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ARTICLE

Contrasting changes in surface waters and barrens over the past 60 years for a subarctic forest–tundra site in northern Manitoba based on remote sensing imagery

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Abstract: Intensified warming in the Arctic and Subarctic is resulting in a wide range of changes in the extent, productivity, and composition of aquatic and terrestrial ecosystems. Analysis of remote sensing imagery has documented regional changes in the number and area of ponds and lakes as well as expanding cover of shrubs and small trees in uplands. To better understand long-term changes across the edaphic gradient, we compared the number and area of water bodies and dry barrens (>100 m²) between 1956 (aerial photographs) and 2008–2011 (high-resolution satellite images) for eight ~25 km² sites near Nejanilini Lake, Manitoba (59.559°N, 97.715°W). In the modern landscape, the number of water bodies and barrens were similar (1162 versus 1297, respectively), but water bodies were larger (mean 3.1×10^4 versus 681 m², respectively) and represented 17% of surface area compared with 0.4% for barrens. Over the past 60 years, total surface area of water did not change significantly (16.7%–17.1%) despite a ~30% decrease in numbers of small (<1000 m²) water bodies. However, the number and area of barrens decreased (55% and 67%, respectively) across all size classes. These changes are consistent with Arctic greening in response to increasing temperature and precipitation. Loss of small water bodies suggests that wet tundra areas may be drying, which, if true, may have important implications for carbon balance. Our observations may be the result of changes in winter conditions in combination with low permafrost ice content in the region, in part explaining regional variations in responses to climate change.

Résumé : L'intensification du réchauffement dans l'Arctique et les régions subarctiques cause de nombreux changements dans l'étendue, la productivité et la composition des écosystèmes aquatiques et terrestres. Une analyse de l'imagerie par télédétection a révélé des changements régionaux dans le nombre et l'étendue des étangs et des lacs ainsi que dans l'agrandissement de la couverture des arbustes et des petits arbres dans les terres hautes. Afin de mieux comprendre les changements à long terme à travers le gradient édaphique, nous avons comparé le nombre et l'étendue des plans d'eau et de la toundra sèche (>100 m²) entre 1956 (photographies aériennes) et 2008–2011 (images satellite à haute résolution) pour huit sites d'environ 25 km² à proximité du lac Nejanilini, Manitoba (59,559°N, 97,715°O). Dans le paysage moderne, le nombre de plans d'eau et de parcelles de toundra était semblable (respectivement 1162 et 1297) mais la superficie des plans d'eau était supérieure à celle des parcelles de toundra (moyennes respectives de $3{,}1 \times 10^4$ et de 681 m²) et représentait 17 % de la surface par rapport à 0,4 % pour la toundra. Au cours des 60 dernières années, la surface totale des plans d'eau n'a pas changée de manière significative (16,7 à 17,1 %) malgré une diminution d'environ 30 % du nombre de petits (<1000 m²) plans d'eau. Toutefois, le nombre et la superficie des parcelles de toundra ont diminué (respectivement de 55 et 67 %) dans toutes les classes de tailles. Ces changements concordent avec le verdissement de l'Arctique en réaction à l'accroissement des températures et des précipitations. La perte des petits plans d'eau pourrait découler de l'asséchement de la toundra mouillée; si c'était le cas, cela pourrait avoir des implications importantes pour le bilan de carbone. Ce que nous observons peut être le résultat de changements dans les conditions hivernales combinés au peu de contenu en glace du pergélisol dans la région, ce qui explique en partie les variations régionales dans les réponses au changement climatique. [Traduit par la Rédaction]

Introduction

Over the past 50 years, the Arctic has warmed ~0.4 °C/decade, four times the global average (IASC 2005). In response, broad areas of the tundra have greened by 10%–20% (Tucker et al. 2001; Stow et al. 2004; Fraser et al. 2011) as shrubs, and, in some areas, graminoids increased in biomass and cover (Raynolds et al. 2006; Epstein et al. 2012; Walker et al. 2012). At the same time, the number and area of lakes and ponds have decreased by 5%–50% over broad regions of Siberia and Alaska (Riordan et al. 2006) due to terrestrial plant in-fill (terrestrialization), evaporation, or drainage (Roach et al. 2011).

