regressions ($P < 0.05$) of NDVI versus year are marked in bold font.

[c] Area showing statistically significant reduction in NDVI based on a pixel-by-pixel evaluation with linear regression.

Table 4. Temporal changes in Normalized Difference Vegetation Indices (NDVI) for each of the thematic classes at Anderson River Delta Migratory Bird Sanctuary, 1972–2003

Final thematic class	Regression of NDVI on year (x)[a]	R^2	P[b]	Total change in NDVI 1972–2003	Total % change in NDVI 1972–2003
Class I	$-0.0035x + 0.2339$	0.412	**0.025**	−0.110	−46.9
Class II	$-0.0059x + 0.3816$	0.639	**0.002**	−0.184	−48.2
Class III	$0.0001x + 0.3673$	0.001	0.932	0.004	1.1
Class IV	$0.0022x + 0.4487$	0.231	0.114	0.069	15.4
Class V	$0.0034x + 0.5091$	0.477	**0.013**	0.106	20.9

[a] The intercept of the regression equation indicates the estimated NDVI value at the start of the study (1972) and the slope value (b) indicates the expected change in NDVI per annum. Total change in NDVI and total % change in NDVI estimates are based on the regression equations.
[b] Statistically significant regressions (P <0.05) of NDVI versus year are marked in bold font.

