ARCTIC
VOL. 65, NO. 3 (SEPTEMBER 2012) P. XXX–XXX

Using Multiple Sources of Knowledge to Investigate Northern Environmental Change: Regional Ecological Impacts of a Storm Surge in the Outer Mackenzie Delta, N.W.T.

STEVE V. KOKELJ,[1,2] TREVOR C. LANTZ,[3] STEVE SOLOMON,[4] MICHAEL F.J. PISARIC,[5] DARREN KEITH,[1] PETER MORSE,[5] JOSHUA R. THIENPONT,[6] JOHN P. SMOL[6] and DOUGLAS ESAGOK[7]

(*Received 2 August 2011; accepted in revised form 21 December 2011*)

ABSTRACT. Field data, remote sensing, and Inuvialuit knowledge were synthesized to document regional ecological change in the outer Mackenzie Delta and to explore the timing, causes, and implications of this phenomenon. In September 1999, a large magnitude storm surge inundated low-lying areas of the outer Mackenzie Delta. The storm was among the most intense on record and resulted in the highest water levels ever measured at the delta front. Synthesis of scientific and Inuvialuit knowledge indicates that flooding during the 1999 storm surge increased soil salinity and caused widespread vegetation death. Vegetation cover was significantly reduced in areas affected by the surge and was inversely related to soil salinity. Change detection analysis, using remotely sensed imagery bracketing the 1999 storm event, indicates severe impacts on at least 13 200 ha of terrestrial vegetation in the outer delta. Inuvialuit knowledge identifying the 1999 surge as anomalous is corroborated by geochemical profiles of permafrost and by a recently published paleo-environmental study, which indicates that storm surge impacts of this magnitude have not previously occurred during the last millennium. Almost a decade after the 1999 storm surge event, ecological recovery has been minimal. This broad-scale vegetation change is likely to have significant implications for wildlife and must be considered in regional ecosystem planning and in the assessment and monitoring of the cumulative impacts of development. Our investigations show that Inuvialuit were aware of the 1999 storm surge and the environmental impacts several years before the scientific and regulatory communities recognized their significance. This study highlights the need for multidisciplinary and locally informed approaches to identifying and understanding Arctic environmental change.

Key words: climate change, Inuvialuit knowledge, Mackenzie Delta, monitoring, multidisciplinary, remote sensing, salinization, storm surge, vegetation change

RÉSUMÉ. La synthèse des données d'exploitation et de télédétection de même que des connaissances des Inuvialuit a été effectuée afin de répertorier les changements écologiques enregistrés dans la région extérieure du delta du Mackenzie Delta et d'explorer la temporisation, les causes et les incidences de ce phénomène. En septembre 1999, une onde de tempête de grande magnitude a inondé les zones de faible élévation de l'extérieur du delta du Mackenzie. Il s'agit de la tempête la plus intense à n'avoir jamais été enregistrée, ce qui s'est traduit par les niveaux d'eau les plus élevés à n'avoir jamais été mesurés à la hauteur du delta. La synthèse des données scientifiques et des connaissances des Inuvialuit nous montre que l'inondation de 1999 a eu pour effet d'augmenter la salinité du sol et a entraîné la mort de la végétation à grande échelle. La couverture végétale a été réduite considérablement dans les zones visées par l'onde et était inversement reliée à la salinité du sol. L'analyse des détections de changement effectuée au moyen de l'imagerie télédétectée dans le cas de la tempête de 1999 laisse entrevoir de fortes incidences sur au moins 13 200 hectares de végétation terrestre dans l'extérieur du delta. Les connaissances des Inuvialuit, qui affirment que l'onde de 1999 était anormale, sont corroborées par les profils géochimiques du pergélisol ainsi que par une étude paléoenvironnementale qui indique que des incidences de cette ampleur découlant d'une onde de tempête ne se sont pas produites à un autre moment donné du dernier millénaire. Près d'une décennie après l'onde de tempête de 1999, le rétablissement écologique était minime. Ce changement de végétation à grande échelle aura vraisemblablement d'importantes incidences sur la faune et doit entrer en considération dans la planification de l'écosystème régional ainsi que dans l'évaluation

[1] Cumulative Impact Monitoring Program, Renewable Resources and Environment, Aboriginal Affairs and Northern Development Canada, Northwest Territories Geoscience Office, PO Box 1500, Yellowknife, Northwest Territories X1A 2R3, Canada
[2] Corresponding author: Steve.Kokelj@aandc.gc.ca
[3] School of Environmental Studies, University of Victoria, PO Box 1700 STN CSC, Victoria, British Columbia V8W 2Y2, Canada
[4] Geological Survey of Canada, Bedford Institute of Oceanography, PO Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada; deceased
[5] Department of Geography and Environmental Studies, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada
[6] Paleoecological Environmental Assessment and Research Lab (PEARL), Department of Biology, Queen's University, Kingston, Ontario K7L 3N6, Canada
[7] Inuvik Hunters and Trappers Committee, Inuvik, Northwest Territories X0E 0T0, Canada

et la surveillance des incidences cumulatives des travaux d'aménagement et de mise en valeur. Nos enquêtes nous ont permis de constater que les Inuvialuit étaient conscients des incidences environnementales de l'onde de tempête de 1999 plusieurs années avant que les scientifiques et le personnel s'occupant de la réglementation ne reconnaissent leur importance. Cette étude fait ressortir la nécessité d'avoir des méthodes multidisciplinaires et de faire appel aux gens de la région pour déterminer et comprendre les changements environnementaux dans l'Arctique.

Mots clés : changement climatique, connaissances des Inuvialuit, delta du Mackenzie, surveillance, multidisciplinaire, télédétection, salinisation, onde de tempête, changement de végétation

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Describing environmental variability and understanding the processes governing heterogeneity at scales appropriate for regional planning and management are central challenges of ecology (Turner, 1989; O'Neill et al., 1997). These problems often hinder northern monitoring and research programs designed to distinguish normal variation from the effects of climate change and natural or anthropogenic disturbance (Walker and Walker, 1991; Smol and Douglas, 2007; Burn and Kokelj, 2009; Smol, 2010). In Arctic coastal settings, the interplay between rising sea levels, decreasing sea-ice extent, warming permafrost, and more frequent and intense storms is likely to increase shoreline erosion and the occurrence and severity of flooding (Manson and Solomon, 2007; Morse et al., 2009; Pisaric et al., 2011). In resource-rich areas of the Arctic, the footprint of anthropogenic disturbance is anticipated to grow as exploration and development intensify (Walker et al., 1987; Forbes et al., 2001; Holroyd and Retzer, 2005; Kemper and Macdonald, 2009). In these settings, cumulative impact monitoring approaches that consider both environmental science and traditional knowledge are a critical tool for resilient ecosystem planning and effective management of resource development (Berkes, 1998; Usher, 2000; Joint Review Panel, 2009).

The Mackenzie Delta (Fig. 1) is a dynamic ecosystem influenced by climate warming and the impacts of oil and gas exploration (Burn and Kokelj, 2009; Pisaric et al., 2011). It is the world's second-largest Arctic delta, providing critical habitat to large populations of resident and migratory fish and wildlife (Mackay, 1963; Nagy, 2002; Stephenson, 2002). The national importance of the delta as staging and breeding habitat for migratory birds was recognized through the establishment of the Kendall Island Bird Sanctuary in 1960 (Fig. 1) (Bromley and Fehr, 2002). The delta includes traditional lands of the Inuvialuit and Gwich'in, who continue to rely on the abundant subsistence resources it provides (Usher, 2002; Thompson and Millar, 2007). These groups possess detailed knowledge of the delta environment, accumulated through long residence in the area, transmitted orally from generation to generation, and maintained by contemporary land-based activities (Jolly et al., 2003; Nichols et al., 2004; Bandringa and Inuvialuit Elders, 2010). Significant discovered and anticipated oil and gas reserves underlie the region (Dixon et al., 1994), and a proposal to construct a pipeline to transport hydrocarbons to southern markets (Imperial Oil Resources Ventures Limited, 2004) was conditionally approved after an extensive public review (Joint Review Panel, 2009).

The geomorphology and ecology of the Mackenzie Delta are shaped by recurrent flooding and sedimentation (Gill, 1972; Lesack and Marsh, 2007). Alluvial vegetation communities typically recover rapidly from freshwater flooding and disturbance (Pearce, 1986; Johnstone and Kokelj, 2008). However, a large portion of the outer Mackenzie Delta recently experienced a widespread and persistent vegetation kill (Figs. 1 and 2) linked to seawater incursion during a severe storm surge in 1999 (Pisaric et al., 2011).

We explore multiple lines of evidence to assess the timing and magnitude of impacts that resulted from this storm surge, determine the cause(s) of the ecological changes, and evaluate the environmental and resource management implications of this large disturbance. To assess the magnitude and timing of impacts on terrestrial ecosystems in the outer Mackenzie Delta, we quantified variability in vegetation and soils at plot and landscape levels and conducted change detection analysis using Landsat imagery. We examined the unique nature of this event using geochemical profiles of permafrost cores from across the study area (Fig. 1). To determine the cause(s) and conditions that may have led to the saltwater incursion, we compiled delta water levels and wind conditions during and preceding the 1999 storm event. During a March 2009 workshop, Inuvialuit experts shared their knowledge and observations of the ecological changes and environmental conditions relevant to storm surges in general, as well as their specific memories of the 1999 storm event. We draw on the results of our study to highlight the importance of using multidisciplinary, regionally focused, and locally informed approaches to track the cumulative impacts of development and global change on northern ecosystems.