Shrinking lakes and ponds and greening of tundra have the potential to shift the carbon balance of high-latitude ecosystems towards stronger carbon sinks (Payette et al. 2004; Stow et al. 2004; Roach et al. 2011). Soil respiration, nitrogen mineralization, plant productivity, and biomass all vary along soil moisture gradients from wet to dry tundra (Dagg and Lafleur 2011). For example, CO_2 uptake in response to warming may be greatest in wet tundra due to the combination of increased plant productivity

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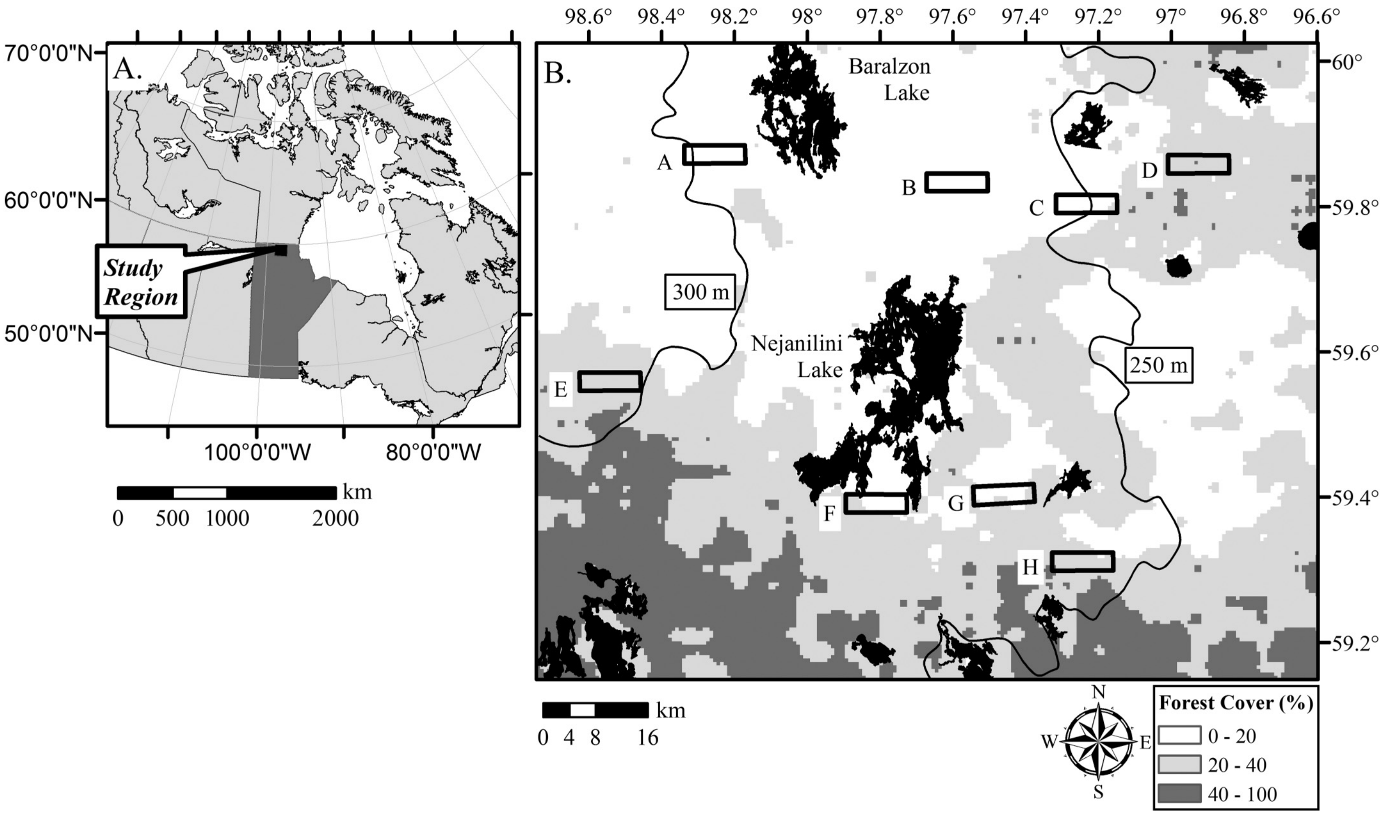
Fig. 1. Location of (A) study region and (B) study sites in the Nejanilini Lake region of northern Manitoba, Canada (Table 1). Rectangles in panel B indicate location of the eight ~25 km² study areas (Table 1). Forest cover based on classification of Landsat image (pan-sharpened) and analyzed iteratively using ENVI EX 4.8 (Exelis Visual Information Solutions 2011) and then summary of percent of forest types within 2.5 km × 2.5 km grid squares overlaid on map. Two contour lines are given to provide sense of east–west elevation change in study region.



and limited soil respiration (Oberbauer et al. 2007; Dagg and Lafleur 2011). Tundra drying may thus result in a greater efflux of carbon.

Regional variation in the magnitude and rate of landscape change is likely important in determining whether the Artic as whole is a source or sink, but this variation is poorly understood (Carroll et al. 2011; Walker et al. 2012). For example, lakes and ponds changed little on the Alaska Coastal Plain (Hinkel et al. 2007) or in the western Hudson Bay Lowlands (Sannel and Kuhry 2011), while other areas have shown little greening, and forests near the tundra border in Alaska have browned (Verbyla 2008). Regional variation may reflect differences in the extent, direction, and timing of temperature and precipitation changes (Callaghan et al. 2011), soil parent materials (Raynolds et al. 2006), or permafrost extent and ice content (Smith et al. 2007).