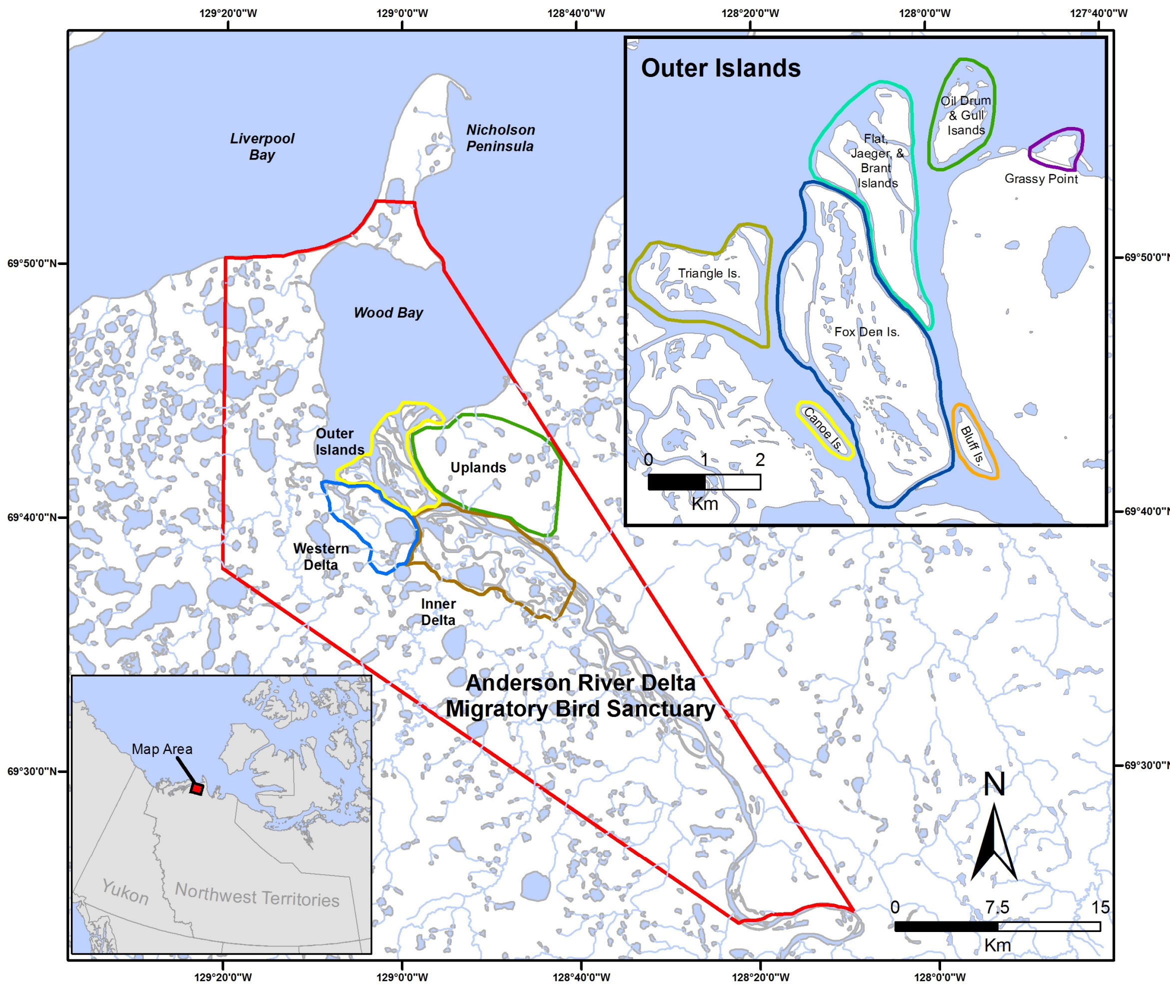

Figure 1. The Anderson River Delta Migratory Bird Sanctuary, Northwest Territories, showing four large Regions of Interest considered in this study and seven smaller Regions of Interest within the Outer Islands of the Anderson River delta

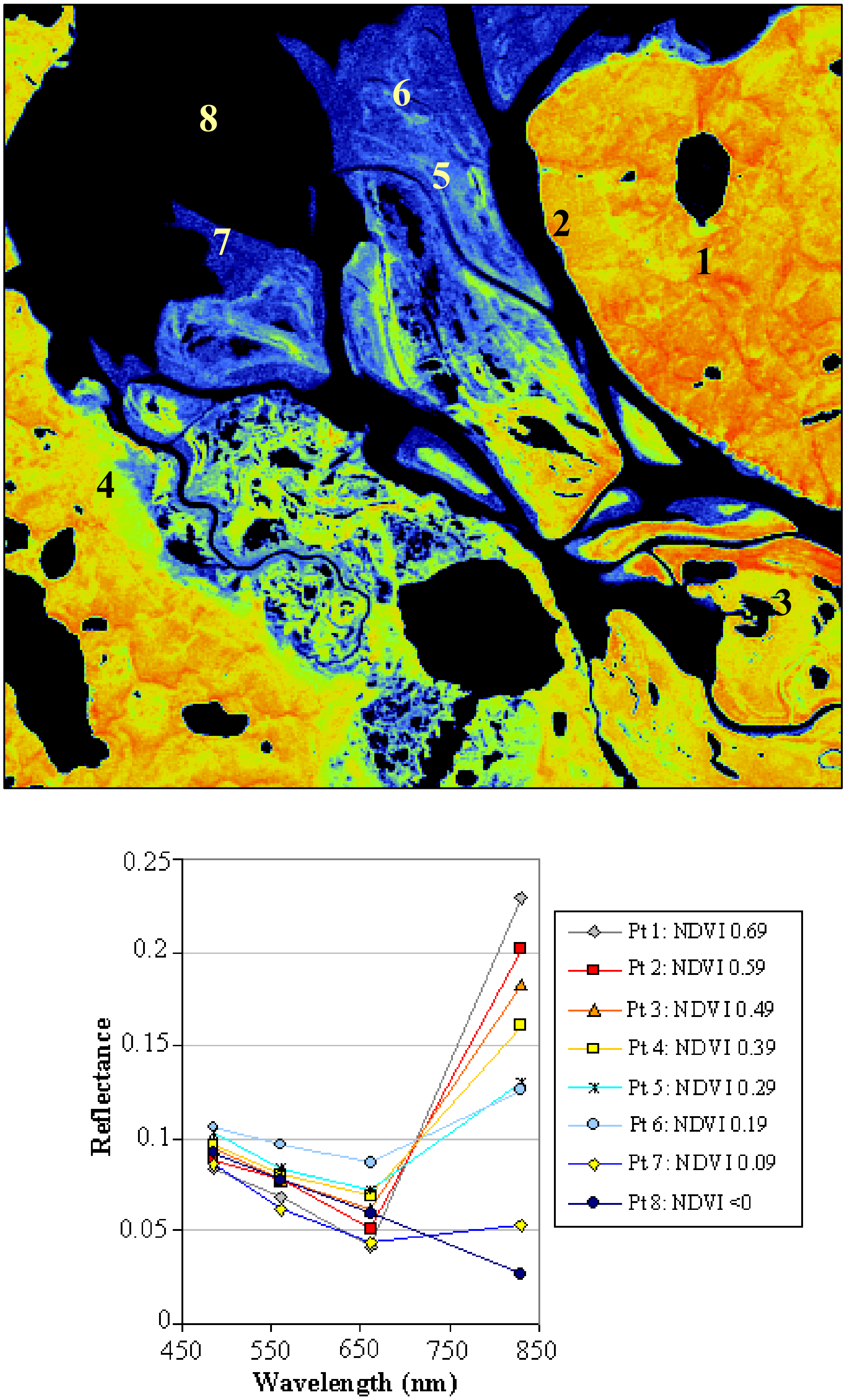

Figure 2. Normalized Difference Vegetation Index (NDVI) image for 18 July 1986, with reflectance plots and the resulting NDVI value for 8 locations within the image