STUDY AREA

Mackenzie Delta

The Mackenzie Delta is a vast low-lying alluvial plain intersected by a network of channels and thousands of lakes (Fig. 1) (Mackay, 1963; Burn and Kokelj, 2009). This dynamic environment, shaped by ice jam flooding in spring and occasional storm surges in summer and fall, has been

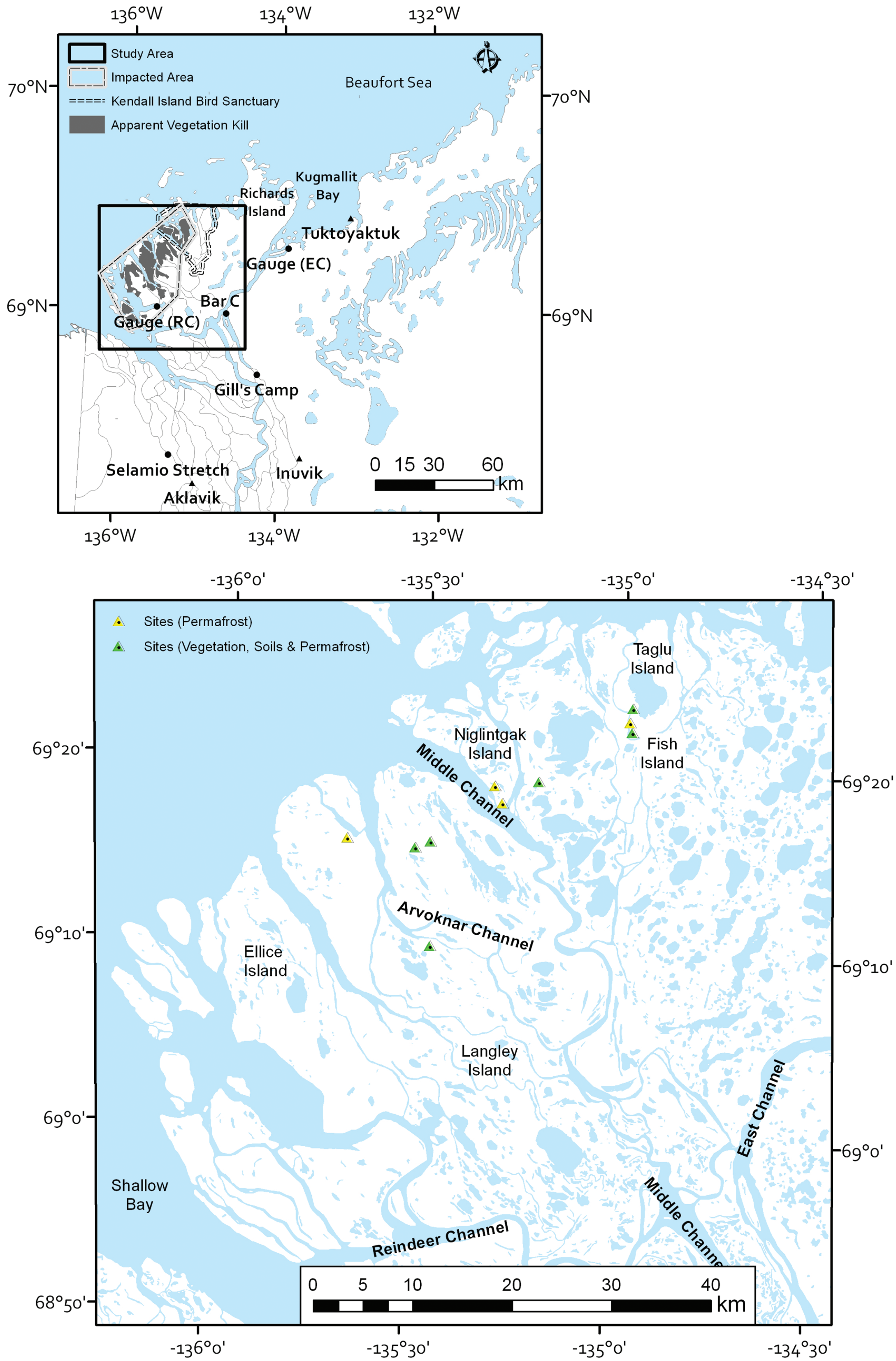

FIG. 1. Map of the study area. The upper panel shows the location of the study area (square outlined in black) within the Mackenzie Delta region, as well as impacted and unimpacted areas, water level gauges (RC – Reindeer Channel gauge 10MC011; EC – East Channel gauge 10LC013), settlements, and other geographic features referred to in the text. The lower panel is an enlargement of the study area showing the locations of sample sites, major channels, and named islands.

building upward and prograding seaward for the past 14 000 years (Hill, 1996; Manson and Solomon, 2007). The delta receives about 128 Mt of sediment annually from the Mackenzie and Peel Rivers (Carson et al., 1998), but only about one-third is added to the alluvial plain, while the remainder is deposited offshore. Recent surveys suggest that significant portions of the subaerial delta front are eroding at rates of several metres per year, suggesting a current phase of transgression (Solomon, 2005).

In this paper, we focus on the low-lying outer Mackenzie Delta, which rises only a few metres above sea level (Mackay, 1963) (Fig. 1). Much of the alluvial plain is flooded with fresh water each year during the spring freshet and occasionally when strong N-NW winds cause storm surges in summer and fall (Mackay, 1963; Manson and Solomon, 2007). The frequency, duration, and timing of inundation affect sedimentation rates, soil moisture and chemistry, and permafrost aggradation, which combine to influence vegetation type (Mackay, 1963; Marsh and Schmidt, 1993; Johnstone and Kokelj, 2008; Morse et al., 2009).

Pointbar vegetation sequences in the outer delta begin with sparsely vegetated communities (*Equisetum arvense* L. and *Arctophila fulva* (Trin.) Rupr.) that are flooded for several weeks every year (Cordes et al., 1984). Permafrost is typically found at the base of the active layer, which may be up to 1.5 m thick (Gill, 1972). With increasing elevation, plant communities become dominated by felt-leaf willow (*Salix alaxensis* (Anderss.) Cov.). These willow thickets, up to 3 m in height, form a narrow band on well-drained point bars and levees immediately adjacent to channels, where flooding and sedimentation are less frequent (Cordes et al., 1984). Deep snowdrifts associated with the tall willows are often underlain by talik (Gill, 1972; Smith, 1975). As distance from the channel increases, Richardson's willow, *S. lanata* subsp. *richardsonii* (Hook.) Skvortsov, typically forms a dense shrub layer between 0.5 and 1.0 m tall with an understory of *Carex aquatilis* Wahlenb., moss, and sparse cover of *Equisetum arvense* L. and *Hedysarum alpinum* L. (Fig. 2C). Active layers between 60 and 100 cm develop over permafrost that aggrades upward with sedimentation and vegetation succession (Morse et al., 2009). We distinguish between these two willow zones by referring to the former as "riparian" and the latter as "willow." Further inland, wet inter-levee basins consist of extensive sedge-wetlands dominated by *Carex aquatilis* and *Eriophorum angustifolium* Honck. (Pearce, 1986; Fig. 2A). In this vegetation zone ("sedge"), a thin, saturated active layer is typically underlain by ice-rich permafrost (Morse et al., 2009). Green alder (*Alnus viridis* subsp. *fruticosa*) is common on slightly more elevated and well-drained surfaces in these communities. The most elevated surfaces of the outer floodplain typically host low shrub tundra-heath communities. These areas are dominated by *Arctostaphylos rubra* (Rehd. & Wils.), *Dryas integrifolia* M Vahl., and Richardson's willow (Kemper and Macdonald, 2009; Fig. 2E) and are referred to throughout this paper as "tundra." Salt-tolerant species assemblages are common in Arctic coastal environments influenced by tides (Jefferies, 1977; Handa et al., 2002), but in portions of the Mackenzie Delta typically inundated by freshwater, these species are relatively uncommon (Pearce, 1986; Johnstone and Kokelj, 2008; Kemper and MacDonald, 2009).

METHODS

Defining the Study Area

To define the study area and select field sites, we used Landsat imagery in combination with aerial and ground reconnaissance. Field observations of impacted vegetation made as early as summer 2000 later prompted the examination of archived Landsat scenes of the study area acquired between June and September in the years 1987–2003. Using this imagery, we determined that a large change in the reflectance of the vegetation had occurred sometime between August 1999 and July 2002 (Fig. 3). Subsequently, we used the change visible on the 2002 Landsat image combined with ground and air reconnaissance between 2005 and 2008 to coarsely define an "impacted area," where vegetation death appeared widespread, and an "unimpacted area," where vegetation appeared to show no signs of death or stress (Fig. 1). In both areas, we examined the variability in soil chemistry, vegetation, and permafrost across vegetation zones. This design yielded data sets that allowed us to test the hypothesis that these indicators differed between impacted and unimpacted areas.

Soils and Vegetation

To assess variability in soil chemistry and vegetation, we established six sites in the summer of 2007, three in the impacted area and three in the unimpacted area. At each site, we set up 1 to 3 transects perpendicular to channels. Most transects traversed plant community sequences that occur across point bars (riparian, willow, sedge, and tundra). To ensure adequate representation in our sampling, an additional tundra transect was established in both the impacted and the unimpacted areas. Depending on the scale of plant community transitions, transect lengths were either 100 or 200 m, with 11 sample points located at 10 or 20 m intervals, respectively. Plot locations were recorded using a Trimble R3 Differential GPS system with Pro XT receivers connected to Ranger field computers. The survey data were post-processed and corrected to sub-centimetre accuracy using Trimble Business Center software and Natural Resources Canada's Canadian Spatial Reference System–Precise Point Positioning program (http://www.geod.nrcan.gc.ca/online_data_e.php).

We visually estimated the percent cover of all vascular plants inside quadrats positioned around the sampling points. Tall shrub cover (willow and alder) was estimated using 5 m^2 quadrats. All other species were estimated using 0.25 m^2 quadrats. Combining these estimates of