To improve understanding of the regional heterogeneity of high-latitude landscape change, we use remote sensing imagery to quantify changes in a low-Arctic landscape located near Nejanilini Lake in northern Manitoba (Fig. 1). We compare the number and area of water bodies (ponds and lakes) and dry, upland barrens in 1956 with the modern landscape (2008–2011) for eight ~25 km² study sites. Our purposes were to (*i*) contrast trends in the number and area of lakes and ponds relative to other Arctic studies to better understand the importance of regional variation in changes in surface waters, (*ii*) use remote-sensing-based comparison of barrens to document long-term change in Arctic landscapes uplands, and (*iii*) consider the potential implications of landscape changes for carbon balance and hydrology of low-Arctic and subarctic regions.

Study region

Nejanilini Lake is located at tree line just north of the western Hudson Bay lowlands, ~140 km west of Hudson Bay (59.559°N, 97.715°W), and just south of the border between Manitoba and Nunavut (Fig. 1). It is part of the Taiga Shield Ecozone (both Seal and Ennadai Lake plains) (National Atlas Information Service 1993). Approximately 21% of the region is covered by lakes and ponds, with the terrestrial portions of the landscape dominated by lowland (peat, muskeg, and sedge fens; 46%) and upland tundra (mesic or dry tundra; 25%) (Umbanhowar, Jr. et al.,[1] and see following text). Barrens are characterized by >80% bare ground and are found on eskers, as well as other hilltops and steep slopes. Bare areas not defined as "barrens" include rock outcrops, disturbed lake margins, and beaches. Prostrate, evergreen shrubs, for example, *Empetrum nigrum* L. and *Vaccinium uliginosum* L., form dense mats in and around barrens, and *Betula nana* L. is common at the margins of many barrens as are surface crusts of dark lichen (species unknown).

The region is located in continuous, low-ice-content permafrost (Heginbottom et al. 1995; Brown et al. 1998 (revised 2001)), with active layer depths of 20–40 cm in lowlands and >1 m in uplands based on ground-penetrating radar and soil pits (C. Geiss, P. Camill, M.B. Edlund, and C.E. Umbanhowar, Jr., unpublished) and peat cores (P. Camill, C. Geiss, M.B. Edlund, and C.E. Umbanhowar, Jr., unpublished). Soils are thin and largely undeveloped crysols, and the surficial geology is dominated by a bouldery sandy diamicton of Precambrian crystalline rocks (Matile and Keller 2006). Soils of barren areas range from coarse sands to unsorted tills. Unvegetated

[1]C.E. Umbanhowar, Jr., P. Camill, M.B. Edlund, C. Geiss, P. Henneghan, and K. Passow. Manuscript in review.

Table 1. Summary characteristics for eight ~25 km² study areas (see Fig. 1 for locations) for modern (2008–2011) landscape.

Site (acquisition date)	Mean elevation (m)	Area (km²)	Upland[a] (%)	Lowland[a] (%)	Water (%)	Water bodies (no.)	Vegetated water bodies[b] (no.)	Dry water bodies[b] (no.)	Barrens (%)	Barrens (no.)	Vegetated barrens (no.)
A (07 08 08)	292	2588	39	30	26	115	21	22	0.04	23	143
B (17 09 09)	280	2510	39	39	19	96	10	13	0.04	20	22
C (25 08 10)	254	2538	37	44	12	308	50	65	0.80	385	330
D (06 08 10)	227	2588	31	56	14	89	7	30	0.58	314	292
E (07 08 10)	315	2588	26	38	15	97	29	10	0.28	127	33
F (18 06 11)	279	2588	38	34	17	164	27	17	0.62	136	112
G (07 08 08)	294	2512	39	37	24	160	14	17	0.23	111	264
H (04 09 09)	276	2588	36	52	9	133	52	65	0.84	182	401
Mean	277.1	—	35.6	41.1	17.1	145.3	26	30	0.43	162.1	199.8
SD	26.7	—	4.7	8.9	5.6	72.8	17.1	22.5	0.32	129.6	141.6

Note: Acquisition date in parentheses shown as day, month, year. SD, standard deviation.

[a]Upland and Lowland classification (Umbanhowar, Jr. et al.[1]) based on Landsat image (pan-sharpened) and analyzed iteratively using ENVI EX 4.8 (Exelis Visual Information Solutions 2011). Upland includes dry heath tundra, mesic tundra, and shrub tundra, and Lowland includes wet tundra (open peatlands and sedge fen) as well as lowland *Picea*–*Larix* forest. Percentages may not add to 100% because burn recovery, upland forest, and exposed bedrock were not included in Upland or Lowland categories.