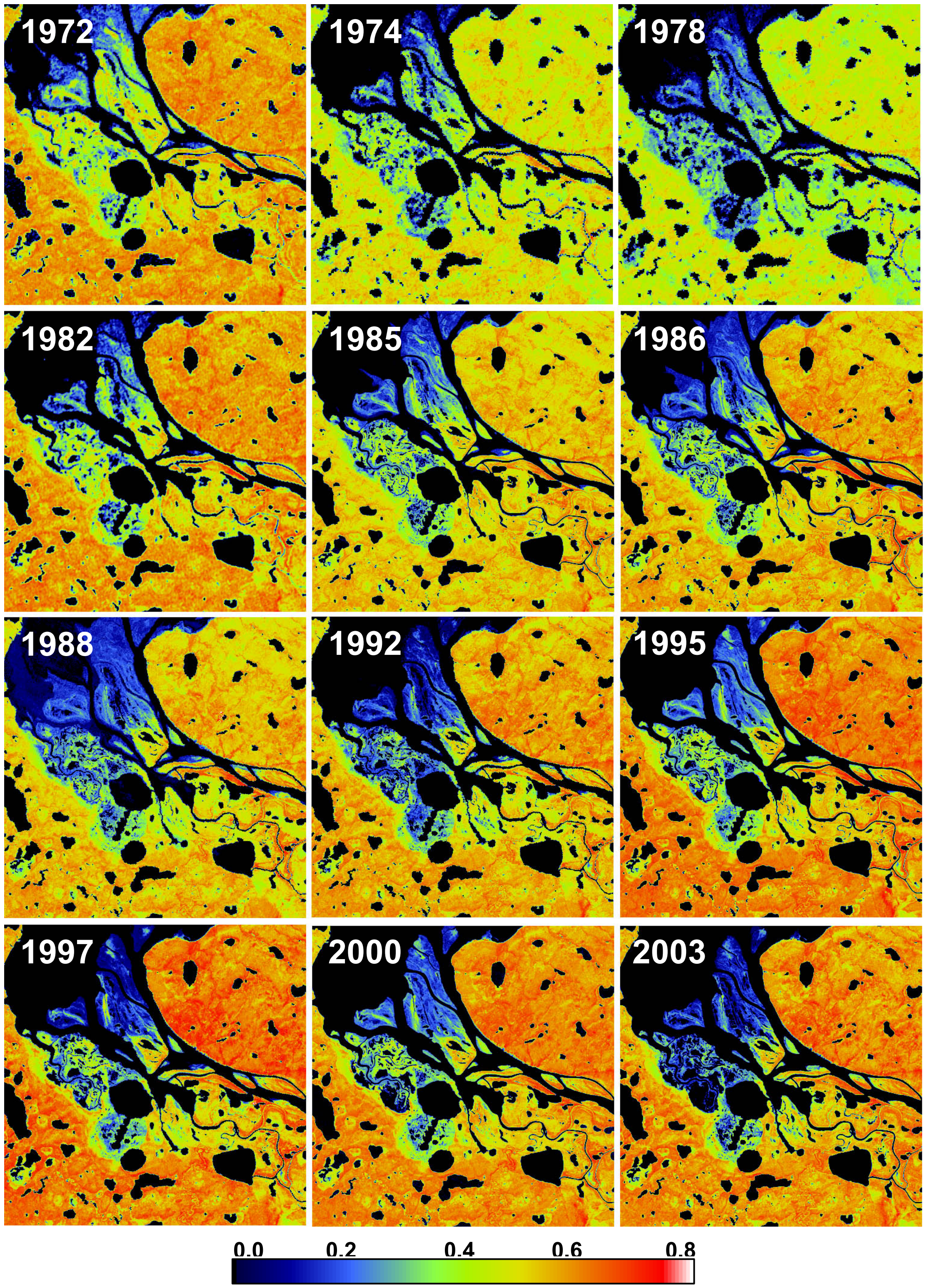

Figure 3. Normalized Difference Vegetation Index (NDVI) images for the Anderson River delta, 1972–2003. NDVI increases from blue to white. Water areas are black.