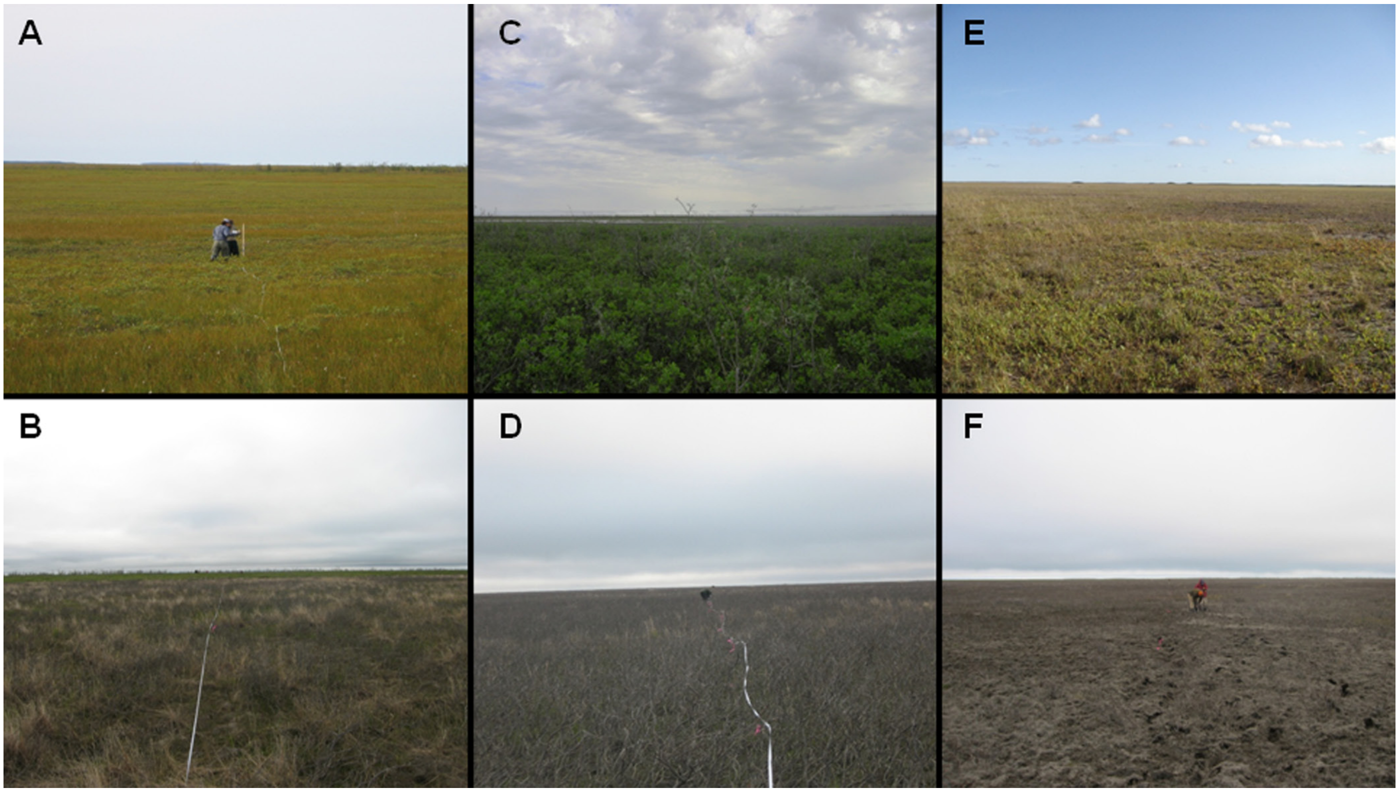

FIG. 2. Photographs of unimpacted (A, C, E) and impacted (B, D, F) vegetation communities in the outer Mackenzie Delta. A, B) sedge wetlands; C, D) willows; and E, F) dwarf shrub-tundra.

canopy cover and understory vegetation yielded values of vegetation cover that frequently exceeded 100%. Organic thickness and active-layer depth were determined at each sampling point, and a composite active-layer soil sample was collected for geochemical analyses. The organic layer was defined as non-mineral soils of partly to well-decomposed organic materials, excluding undecomposed surface litter. Active-layer depths were determined by pushing a calibrated steel probe to depth of refusal. Composite soil samples were collected using an Eijkelkamp soil sampler, bagged, and stored in a cool dark place until returned to the laboratory for analysis. Samples were evaluated for gravimetric moisture content, pH, electrical conductivity (EC) of soil solution, and water-soluble ions, following McKeague (1978).

To test for significant differences in soil chemistry, moisture, and vegetation cover, we used a factorial analysis of variance to examine the effects and interactions between site condition (impacted or unimpacted) and vegetation zone. Since all models that were examined showed significant interactions between impact and vegetation zone, Tukey's HSD procedure was also used to test for significant differences among individual means. To compare soil conditions with vegetation cover across all sites, we also performed linear regression analysis of vegetation cover vs. EC. To meet the assumptions of normality and equal variance, EC, ionic concentrations, soil moisture, and vegetation cover were log-transformed.

NDVI and Change Detection Analysis

To provide a more detailed estimate of the areal extent of impacted terrain, we performed change detection analysis with PCI Geomatica software using normalized difference vegetation index (NDVI) images derived from Landsat Thematic Mapper. Images that bracketed the vegetation dieback event were selected to maximize cloud-free area (> 90%) and phenological stability and minimize differences in sun angle. Several candidate scenes from data archives were ruled out because of extensive cloud cover, poor phenological matching, or imaging errors incurred during acquisition. Landsat-5 images of the study area taken on nearly the same midsummer anniversary date for 1986 and 2005 met the selection criteria, and eliminated cross-platform satellite calibration differences. Four images processed to Level-1G were obtained from the Earth Resources Observation and Science (EROS) Center (23 July 1986, LT5064011008620410 and LT5064012008620410; 27 July 2005, LT5064011000520810 and LT5064012000520810). The Atmospheric/Topographic Correction for Satellite Imagery (ATCOR) model in the PCI software package was used to apply radiometric and atmospheric corrections to each image (Richter and Schläpfer, 2011), and then an NDVI image was generated for each scene. The NDVI scenes, paired by year, were mosaicked to create a single coverage image for each year (PCI Geomatics, 2001). The NDVI image from 2005 was geometrically co-registered to the 1986 image using nearest-neighbour re-sampling to

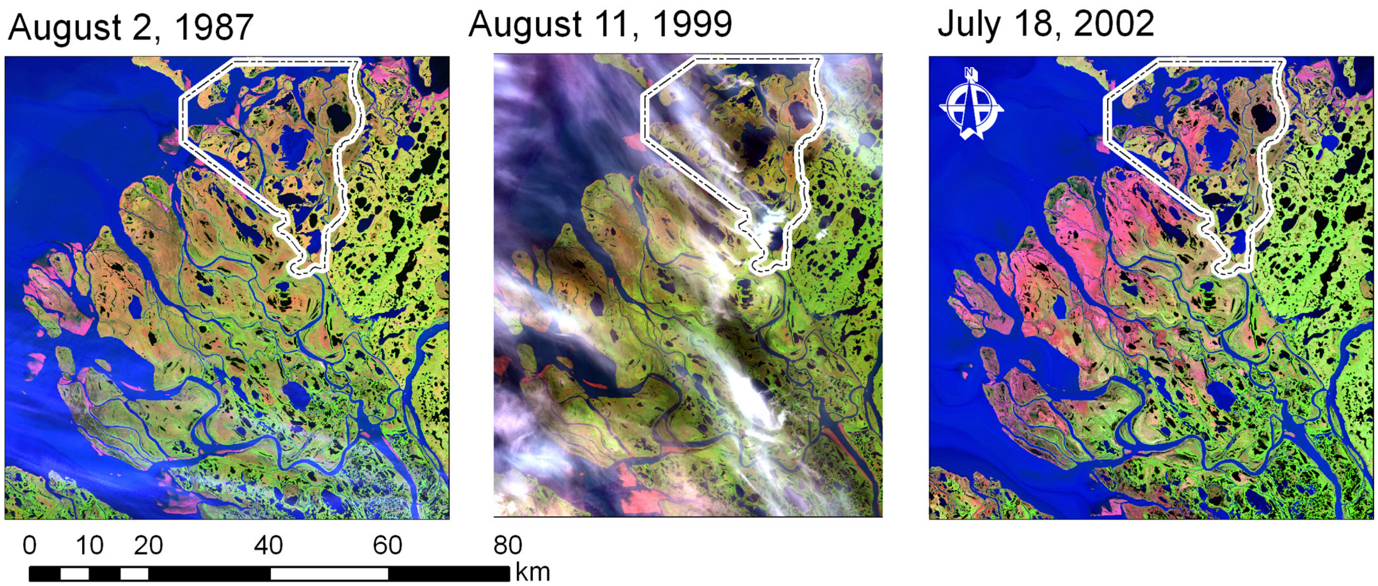

FIG. 3. False-colour infrared images of the outer delta from the Landsat archive. All images are false-colour composites of bands 4, 3, and 2 and were radiometrically corrected using ENVI (2006). The Kendall Island Bird Sanctuary is delineated on each image.

match geographic locations of mosaic pixels between years while maintaining the integrity of the individual NDVI values. Subsequently, after masking out clouds, cloud shadows, and water bodies, we subtracted the 1986 mosaic image from the 2005 mosaic image to detect vegetation changes. The ATCOR modeling caused our NDVI data to be scaled differently from uncorrected input data; however, spectral variation in our dataset is constrained among all scenes, so our change detection is robust. Image difference data ranged from -1 to 1. Large decreases indicate vegetation dieback, increases indicate greening, and zero values indicate no change. We used thresholds of +0.2 and -0.2 to provide conservative estimates of the extent of vegetation change (dieback and greening) between the two NDVI images.

Permafrost

To investigate whether past salinization events can be detected in geochemical profiles from near-surface permafrost, we obtained soil cores at impacted and unimpacted sites that extended to depths of 2.5 m, passing through the active layer into the permafrost. The unimpacted sites were clustered around Taglu Island, moderately impacted sites were in the vicinity of Niglintgak, and highly impacted areas were on North Ellice and adjacent islands (Fig. 1). Cores were obtained using a 10 cm diameter CRREL core barrel in late August of 2004, 2005, and 2006 and in March 2006. Active-layer depths were determined at the sampling locations in late August so that the position of the permafrost table could be estimated. The samples were sectioned into 10 cm intervals, sealed in bags, and stored in a cool dark place until they were analyzed for soil moisture content and salinity following the methods of McKeague (1978).

Meteorological Data

Climate data for Tuktoyaktuk (Environment Canada, 2009) and hydrometric data (Water Survey of Canada, 2010) were compiled to investigate the 1999 storm and surge characteristics and to compare with other recent historical storm events in the region. Data on wind speed and direction were obtained from Manson and Solomon (2007). For major storms, relative intensity was estimated as the duration multiplied by mean wind speed. Water Survey of Canada stage data were obtained for the Mackenzie River, from Reindeer Channel at Ellice Island (gauge 10MC011), located on the west side of the delta 35–40 km from the channel mouth on Mackenzie Bay, and from East Channel above Kittigazuit Bay (gauge 10LC013), approximately 4 km upstream from the channel mouth (Fig. 1). Data were originally reported relative to an assumed vertical datum and then corrected to the Canadian Gravimetric Geoid (CGG) 2005 vertical datum by the National Hydrology Research Institute (M. Russell, Environment Canada, pers. comm. 2009).

Inuvialuit Knowledge

In March 2009, the Inuvialuit Joint Secretariat organized a two-day workshop in Aklavik to provide Inuvialuit land users with an opportunity to discuss the impacted area of the outer delta. The hunters and trappers committees of three communities each nominated several individuals who travel and hunt extensively in the outer Mackenzie Delta to attend the workshop. A total of nine hunters were selected: four from Aklavik, three from Inuvik, and two from Tuktoyaktuk. At least one youth from each community also attended. To avoid bias, the floor was immediately opened to the Inuvialuit experts to discuss storm surges among themselves, as well as the related phenomena of recent environmental change in the delta. Presentations of scientific perspectives were given only after discussions amongst the Inuvialuit experts had been exhausted. The Inuvialuit experts remembered the specific storm surge event and discussed it in detail while seated around a map of the delta. Several note-takers recorded the expert statements and submitted their summary to the respective hunters and trappers committees for review. Our summary of Inuvialuit knowledge of the hydrology, meteorology, and environmental change underlying the frequency, severity, and impact of storm surges in the outer Mackenzie Delta is based on this meeting.