[b]Areas that contained water in 1956 imagery but in the modern imagery (2008–2011) were dominated by either vegetation or exposed rocks or sediment. Vegetated areas appeared green or brown (mosses) and were rough in appearance and frequently indistinguishable from the surrounding vegetation. Dry water bodies were typically highly reflective and rough or smooth, depending on composition of exposed bottom (Fig. 2E).

bedrock and frost-heaved and frost-shattered bedrock blocks are exposed at the surface (Anderson et al. 2005).

Mean elevation is 264 m, rising from east to west from ~170 to ~300 m (Fig. 1). Average temperatures in the region range from –25 to –30 °C (winter) and from 10 to 15 °C (summer), and monthly precipitation ranges from 15 to 30 mm (winter) and from 30 to 60 mm (summer). The nearest weather station recording climatological data are Churchill (150 km southeast), near Hudson Bay, where Sannel and Kuhry (2011) noted a 0.18 °C/decade increase in mean annual air temperature and a 19% increase in winter precipitation (November–April) from 1954 to 2005. Climate change in northern Manitoba is expected to bring a 3–4 °C increase in temperature and 10%–20% increase in winter and summer precipitation by 2050 compared with the 1971–1990 average (Plummer et al. 2006).

Methods

We identified eight 25 km² sample sites (Fig. 1), with four each located in the northern and southern parts of the study region (Table 1). The southern sites were located near the tundra–forest border. Study sites were located to (*i*) capture the south–north decrease in forest cover (Fig. 1) and (*ii*) maximize overlap between available historic and modern imagery.

Historic panchromatic vertical aerial photographs were obtained directly from the Canadian National Air Photo Library, Ottawa, or from the GeoManitoba Airphoto Library, Winnipeg. The photography was flown 4–7 July 1956 at a scale of 1:60 000 ft (1 ft = 0.3048 m) (154 mm focal length lens). The photos were scanned at 600 dpi prior to analysis, resulting in a spatial resolution of ~1.8–2.4 m/pixel, depending upon elevation of the local ground surface. Comparison of the scanned images with known features on the ground indicated a minimum cutoff of 100 m² for objects to be included in our analysis. Modern water bodies and barren areas are based on 2008–2011 high-resolution (Ikonos-2, WorldView-2, Geo-eye-1, or Quickbird), pan-sharpened red–green–blue (RGB) imagery (0.5–1.0 m resolution). See Table 1 for acquisition dates of modern imagery.

We rectified and georeferenced the historic imagery to the modern imagery using ArcMap 10.0 (Environmental Systems Research Inc. 2011). A minimum of 30 control points (outcroppings, islands, and other distinctive features) were used per study site. A second-order polynomial transformation was used for each site, and root mean square error (RMSE) for the eight sites ranged from 2.4 to 3.9 m. The large RMSE, relative to pixel resolution, in part reflects the large sizes of the different sites as well as the challenge of locating control points on the older photos.

Delineation of water and barrens was done manually (Sannel and Brown 2010) in two stages. A first-stage delineation of each area was done by different individuals, and the second stage was done by the lead author to eliminate bias resulting from different interpreters and to ensure that the overlap of barrens or water bodies between years (1956 to modern) was not missed by spatial distortions in the georeferenced imagery suggested by the high RMSE relative to pixel resolution. ArcMap was used to calculate area of each delineated polygon. No formal ground truthing was conducted for the eight sites. However, low-level aerial photography and on-the-ground surveys of barrens and water bodies were available (from 2008 to 2009, Fig. 2) for nearby areas, and were compared informally with modern imagery to aid in developing the delineations of water bodies and barrens.

Mean elevation for each of the study sites, and elevation of all delineated areas, was estimated by overlay of the 1:50 000 Canadian Digital Elevation Data (CDED). The CDED was downloaded from GeoBase (http://www.geobase.ca/). We calculated the relative elevation of water bodies and barrens as the difference between their elevation (centroid of polygon) and mean elevation of the surrounding area (1 km radius). Water-body connection to a drainage network was identified by overlay of National Hydro Network streams (downloaded from GeoBase). Status (vegetated or bare) of water bodies present in 1956 but absent in the modern imagery was determined manually and designation was based on majority cover.