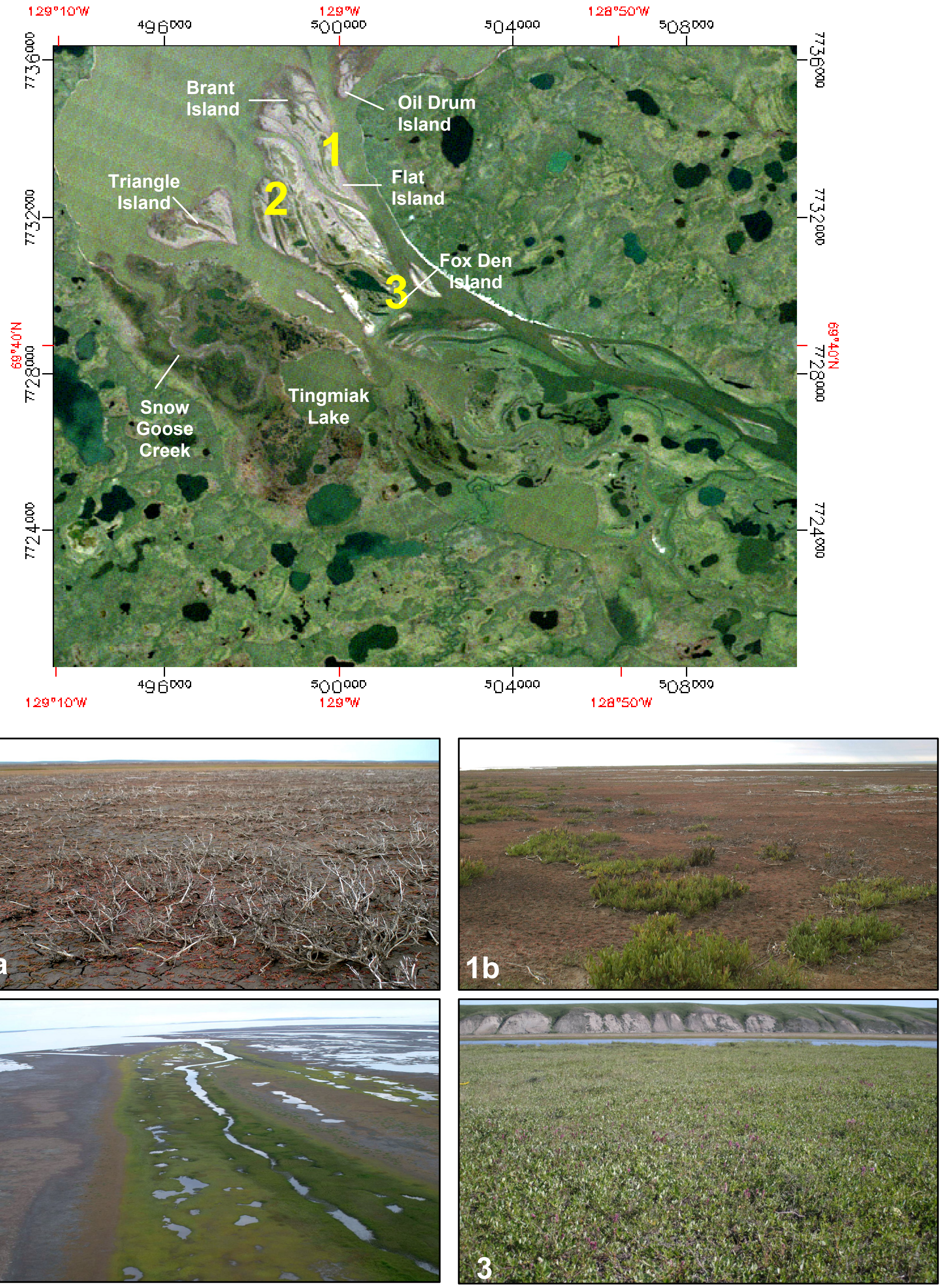

Figure 4. Top panel is a near true colour image of the study area derived from bands 3, 2, and 1 of a Landsat 5 Thematic Mapper scene for 2 August 2003. Bottom panel photographs were taken at sites 1a, 1b, and 2 on 10 August 2004 and at site 3 on 2 August 2003. Site 1a depicts a barren or very sparsely vegetated area with a Normalized Difference Vegetation Index (NDVI) value of 0.25 or less. Site 1b is typical of areas with some vegetation (NDVI of 0.25 to 0.30). Site 2 is relatively well vegetated (NDVI of 0.3 or more). Photograph 3 depicts the abundant ground cover found in lush lowland areas or dwarf shrub tundra (NDVI of 0.4 or greater).