RESULTS

The Instrumental Record

In September 1999, a major storm, originating as a low-pressure system in the Gulf of Alaska, tracked across Alaska and the Yukon. On 22 September, offshore winds in the Mackenzie Delta region reached speeds of 43 km h^{-1}. When the storm arrived at the Beaufort Sea Coast on 23 September, it re-intensified (Small, 2009) and storm winds shifted direction (Fig. 4A). By 24 September, winds from the northwest (310˚) reached 76 km h^{-1} (21 m s^{-1}) and were sustained for approximately 36 hours (Fig. 4A). As northwest winds intensified, water levels in the central delta rose more than 2 m above the mean water level for the preceding five days (Fig. 4B). A peak daily water level of 2.5 m above Canadian Gravimetric Geoid at Reindeer Channel exceeds maximum elevations of the outer delta plain and suggests that the surge inundated most alluvial terrain within 20 to 30 km of the coast. Synthetic Aperture Radar data confirmed that significant portions of Langley and Ellice Islands were inundated on September 25 and 26 (Solomon et al., 2005). In contrast with the approximate 2 m water-level rise in the central delta, the levels at the eastern outlet of the delta increased by approximately 1 m (Fig. 4B).

Among major storms in the 1990s, the 1999 storm is the most extreme on the basis of duration, wind speed, and intensity (Table 1). This storm event caused higher water levels than a major storm event in 1993 at both Reindeer Channel at Ellice Island and East Channel at Kittigazuit (Table 1) (Manson and Solomon, 2007). In fact, the water-level data from 1982 to 2004 indicate that the 1999 storm surge produced the highest September water levels on record at both Reindeer Channel and East Channel.

Inuvialuit Observations

The 1999 storm surge was remembered as one of unprecedented impacts by several Inuvialuit experts at the 2009 Aklavik workshop. Experts remembered the details of the 1999 event within the context of an increase in the frequency of storm surges in general. A number of factors were understood to be involved in this increase. Warmer summers have resulted in a longer open water season, leaving more time for storm events to occur. Participants noted that there have been increasing numbers of storms with high winds from the west and northwest, which are known to cause storm surges. In general, the periods of relatively calm weather have decreased relative to Inuvialuit observations of past norms.

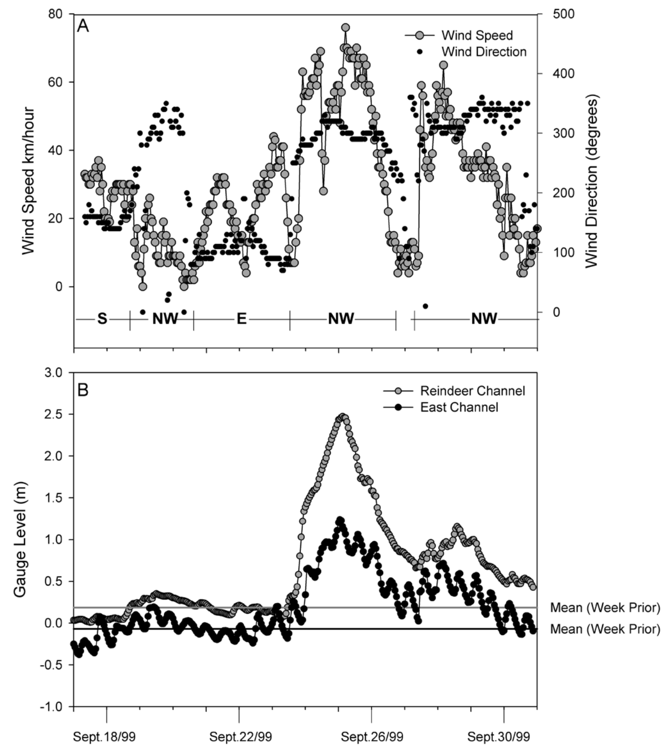

FIG. 4. Wind and water levels preceding and during the September 1999 storm surge, Mackenzie Delta. A) Shaded circles indicate wind speed and dots indicate wind directions at Pelly Island for 18–30 September 1999. Dominant wind directions are indicated along the lower x-axis. B) Water levels for Reindeer Channel at Ellice Island (10MC011) and East Channel at Kittigazuit (10LC013). Horizontal lines show mean water levels for the seven days before 18 September. Data are from the Water Survey of Canada.

> When you get a west wind and north wind it blows salt water into the delta—especially when the river is low.
> (Sam Lennie Sr., Inuvik)

The severity of storm surge impacts is understood by the Inuvialuit experts to be associated in part with seasonal differences in water levels in the Mackenzie River delta. In fall, when severe storm surges typically occur, the river is low and the relative effects of the surge on water levels can be significant and extend far into the delta. It is common knowledge that a storm surge can cause water levels at Inuvik or Aklavik to rise significantly.

> I noticed about four years ago when we had a storm surge when there was very low water that not much fresh water was coming out of the delta so the storm

TABLE 1. Storm duration, intensity, wind speed and direction, and peak water levels for major storm events in the Mackenzie Delta during the 1990s.

Start date	Duration (hours)	Intensity[1]	Mean wind speed (km hr^{-1})	Peak wind speed (km hr^{-1})	Mean wind direction (˚)	Peak wind direction (˚)	Peak level (m asl) East Channel	Peak level (m asl) Reindeer Channel
21 September 1993	27	1971	73	96	284	290	0.68	1.53
21 August 1994	13	793	61	69	289	290	NA	1.33
27 August 1996	12	683	57	65	287	290	0.60	NA
16 August 1998	8	465	58	70	275	290	0.32	0.60
23 September 1999	36	2181	60	76	300	305	0.98	2.10

[1] Storm intensity was defined as the duration of the storm multiplied by the mean wind speed.

> surge could go in. That year there wasn't much water in the Delta. That year [the delta was so low] there were places you could normally go but [that year] you couldn't go. You had to stick to bigger channels.
>
> (Douglas Esogak, Inuvik)

The 1999 storm surge event is particularly well remembered because of the extreme inundation that occurred. Individuals from Inuvik remembered that the East Channel water level rose approximately five feet (~ 1.5 m) at Inuvik during a September storm surge about 10 years ago. The experts also described a September storm surge about 10 years ago that picked up and moved two structures: the "police cabin" and the search-and-rescue cabin of the Aklavik Hunters and Trappers Committee. These structures, located on the western side of the West Channel, were moved approximately 3 km inland. A youth participant to the workshop, Andrew Archie (Aklavik), recalled that at this same time, his family was camping on the coast on the western side of the West Channel when a storm surge occurred. They were forced to travel by boat to a safer location, leaving their tent and equipment behind. Danny C. Gordon of Aklavik recounted that salt water came into the delta and flooded the land around his cabin in the Blow River delta during a September storm surge in the late 1990s. Danny C. Gordon also recounted that during the same storm surge, Ned Kayutak of Aklavik took water for tea from a creek near his camp about 15 miles (~ 24 km) downriver from Aklavik, and the water was salty. Expert Billy Storr (Aklavik) commented that it was salty at that time right up to Selamio's Stretch [20 km downriver from Aklavik], which he noted was unusually far upriver for salt water. On the basis of these recollections, workshop participants approximated that this event had occurred 10 years prior to the year of the workshop. Using the age of Andrew Archie at the time of the event, as well as one expert's memory of the outboard he owned at the time of the event, the group came to a consensus that an extreme storm surge occurred in 1999.

Workshop participants also described a vegetation die-off beginning in the summer of 2000 as one of the immediate effects of the 1999 storm surge. Experts suggested that the vegetation dieback resulted because the inundation occurred late in the season. Danny C. Gordon (Aklavik) described the fall surge that flooded the land around his cabin in the Blow River delta and how the ground froze immediately afterward, trapping the salts in the soil. He also indicated that widespread vegetation death had not previously been associated with storm surge flooding.

Inuvialuit experts also made a connection between the die-off of willows and grasses and changes in the use of the area by wildlife. Moose were commonly seen in parts of the affected area before the 1999 surge but now are seen less frequently. The area was also a very important waterfowl hunting area for Inuvialuit in the past, and experts described how there were once "lots of geese" in the area, but now there are "hardly any." Geese are now described as flying high over the area.

> Geese used to stage in the outer islands in the thousands—now they go right over. Last year in Herschel there were lots of snow geese coming straight off the ocean. It seemed too early—in the middle of August—to be the Banks Island geese. They don't stop anymore because of the killed vegetation. They are going over or moving further into the delta. Now I see them at Bar C, and they are even nesting in the delta between Aklavik and Inuvik. I saw moulted geese swimming in Napoiak Channel.
>
> (Douglas Esogak, Inuvik)

The environmental effects of the 1999 surge event appear to have directly affected Inuvialuit subsistence activities. Experts from Tuktoyaktuk (Charles Pokiak and David Nasagaloak) indicated that this area has not been used by hunters from Tuktoyaktuk for some time. In general, the present lack of waterfowl in the affected area has meant that Inuvialuit from Inuvik, Tuktoyaktuk, and Aklavik seek out different areas for waterfowl hunting. Opportunistic moose hunting that formerly occurred in the affected area now appears to be less viable. More frequent storms resulting from high west winds are also blamed for reshaping the coastal zone through build-up of sediment and slumping. This process has caused changes in water depth at known sites, affecting coastal navigation by Inuvialuit land users.