R (R Development Core Team 2006) was used for all statistical summaries and analyses. Paired t tests (two-tailed; number of sites, $n = 8$) were used to compare number and total area of barrens and water bodies for 1956 versus modern imagery. We further investigated these changes by comparing percent change in number and area of water bodies and barrens subdivided by size classes (Fig. 4). Single sample t tests were used to compare percent change in each size class against zero. The raw t statistic is presented for each comparison as are p values adjusted using a Sidak single-step correction to control for type I error ($\alpha = 0.01$) for each set of comparisons. Linear models were used to test for differences in relative elevation among size classes for barrens and water bodies, respectively. For each test, homogeneity of variance was confirmed using the Breusch pagan test. If the linear model indicated a statistically significant difference, then pairwise differences among sizes classes were tested using Tukey's HSD (honestly significant difference; $\alpha = 0.01$). Differences in relative elevation were also contrasted, separately, for barrens and water bodies that were present (persist) in both 1956 and modern imagery, absent modern (disappear), or present modern but absent 1956

Fig. 2. Remote sensing images from (A) 1956 and (B) 2008–2011 (modern) with delineated water bodies and barrens outlined in white and black, respectively; low-altitude, oblique photos showing examples (C) and (D) of barrens (black arrows) and water bodies; and on the ground photos of (E) partially exposed bottom of a pond and (F) surface of a barren. Image for panel A was taken 4–7 July 1956 at a scale of 1:60 000 ft (1 ft = 0.3048 m), scanned at 600 dpi, and has a spatial resolution of ~1.8–2.4 m. Image for panel B is from June 2011 and is Worldview-2 imagery with a spatial resolution of 0.5 m. Images in panels C–F were taken in July of 2008 or 2009, and spatial scale indicated for each image is only approximate for the image foreground near each scale bar.