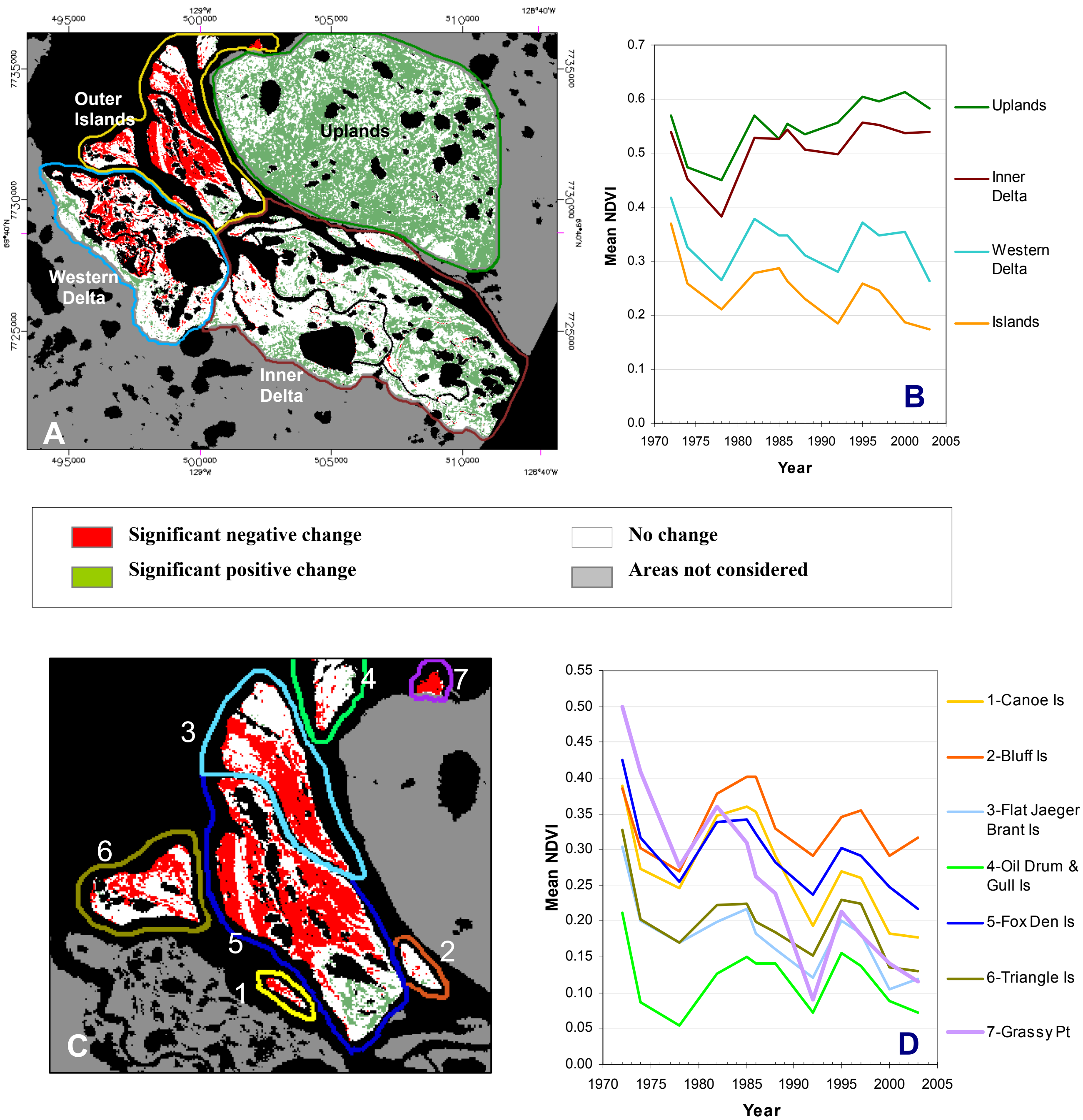

Figure 5. A: Outline of the 4 large Regions of Interest, showing areas of change in Normalized Difference Vegetation Index (NDVI) over the 31-year study period. B: Graph showing the NDVI time series for each region. C: Outline of the 7 small Regions of Interest within the Outer Islands region, showing areas of change. D: Graph showing the NDVI time series for each region.