Field Measurement of Soils and Vegetation

Field sampling showed that soils in impacted areas had higher electrical conductivities (EC) and ionic

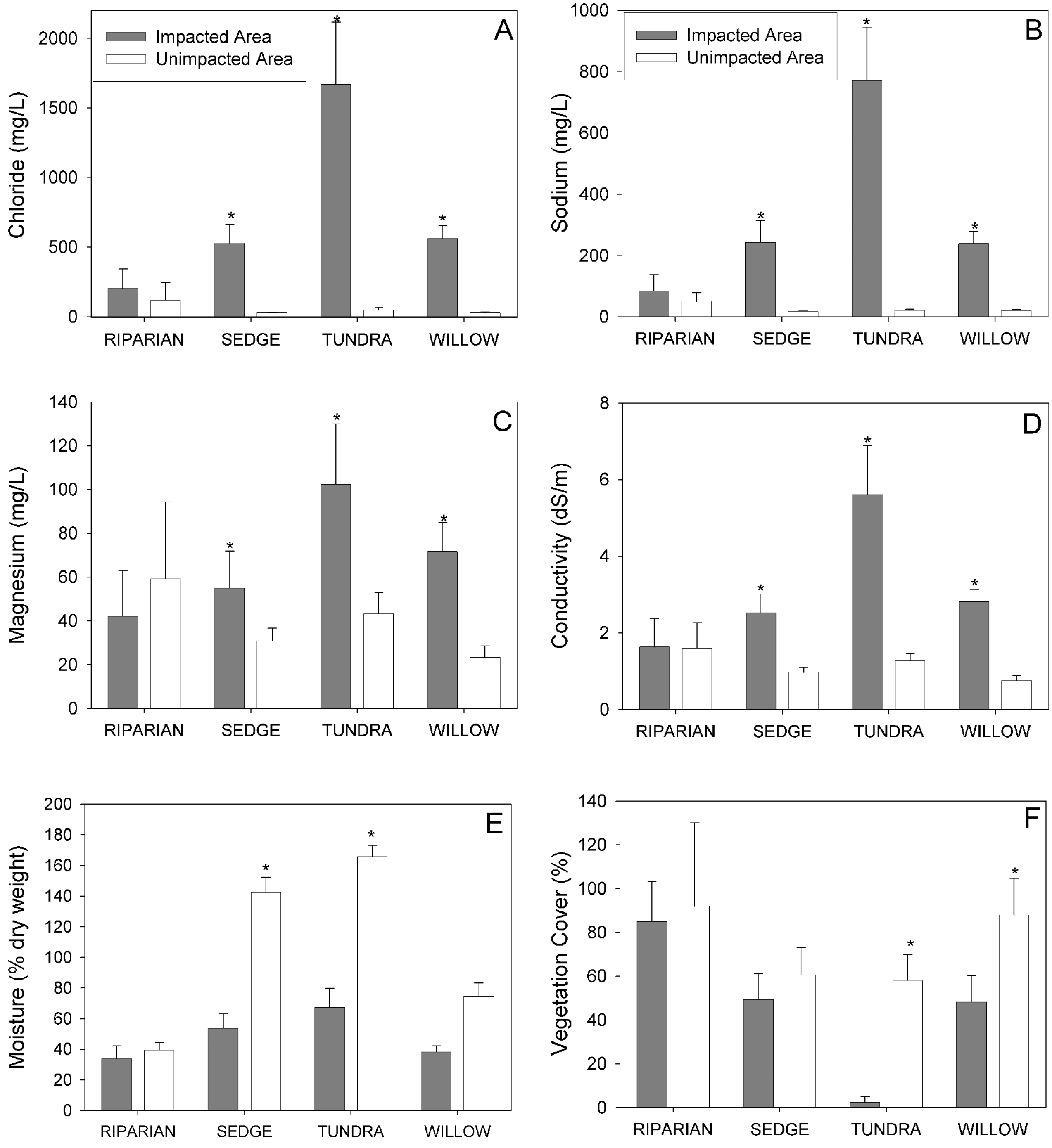

FIG. 5. Soil and vegetation characteristics measured in different vegetation types (riparian, sedge wetland, tundra, and willow communities) in impacted and unimpacted portions of the study area. Bars show means for: (A) chloride, (B) sodium, (C) magnesium, (D) electrical conductivity, (E) gravimetric soil moisture content, and (F) vegetation cover. Error bars show the 95% confidence intervals of the mean (untransformed). The (*) indicates significant differences ($p < 0.05$, Factorial ANOVA and Tukey HSD) between disturbed and undisturbed sites.

concentrations and lower moisture contents than unimpacted soils, but the effects were dependent on vegetation type. All models showed significant interactions between site condition (impacted vs. unimpacted) and vegetation type (Table 2). Soil chloride, sodium, and magnesium concentrations and EC in impacted sedge, tundra, and willow communities were significantly greater than at unimpacted sites (Fig. 5). A significant increase in soil ionic concentrations and EC was not observed at impacted riparian sites. The highest chloride, sodium, and magnesium concentrations and EC were measured at the impacted tundra sites, where the contrast with disturbance status was also the greatest (Fig. 5A–D). Soil moisture was significantly lower in impacted sedge and tundra communities, but did not differ with disturbance at riparian and willow communities (Fig. 5E).

TABLE 2. Results of factorial ANOVA (Site Condition × Vegetation Type) comparing soil characteristics and vegetation at sites in the outer Mackenzie Delta, N.W.T.

Response	Effect	F value	df	*p*
Chloride	Site Condition	752.2	1,122	< 0.001
	Vegetation type	10.1	3,122	< 0.001
	Impact × Vegetation Type	4.2	3,122	< 0.001
Sodium	Site Condition	759.2	1,122	< 0.001
	Vegetation Type	10.6	3,122	< 0.001
	Impact × Vegetation Type	20.4	3,122	< 0.001
Magnesium	Site Condition	71.6	1,122	< 0.001
	Vegetation Type	5.8	3,122	< 0.001
	Impact × Vegetation Type	1.4	3,122	< 0.01
Conductivity	Site Condition	244.0	1,122	< 0.001
	Vegetation Type	12.9	3,122	< 0.001
	Impact × Vegetation Type	1.4	3,122	< 0.001
Moisture	Site Condition	24.0	1,122	< 0.001
	Vegetation Type	1.4	3,122	0.25
	Impact × Vegetation Type	5.0	3,122	< 0.01
Vegetation Cover	Site Condition	25.1	1,122	< 0.001
	Vegetation Type	9.7	3,122	< 0.001
	Impact × Vegetation Type	3.0	3,122	0.03

Higher EC in impacted tundra and willow communities (up to 8.8 dS/m) corresponded with reduced vegetative cover (Fig. 5D, F). Electrical conductivity of soil solution was also elevated at impacted sedge sites, but vegetation cover was not significantly lower. At the sites where EC was highest, the cover of living vegetation was low to completely absent (Figs. 2D and F, 6). Differences in the electrical conductivity of the soil solution also showed a significant relationship with vegetation cover (Fig. 6). Impacted field sites with low vegetation cover showed large reductions in NDVI between 1986 and 2005 (-NDVI Δ), whereas unimpacted and impacted sites with higher vegetation cover typically showed little change in NDVI (Fig. 7). The relationship between plot-level vegetation cover and NDVI shown in Figure 7 suggests that NDVI can be used to estimate the spatial extent and severity of impacts to vegetation communities in the outer Mackenzie Delta.

Remotely Sensed Data

A sequence of remotely sensed images obtained during mid-summer in 1987, 1999, and 2002 shows clear changes in spectral reflectance over large areas of the outer delta between August 1999 and August 2002 (Fig. 3). The change detection analysis using 1986 and 2005 imagery was constrained to the "impacted area" and the Kendall Island Bird Sanctuary indicated in Figure 8. The analysis showed that areas with decreases in NDVI of more than 0.2 include the terrain west of Middle Channel, northern Langley Island, the central northern portions of Ellice Island, the large island to the north of Ellice Island, and isolated patches within the Kendall Island Bird Sanctuary (Fig. 8). Overall, NDVI decreased by more than 0.2 in approximately 13 200 ha of the impacted area (Fig. 8). There were also several areas of the outer delta that exhibited increases in NDVI from 1986 to 2005. These low-lying areas, located close to the delta front and along major channels, are frequently dominated by emergent vegetation (Fig. 8). In total, NDVI increased by more than 0.2 in approximately 7079 ha of the impacted area (Fig. 8). Inuvialuit observations and more extensive Landsat coverage indicate that impacted areas extend southwest towards Shallow Bay and westward to the Blow River delta.

Permafrost Chemistry

In unimpacted areas, the active layer and near-surface permafrost had lower soluble Cl^- concentrations than in impacted areas (Fig. 9). In the vicinity of Taglu Island, soil soluble Cl^- concentrations within the active layer and near-surface permafrost were generally less than 100 mg/L (Fig. 9). At moderately impacted sites in the Niglintgak area, elevated Cl^- concentrations throughout the top 1.5 m of profiles reached 2000 mg/L. At highly impacted sites, active layer Cl^- concentrations reaching 10 000 mg/L were an order of magnitude greater than in the underlying permafrost or active-layer soils at undisturbed sites (Fig. 9).

DISCUSSION

The 1999 Storm

Multiple lines of evidence indicate that a storm surge in September 1999 caused extensive flooding of the outer Mackenzie Delta, which resulted in unprecedented ecological impacts. The high winds and sustained storm intensity place the 1999 storm among the top five open water season storms during the 40-year period of record from Tuktoyaktuk (Table 1) (Manson and Solomon, 2007). From 24 to 25 September 1999, water levels at the central delta front were more than 2 m higher than those of the preceding week and the highest levels recorded between 1982 and 2004 (Fig. 4; Water Survey of Canada, 2010). Water level data, Inuvialuit observations of the 1999 surge, and the distribution of wave-washed debris visible on aerial photographs suggest that even the most elevated surfaces of the outer delta plain were inundated by this event. Significant impacts to soils and vegetation more than 30 km inland from the delta front, as well as the detection of saline waters in channels within 20 km of Aklavik by Inuvialuit observers, indicate the remarkable extent of the marine incursion that resulted from this storm event.

Surge Impacts

Together, the data on soils and vegetation, NDVI change detection analysis, and Inuvialuit observations indicate that the September 1999 storm surge caused soil salinization and severe impacts to vegetation across much of the outer

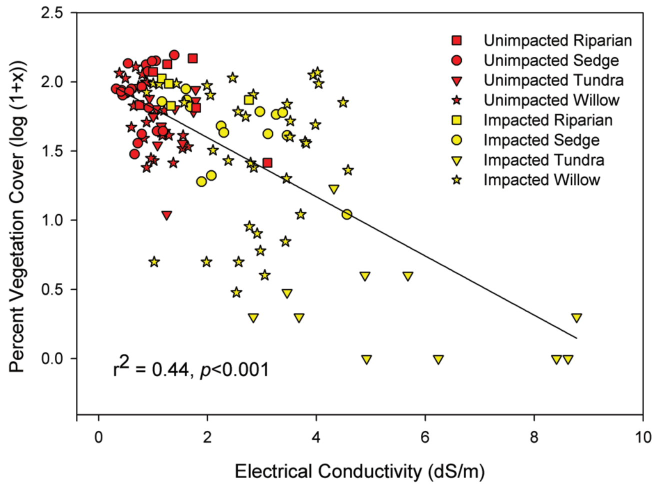

FIG. 6. Plot of percentage vegetation cover against soil electrical conductivity (EC) for sampling plots in the outer Mackenzie Delta. The line shows the least squares regression of vegetation cover vs. EC.