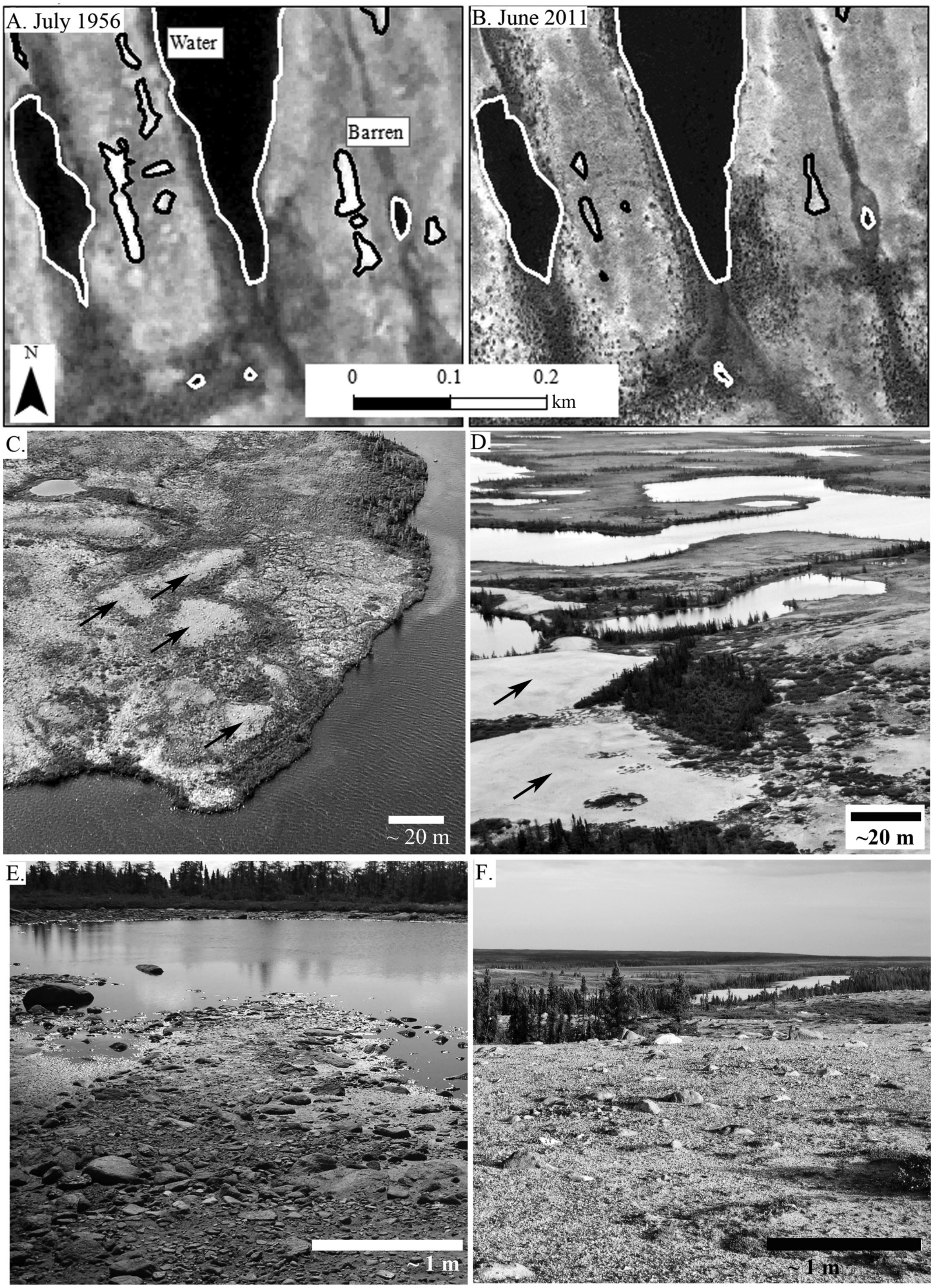
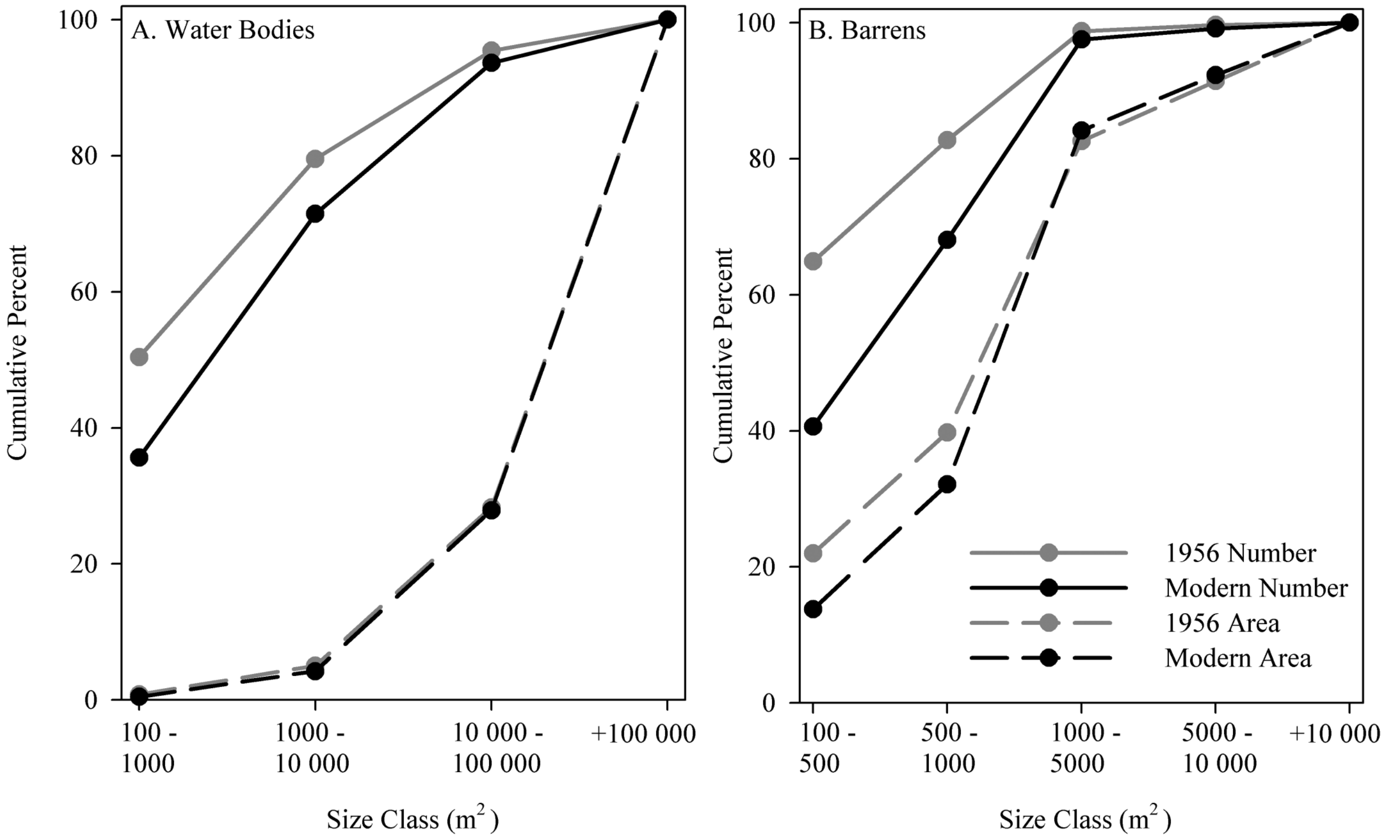


Fig. 3. Cumulative frequency distributions for total area and number of (A) water bodies and (B) barrens as a function of size class.