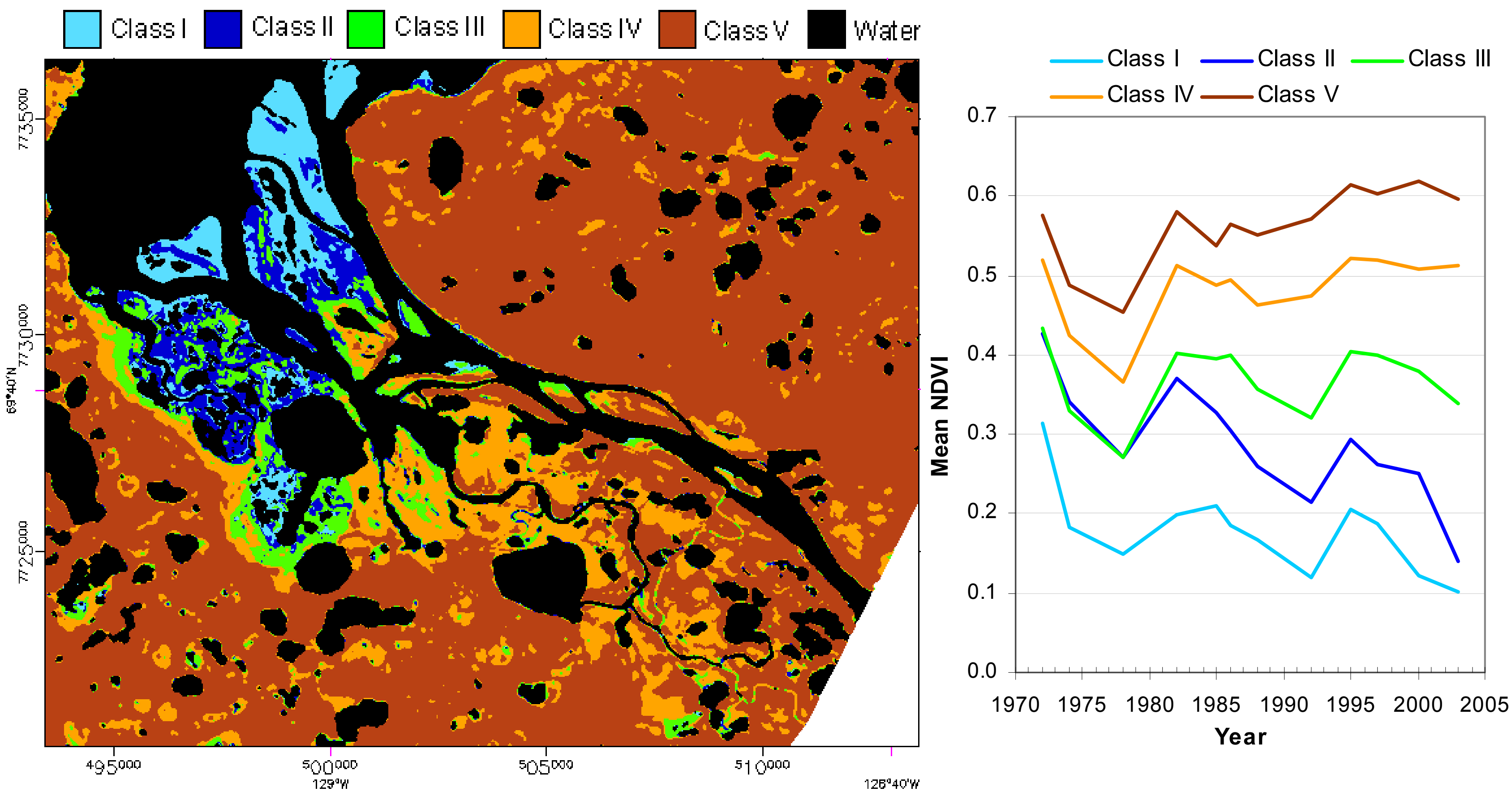

Figure 6. Five thematic classes of vegetation change over time at Anderson River Delta Migratory Bird Sanctuary, Northwest Territories, 1972–2003. Statistically significant declining trends in Normalized Density Vegetation Indices (NDVI) were noted for lowland Classes I and II, and a positive trend was observed for upland tundra (Class V).