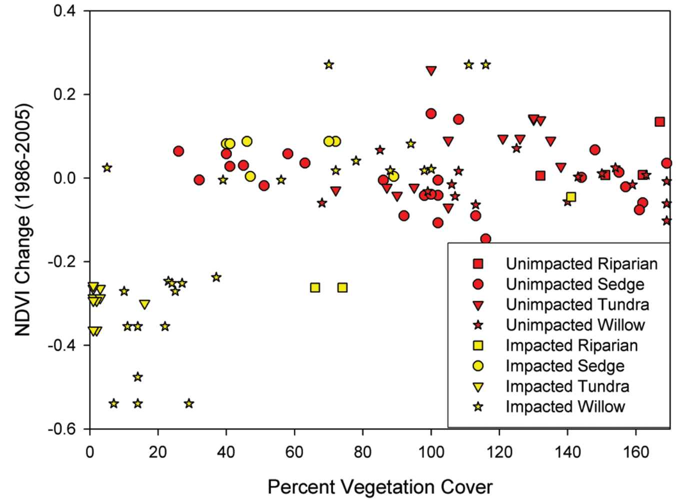

FIG. 7. Plot of the change in normalized difference vegetation index (NDVI) against vegetation cover for sampling plots in the outer Mackenzie Delta.

Mackenzie Delta (Figs. 5–9). More than seven years after this disturbance, extensive areas of impacted vegetation persisted in association with high soil salinity (Fig. 5). The low-shrub tundra communities, which occupy the highest alluvial surfaces of the outer delta, were the most severely impacted. Elevated soil EC and Cl^- concentrations characterized these extensive areas virtually devoid of live vegetation (Figs. 2, 5–8). Impacted willow communities also had elevated soil salinities and lower vegetation cover than unimpacted sites (Figs. 5–7). A decline in alder growth and widespread mortality immediately following the 1999 storm surge indicate that saltwater inundation led to abrupt ecological impacts (Pisaric et al., 2011; Deasley et al., 2012). Change detection analysis of NDVI images shows that, following the 1999 storm surge, vegetation dieback affected more than 13 000 ha of terrain in the central outer delta alone (Fig. 8). Inuvialuit accounts of stressed and dying shrubs in the western Mackenzie and Blow River deltas indicate that impacts of the 1999 storm surge extended well beyond the areas shown in Figure 1.

Causes of the Saline Incursion

Over the past half century, the Mackenzie Delta has been affected by several storms similar in magnitude to the 1999 event (Manson and Solomon, 2007), but these did not cause widespread salinization or vegetation die-off (Pisaric et al., 2011). Possible explanations for the unique effects of the 1999 storm include the preconditioning of the water column by marine upwelling induced by offshore winds and the intensity and duration of the storm (Table 1). Typically, Mackenzie Bay is characterized by a stratified water column with cold marine waters underlying a plume of warm, turbid river water that extends tens of kilometres offshore (Hill and Nadeau, 1989; Carmack and Macdonald, 2002). In September 1999, several days of strong offshore winds preceded storm intensification and the shift of winds to NNW, which caused the record storm surge (Table 1; Fig. 4). Periods of sustained offshore winds (southerly and easterly) can cause upwelling of cold marine waters and an increase in surface water salinity (Carmack and Macdonald, 2002). This phenomenon was noted by the Inuvialuit land users during discussions on the outer delta: Tuktoyaktuk experts Charles Pokiak and David Nasagaloak indicated that the water around Tuktoyaktuk (more than 35 km from the nearest distributary) is typically brackish and turbid because of the freshwater outflow of the East Channel, but they also observed that easterly winds “clear up the water” along the coast and can make it colder and more salty.

Limited field data indicate that during moderate surges (> 1 m), water temperatures may decrease and salinities may slightly increase in outer delta channels (Jenner and Hill, 1991). These observations suggest that even moderate onshore wind events can mix the water column and cause saline waters to enter channels in the outer delta (Hill et al., 2001).

During storm surges generated by NW winds, the sheltering effect of Richards Island may contribute to the variable water level responses between the central delta and the East Channel outlet (Figs. 1, 4). During the 1999 storm, water levels in the central outer delta, exposed directly to the onshore winds, increased by over 2 m in contrast with the eastern outlet at Kugmallit Bay where the stage increased by about 1 m (Fig. 4). The track of the storm and the associated timing and duration of the storm surge may have caused discharge to divert from the central delta towards the East Channel outflow at Kugmallit Bay (Fig. 1). This could facilitate the incursion of marine waters into the central delta as apparently occurred during the 1999 storm surge.

Unprecedented Impacts

The mass mortality of long-lived alder in association with the 1999 storm surge (Pisaric et al., 2011) supports the Inuvialuit knowledge that similar events have not occurred

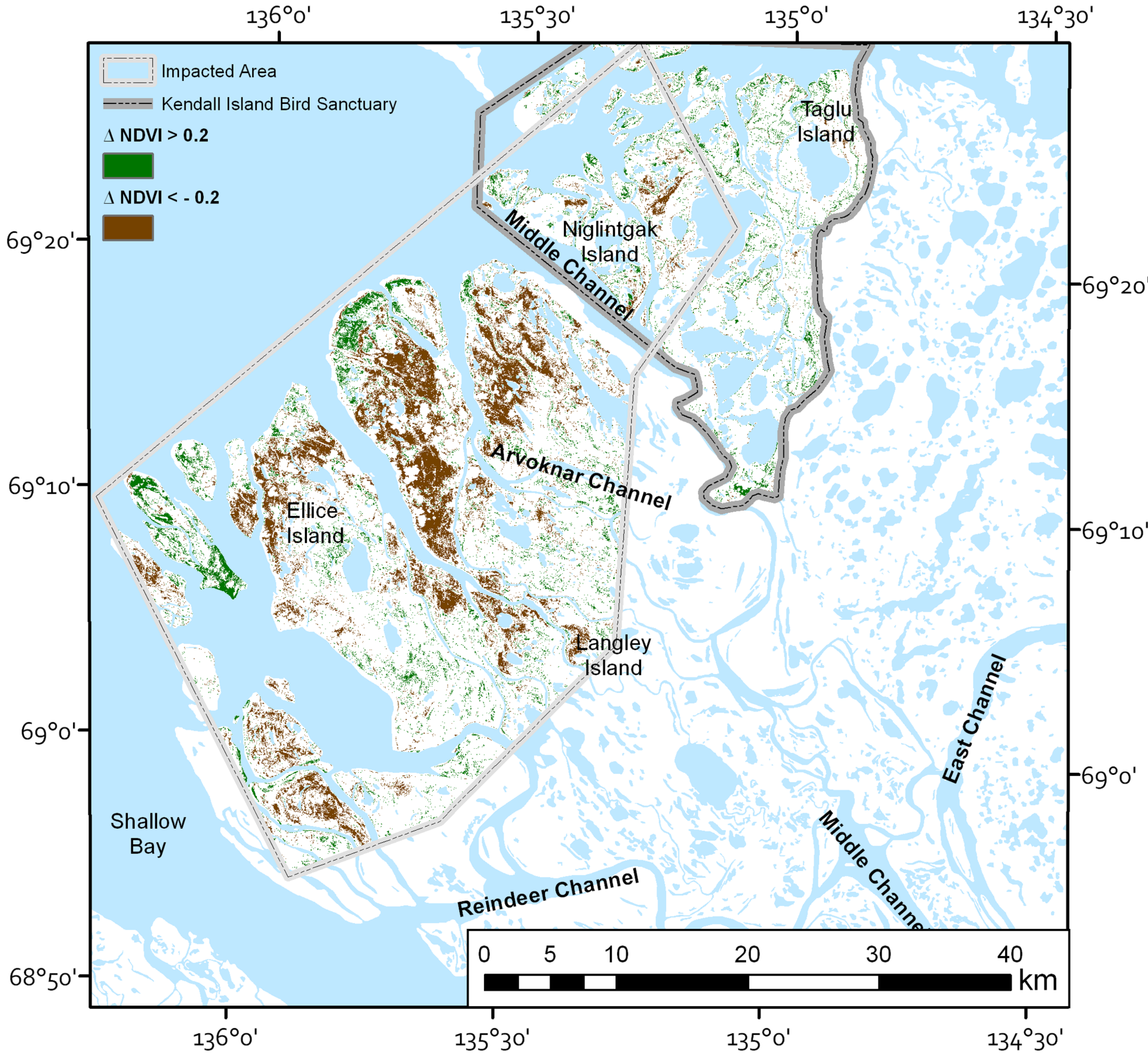

FIG. 8. Map of the study area showing the results of the NDVI change detection analysis based on images from 1986 and 2005. Pixels exhibiting increases greater than 0.2 are mapped as green, and pixels showing decreases greater than 0.2 are mapped as brown.

in the last 50 years. Paleolimnological evidence from an outer delta lake ecosystem indicates a striking shift from freshwater to brackish diatom species following the 1999 storm surge event (Pisaric et al., 2011). This record suggests that the recent ecological impact is unprecedented over the more than 1000 year history of this lake ecosystem. The terrestrial permafrost cores are not constrained by radiocarbon dates, but the profiles likely represent at least hundreds of years of sediment deposition (Fig. 9). If saline flooding events occurred throughout the depositional histories of the permafrost core sites, salts should be sequestered at depth by alluvial sedimentation, surface aggradation, and a rising permafrost table (Gill, 1972; Kokelj and Burn, 2005). Geochemical profiles from impacted terrain show that elevated soil Cl^- concentrations were restricted to the active layer and only the top few decimetres of permafrost, indicating recent salinization (Fig. 9). The low Cl^- concentrations at depth suggest that saline flooding of elevated alluvial environments was uncommon in the past.

Salt concentrations in outer delta soils remain elevated almost a decade after inundation by the saline storm surge. Water level records suggest that the most elevated and highly impacted areas have not been flooded by surges since the 1999 event, so recurrent inundation cannot explain the sustained effects. Elevated salinities likely persist because a frozen active layer inhibits removal of salts by spring flooding, and the low gradient of the alluvial landscape impedes lateral drainage.