(appear); Kruskal–Wallis tests were used for these comparisons because of problems with normality and (or) non-homogeneity of variance that could not be transformed. If size classes were significantly different, then pairwise Wilcoxon comparisons were performed, adjusting p values with Sidak single-step correction (α = 0.01). Area (log-transformed) of barrens and water bodies that appeared or disappeared were compared using independent two-sample t tests, and equal variances were not assumed, so Welch's approximation to degrees of freedom was used. Possible effects of image acquisition date on presence or absence of water was assessed by correlating (separately) month or year that images were captured with percent of water bodies that were dry across the eight sites.

Results

Modern landscape

For the eight study sites, water bodies (>100 m^2) covered an average 17.1% (range 9%–26%) of the modern landscape (Table 1). Average area of individual water bodies was 23 294 m^2 (Table 2). Small water bodies (<0.1 ha) represented nearly 50% of total numbers but <1% of total area (Fig. 3). They were almost always surrounded by lowland vegetation (based on ground truthing, and formal classification of Landsat imagery (Umbanhowar, Jr. et al.[1])), and 60% were connected to a drainage network. Water bodies were on average 0.14 m below the local elevation (Table 3).

Barrens (>100 m^2) occupied only 0.43% (range 0.04%–0.84%) of the modern landscape (Table 1). Average area of barrens was 681 m^2 (Table 2). Nearly 70% of barrens were <0.1 ha, but in contrast to water bodies, small barrens represented a larger percentage (~30%) of total barrens area (Fig. 3). Barrens were located in uplands, were most commonly abutted by dry heath tundra (based on ground truthing and Umbanhowar, Jr. et al.[1]), and were on average 2.4 m above local elevation (Table 3).

Changes in water bodies

From 1956 to modern, the average number of water bodies decreased significantly by 21% (t = 3.98; degrees of freedom, df = 7; p = 0.005), but average total area showed only a slight, insignificant (t = –1.42, df = 7, p = 0.19) increase of 2% (Table 2). Change was greatest for small (100–1000 m^2) ponds which decreased in number and area by 20%–40% (Fig. 4). More water bodies coalesced (80 to 40) from 1956 to modern than split (27 to 59) over the same time period.

Approximately three times as many water bodies disappeared (456) than appeared (147) from 1956 to modern (Table 3). Water bodies that appeared were about half the size of those that disappeared (318 versus 534, independent sample t test, df = 335.97, p = 0.002) (Table 3). Small water bodies were located ~1 m higher in the landscape than larger water bodies (linear model, F = 16.3, df = 3, 1467, p < 0.001) in 1956 (Fig. 5). There was not, however, a significant difference in relative elevation among water bodies that disappeared, persisted, or appeared (Kruskal–Wallis, K = 4.77, df = 2, p = 0.09), reflecting, in part, that over ~70% of water bodies in both sets of imagery were in the two smallest size classes (Fig. 3). A majority (67%) of water bodies that persisted were connected to a drainage network while conversely a similar percentage (70%) of water bodies that disappeared were not connected (Table 3).

To distinguish seasonal from permanent loss of water, we recorded the presence or absence of bare sediment (and rocks) or vegetation in the modern imagery for locations where water bodies had disappeared. For the eight study sites, an average 44.8% (range 19%–74%) of former water bodies had become vegetated since 1956. Exposed sediment or rocks were visible for the remaining water bodies that had disappeared. If only vegetated water bodies are considered to have disappeared, the percentage drop in number of small water bodies (100–1000 m^2) is less (16%) but is still statistically significant

Fig. 4. Percent change in area and number by size class of water bodies (A and C) and barrens (B and D) from 1956 to 2008–2011 (modern) based on eight ~25 km sites (Fig. 1). Solid line in each box is median, and dashed line is mean. Upper bound of box is 75th percentile while lower bound is 25th percentile (in panel B upper and lower bounds are so close to zero for number of water bodies in +100 000 class that they are not visible). Results of single sample *t* tests statistical tests given above or below each box as an unadjusted *t* score and an adjusted *p* value (p_a). The *p* values were adjusted using the Sidak single-step correction to control for type I error (α = 0.01) for each set of comparisons. A significant result indicates mean was <0 or >0.