The lack of revegetation at many impacted sites also indicates that saline incursions were uncommon across

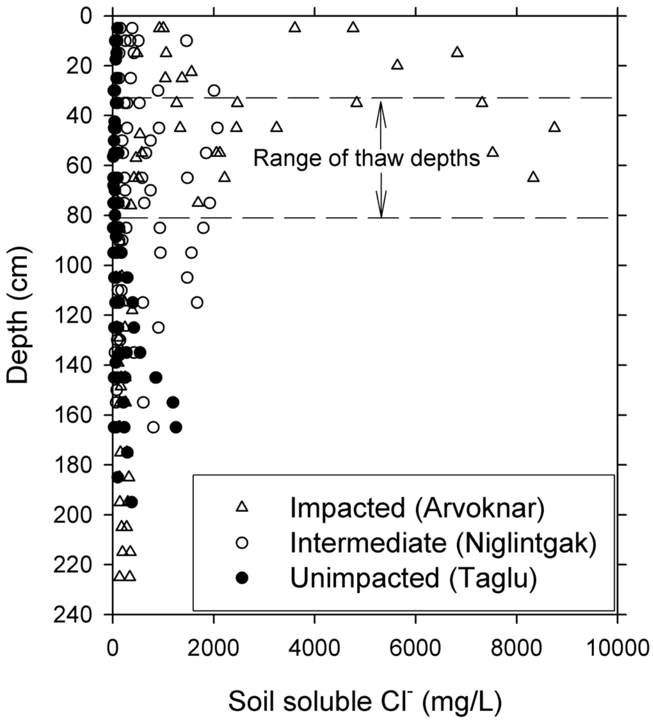

FIG 9. Soluble ion concentrations in the active layer and near-surface permafrost for the Taglu, Niglintgak, and Arvoknar Channel areas.

much of the delta. Alluvial surfaces affected by spring flooding and high sedimentation rates are typically recolonized by early successional species within one or two years (Pearce, 1986), but eight years after the 1999 storm surge, the most saline surfaces showed little or no re-colonization (Figs. 2, 5). Over this same time period, several emergent surfaces impacted by spring flooding have greened (Figs. 2, 8). Interestingly, the most severely impacted sites we sampled (EC: 2 – 8 dS/m) are well within the tolerances of a number of Arctic plant species common in tidal areas (Jefferies, 1977; Porsild and Cody, 1980; Srivastava and Jefferies, 1995; Handa et al., 2002). The slow ecological recovery of alluvial surfaces in the outer delta is likely due to the lack of salt-tolerant seed sources, suggesting that large-scale salinization has not been the major driver in shaping the ecology of this ecosystem (Johnstone and Kokelj, 2008; Kemper and MacDonald, 2009).

The observed impact on vegetation following the 1999 storm has almost certainly had consequences for wildlife, as suggested by Inuvialuit hunters, who note that the abundance of geese staging in this part of the delta has declined over the past decade. With the anticipated rise in sea levels and increases in the magnitude and frequency of storms (Manson and Solomon, 2007), saline incursions could become more common in the future. The slow vegetation recovery following the 1999 storm and potential for cumulative habitat loss with future disturbance have significant implications for the ecosystem and resource management.

Monitoring Northern Environmental Change

Effective environmental management is predicated on a basic understanding of natural variability and a monitoring system that is capable of detecting and reporting departures from baseline conditions. Understanding the magnitude of storm surge impacts and the trajectories of ecological recovery is central to assessing, monitoring, and managing the cumulative impacts of development in the outer Mackenzie Delta (Joint Review Panel, 2009). While approaches such as ours can yield important knowledge on northern environmental change (e.g., Pisaric et al., 2011), they provide little certainty that information will be collected and reported at spatial or temporal scales relevant to resource managers, communities, or industry. The fact that a regional-scale environmental change can go undocumented by scientists, regulators, and industry for more than a decade in an area of high cultural, ecological, and development significance (Pisaric et al., 2011) suggests the need to focus northern baseline monitoring and research on scales and issues relevant to communities and environmental managers. Our experiences in obtaining and analyzing information on the recent ecological change in the outer delta highlighted several key elements of effective northern monitoring strategies.

The cumulative impacts of climate change and northern development are complex in nature and require a holistic understanding of the environment. Multidisciplinary approaches involving collaboration of communities, scientists, and resource managers and focused on priority issues or regions are most likely to address questions relevant to the North, improve the explanative power of monitoring and research efforts, and yield information useful to northern decision makers. Investigating the regional ecological change resulting from the 1999 storm surge required multidisciplinary effort, and northern research partners played a central role.

It is now widely recognized that northern monitoring programs must be informed by local expertise and should involve Northerners in all stages possible—from developing monitoring objectives to using results (Huntington et al., 2004; Moller et al., 2004; Eisner et al., 2009). Successful community-based projects are typically the result of cooperation and knowledge sharing among the community, scientists, and resource managers (Kendrick et al., 2005; Parlee et al., 2005). The information shared by Inuvialuit knowledge holders regarding environmental change in the outer Mackenzie Delta illustrates the value and relevance of the knowledge that communities possess. Many land users were aware that widespread ecological change had occurred following the 1999 storm and might have identified this as a priority issue as early as 2000. Developing mechanisms to promote knowledge sharing among traditional knowledge holders, scientists, and resource managers, with thematic or regional emphasis, will help focus monitoring and research initiatives and contribute to the more timely detection and reporting of environmental change.

The capacity to analyze monitoring data and the ability to communicate results to relevant audiences are also key components of a northern environmental monitoring system. Much of the data analyzed to describe the 1999 storm surge and its impacts consisted of archived remote sensing or hydrometric data. In this regard, northern monitoring programs should be guided by a framework that promotes multidisciplinary syntheses and supported by the capacity to transform data into information that is relevant to northern communities and resource managers.

Areas of cultural, ecological, and development significance such as the Mackenzie Delta are ideal for piloting environmental monitoring approaches. Such initiatives must be guided by clear objectives and questions, a process that requires the engagement of the scientists, northern communities, environmental managers, and industry who will use the information. Development of regional or issue-driven programs, including the conceptualization, design, collection, and management of data and reporting, should be guided by basic standards and principles. These will help ensure that partners are engaged at the appropriate times and that the right information is being collected, analyzed, and reported in a suitable fashion.

SUMMARY

We synthesize multiple sources of information to document a storm surge that flooded much of the outer Mackenzie Delta in September 1999. The event was significant both because it was unprecedented and because saline inundation caused vegetation die-off over an area of more than 130 km^2. Vegetation recovery in this important ecosystem has been slow. More than a decade after the disturbance, some terrain types have saline soils and remain almost completely devoid of vegetation. Inuvialuit knowledge and the analysis of permafrost cores suggest that extensive saltwater inundation in the outer delta has been uncommon in the past. Rising sea levels and a greater extent and duration of the open water season due to climate warming could increase the magnitude and frequency of storm surges and the impacts to Arctic coastal ecosystems. The broad-scale ecological changes to the outer Mackenzie Delta caused by the 1999 storm surge have implications for wildlife and in the assessment, monitoring, and management of the cumulative impacts of development. This study highlights the need for coordinated monitoring and research that is multidisciplinary, regionally relevant, and locally informed. Such efforts are vital to sound policy development and resource management in Canada's changing North.

DEDICATION

This paper is dedicated to our friend and colleague Steve Solomon. His gift of working with others and his willingness to share ideas has stimulated much of our work. Steve's presence will be greatly missed by the North. His passion, ideas, and spirit will continue to inspire us.

ACKNOWLEDGEMENTS

The work was supported by funds received through the Northern Energy Development Initiative, the Cumulative Impact Monitoring Program and Northern Scientific Training Program of Aboriginal Affairs and Northern Development Canada, Natural Resources Canada, Global Forest Research, the Canon National Parks Science Scholars Program, the Killam Trusts, the Inuvialuit Joint Secretariat, the Polar Continental Shelf Program, the Aurora Research Institute, and the Natural Sciences and Engineering Research Council of Canada: Discovery grants to T.C. Lantz, M.F.J. Pisaric, and J.P. Smol, Northern Supplement to M.F.J. Pisaric, and the Northern Chairs Program. The interest and support of the Aklavik, Inuvik, and Tuktoyaktuk Hunters and Trappers Committees and the Inuvialuit Game Council are gratefully acknowledged. We thank Mark Russell of the National Water Research Institute for providing summary hydrometric data (Water Survey of Canada). Marc Cassas, Robert Jenkins, Brin Livingstone, Michael Palmer, Pippa Seccombe-Hett, Rory Tooke, and Anika Trimble assisted in fieldwork. The comments of three anonymous reviewers improved this manuscript.

REFERENCES

Bandringa, R.W., and Inuvialuit Elders. 2010. Inuvialuit *nautchiangit*: Relationships between people and plants. Inuvik: Inuvialuit Cultural Resource Centre and McCallum Printing Group.

Berkes, F. 1998. Indigenous knowledge and resource management systems in the Canadian Subarctic. In: Berkes, F., and Folke, C., eds. Linking social and ecological systems: Management practices and social mechanisms for building resilience. Cambridge: Cambridge University Press. 98–128.

Bromley, B., and Fehr, A. 2002. Birds. In: Black, S., and Fehr, A., eds. Natural history of the Western Arctic. Inuvik: Western Arctic Handbook Project. 45–54.

Burn, C.R., and Kokelj, S.V. 2009. The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes 20(2):83–105, doi:10.1002/ppp.655.

Carmack, E.C., and Macdonald, R.W. 2002. Oceanography of the Canadian Shelf of the Beaufort Sea: A setting for marine life. Arctic 55(Suppl. 1):29–45.

Carson, M.A., Jasper, J.N., and Conly, F.M. 1998. Magnitude and sources of sediment input to the Mackenzie Delta, Northwest Territories, 1974–94. Arctic 51(2):116–124.

Cordes, L.D., McLennan, D.S., and Pearce, C.M. 1984. Alluvial ecosystems on the Mackenzie Delta, N.W.T. Vancouver: Environment and Socio-economic Services, BC Hydro.

Deasley, K., Korosi, J.B., Thienpont, J.R., Kokelj, S.V., Pisaric, M.F.J., and Smol, J.P. 2012. Investigating the response of Cladocera to a major saltwater intrusion event in an Arctic lake from the outer Mackenzie Delta (NT, Canada). Journal of Paleolimnology 48(2):287–296, doi:10.1007/s10933-012-9577-6.

Dixon, J., Morrell, G.R., and Dietrich, J.R. 1994. Petroleum resources of the Mackenzie Delta and Beaufort Sea. Part 1: Basin analysis. Bulletin 474. Ottawa: Geological Survey of Canada.

Eisner, W.R., Cuomo, C.J., Hinkel, K.M., Jones, B.M., and Brower, R.H., Sr. 2009. Advancing landscape change research through the incorporation of Iñupiaq knowledge. Arctic 62(4):429–442.

ENVI. 2006. ENVI User's guide, version 4.3. Boulder, Colorado: Research Systems, Inc.

Environment Canada. 2009. National climate data and information archive.http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html. Ottawa: Environment Canada.

Forbes, B.C., Ebersole, J.J., and Strandberg, B. 2001. Anthropogenic disturbance and patch dynamics in circumpolar Arctic ecosystems. Conservation Biology 15(4):954–969.

Gill, D. 1972. The point bar environment in the Mackenzie River Delta. Canadian Journal of Earth Sciences 9:1382–1393.

Handa, I.T., Harmsen, R., and Jefferies, R.L. 2002. Patterns of vegetation change and the recovery potential of degraded areas in a coastal marsh system of the Hudson Bay lowlands. Journal of Ecology 90:86–99.

Hill, P.R. 1996. Late Quaternary sequence stratigraphy of the Mackenzie Delta. Canadian Journal of Earth Sciences 33(7):1064–1074.

Hill, P.R., and Nadeau, O.C. 1989. Storm-dominated sedimentation on the inner shelf of the Canadian Beaufort Sea. Journal of Sediment Petrology 59(3):455–468.

Hill, P.R., Lewis, C.P., Desmarais, S., Kauppaymuthoo, V., and Rais, H. 2001. The Mackenzie Delta: Sedimentary processes and facies of a high-latitude, fine-grained delta. Sedimentology 48(5):1047–1078.

Holroyd, P., and Retzer, H. 2005. A peak into the future: The potential landscape impacts from gas development in northern Canada. Drayton Valley, Alberta: The Pembina Institute.

Huntington, H., Callaghan, T., Fox, S., and Krupnik, I. 2004. Matching traditional and scientific observations to detect environmental change: A discussion on Arctic terrestrial ecosystems. Ambio Special Report 13:18–23.

Imperial Oil Resources Ventures Limited. 2004. Overview and impact summary, Vol. 1. In: Environmental Impact Statement for the Mackenzie Gas Project. http://www.mackenziegasproject.com/theProject/regulatoryProcess/applicationSubmission/Applicationscope/EIS.html.

Jefferies, R.L. 1977. Vegetation of salt marshes at some coastal sites in Arctic North America. Journal of Ecology 65:661–672.

Jenner, K.A., and Hill, P.R. 1991. Sediment transport at the Mackenzie Delta-Beaufort Sea interface. In: Marsh, P., and Ommaney, C.S.L., eds. Mackenzie Delta: Environmental interactions and implications of development. Proceedings of the Workshop on the Mackenzie Delta, 17–18 October 1989. Saskatoon: Environment Canada. 39–51.

Johnstone, J.F., and Kokelj, S.V. 2008. Environmental conditions and vegetation recovery at abandoned drilling mud sumps in the Mackenzie Delta region, NWT, Canada. Arctic 61(2):199–211.

Joint Review Panel. 2009. Foundation for a sustainable northern future: Report of the Joint Review Panel for the Mackenzie Gas Project, 2 vols.

Jolly, D., Fox, S., and Thorpe, N. 2003. Inuit and Inuvialuit knowledge of climate change in the Northwest Territories and Nunavut. In: Oakes, J., and Riewe, R., eds. Native voices in research. Winnipeg, Manitoba: Native Studies Press, University of Manitoba. 280–290.

Kemper, J.T., and MacDonald, S.E. 2009. Effects of contemporary winter seismic exploration on Low Arctic plant communities and permafrost. Arctic, Antarctic, and Alpine Research 41(2):228–237.

Kendrick, A., Lyver, P.O'B., and Łutsël K'é Dene First Nation. 2005. Denésǫłiné (Chipewyan) knowledge of barren-ground caribou (*Rangifer tarandus groenlandicus*) movements. Arctic 58(2):175–191.

Kokelj, S.V., and Burn, C.R. 2005. Geochemistry of the active layer and near-surface permafrost, Mackenzie Delta region, Northwest Territories, Canada. Canadian Journal of Earth Sciences 42(1):37–48.

Lesack, L.F.W., and Marsh, P. 2007. Lengthening plus shortening of river-to-lake connection times in the Mackenzie River Delta respectively via two global change mechanisms along the Arctic coast. Geophysical Research Letters 34, L23404, doi:10.1029/2007GL031656.

MacKay, J.R. 1963. The Mackenzie Delta area, N.W.T. Geographical Branch Memoir 8. Ottawa: Department of Mines and Technical Surveys.

Manson, G.K., and Solomon, S.M. 2007. Past and future forcing of Beaufort Sea coastal change. Atmosphere-Ocean 45:107–122, doi:10.3137/ao.450204.

Marsh, P., and Schmidt, T. 1993. Influence of a Beaufort Sea storm surge on channel levels in the Mackenzie Delta. Arctic 46(1):35–41.

McKeague, J.A., ed. 1978. Manual on soil sampling and methods and analysis, 2nd ed. Ottawa: Soil Research Institute, Agriculture Canada.

Moller, H., Berkes, F., Lyver, P.O., and Kislalioglu, M. 2004. Combining science and traditional ecological knowledge: Monitoring populations for co-management. Ecology and Society 9(3): 2. http://www.ecologyandsociety.org/vol9/iss3/art2/.

Morse, P.D., Burn, C.R., and Kokelj, S.V. 2009. Near-surface ground-ice distribution, Kendall Island Bird Sanctuary, western Arctic coast, Canada. Permafrost and Periglacial Processes 20(2):155–171, doi:10.1002/ppp.650.

Nagy, J. 2002. Mammals. In: Black, S., and Fehr, A., eds. Natural history of the Western Arctic. Inuvik: Western Arctic Handbook Project. 55–68.

Nichols, T., Berkes, F., Jolly, D., Snow, N.B., and the Community of Sachs Harbour. 2004. Climate change and sea ice: Local observations from the Canadian Western Arctic. Arctic 57(1):68–79.

O'Neill, R.V., Hunsaker, C.T., Jones, K.B., Riitters, K.H., Wickham, J.D., Schwartz, P.M., Goodman, I.A., Jackson, B.L., and Baillargeon, W.S. 1997. Monitoring environmental quality at the landscape scale. Bioscience 47(8):513–519.

Parlee, B., Manseau, M., and Łutsël K'é Dene First Nation. 2005. Using traditional knowledge to adapt to ecological change: Denésǫłiné monitoring of caribou movements. Arctic 58(1):26–37.

PCI Geomatics. 2001. PCI Geomatics, using PCI software. Richmond Hill, Ontario: PCI Geomatics.

Pearce, C.M. 1986. The distribution and ecology of the shoreline vegetation on the Mackenzie Delta, N.W.T. PhD thesis, Department of Geography, University of Calgary. 400 p.

Pisaric, M.F.J., Thienpont, J.R., Kokelj, S.V., Nesbitt, H., Lantz, T.C., Solomon, S., and Smol, J.P. 2011. Impacts of a recent storm surge on an Arctic delta ecosystem examined in the context of the last millennium. Proceedings of the National Academy of Sciences of the United States of America 108(22):8960–8965, doi:10.1073/pnas.1018527108.

Porsild, A.E., and Cody, W.J. 1980. Vascular plants of continental Northwest Territories, Canada. Ottawa: National Museums of Canada.

Richter, R., and Schläpfer, D. 2011. Atmospheric/topographic correction for satellite imagery. ATCOR-2/3 user guide, version 8.0.2. Wessling, Germany: DLR – German Aerospace Centre. 202 p. http://www.rese.ch/pdf/atcor3_manual.pdf.

Small, D. 2009. Beaufort coast wind climatology and case study of a high wind event. MSc thesis, McGill University, Montreal, Quebec. 87 p.

Smith, M.W. 1975. Microclimate influences on ground temperatures and permafrost distribution, Mackenzie Delta, Northwest Territories. Canadian Journal of Earth Sciences 12(8):1421–1438.

Smol, J.P. 2010. The power of the past: Using sediments to track the effects of multiple stressors on lake ecosystems. Freshwater Biology 55(Suppl. 1):43–59.

Smol, J.P., and Douglas, M.S.V. 2007. From controversy to consensus: Making the case for recent climate change in the Arctic using lake sediments. Frontiers in Ecology and the Environment 5(9):466–474.

Solomon, S.M. 2005. Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, Northwest Territories, Canada. Geo-Marine Letters 25(2-3):127–137.

Solomon, S.M., Whalen, D., Saper, R., and Mulvie, J. 2005. Measuring the extent of storm surge flooding on the Mackenzie River delta, Northwest Territories, Canada using synthetic aperture radar. Proceedings of the 8th International Conference on Remote Sensing for Marine and Coastal Environments, 17–19 May 2005, Halifax, Nova Scotia. CD-ROM.

Srivastava, D.S., and Jefferies, R.L. 1995. The effect of salinity on the leaf and shoot demography of two Arctic forage species. Journal of Ecology 83:421–430.

Stephenson, S.A. 2002. Freshwater fishes. In: Black, S., and Fehr, A., eds. Natural history of the Western Arctic. Inuvik: Western Arctic Handbook Project. 70–76.

Thompson, A., and Millar, N. 2007. Traditional knowledge of fish migration and spawning patterns in Tsiigehnjik (Arctic Red River) and Nagwichoonjik (Mackenzie River), Northwest Territories. Gwich'in Renewable Resource Board Report 07-01.

Turner, M.G. 1989. Landscape ecology: The effect of pattern on process. Annual Review of Ecology and Systematics 20:171–197.

Usher, P.J. 2000. Traditional ecological knowledge in environmental assessment and management. Arctic 53(2):183–193.

———. 2002. Inuvialuit use of the Beaufort Sea and its resources, 1960–2000. Arctic 55(Suppl. 1):18–28.

Walker, D.A., and Walker, M.D. 1991. History and pattern of disturbance in Alaskan Arctic terrestrial ecosystems: A hierarchical approach to analyzing landscape change. Journal of Applied Ecology 28:244–276.

Walker, D.A., Cate, D., Brown, J., and Racine, C. 1987. Disturbance and recovery of Arctic Alaskan tundra terrain: A review of recent investigations. CRREL Report 87-11. Hanover, New Hampshire: U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Water Survey of Canada. 2010. Hydrometric data (HYDAT). http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm.2