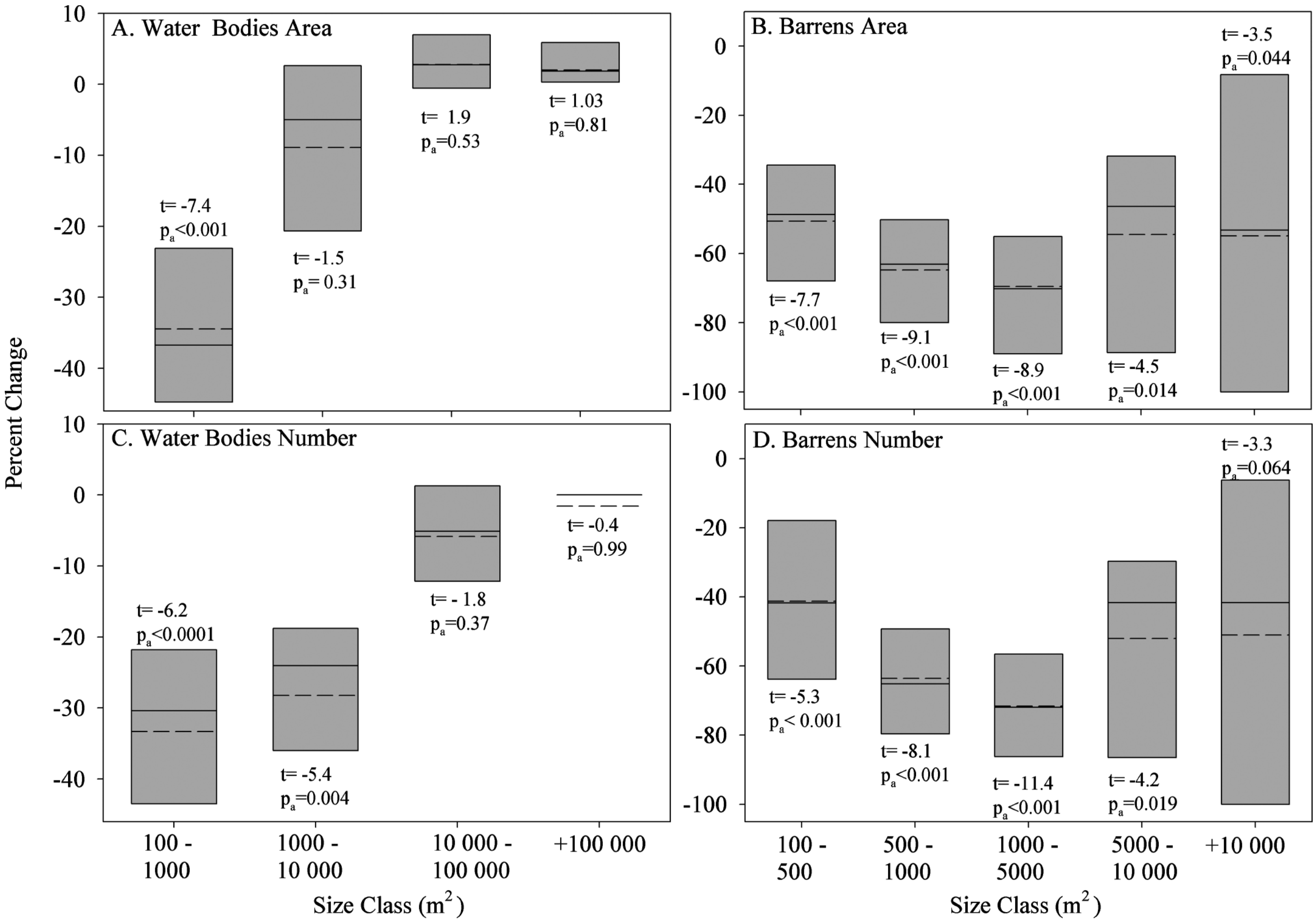


Table 2. Mean (±1 SD) number and total area (m²) per site, and mean and median area of (A) water bodies and (B) barrens for 1956 and 2008–2011 (modern) imagery. Percent change from 1956 to modern is given in italics below each column. The total number (summed across all eight sites) of water bodies and barrens that split or coalesce from 1956 to modern is given in last two columns of table.

	Number	Total area (m²)	Mean area (m²)	Median area (m²)[a]	Split (no.)	Coalesce (no.)
(A) Water bodies						
1956	184.1 (97.1)	4.3×10^6 (1.3×10^6)	23 294	742 (251, 5098)	27	80
2008–2011	145.3 (72.8)	4.4×10^6 (1.3×10^6)	30 131	1055 (299, 9778)	—	—
Percent change	–21	2	29	*42*	—	—
(B) Barrens						
1956	361.9 (247.2)	3.1×10^5 (1.6×10^5)	844	355 (196, 812)	190	84
2008–2011	162.2 (129.4)	1.1×10^5 (8.3×10^4)	681	245 (149, 532)	—	—
Percent change	–55	–67	–19	*–31*	—	—

[a]Values in parentheses show 25th and 75th percentiles.

(t = –5.23, df = 7, p = 0.001). Separate correlations of percent of water bodies with exposed bottoms with month (r = 0.30, df = 6, p = 0.47) and year (r = 0.06, df = 6, p = 0.88) of image (modern) acquisition (Table 1) were not significant, but our data do not allow us to determine when (year or month) drying occurred.

Changes in barrens

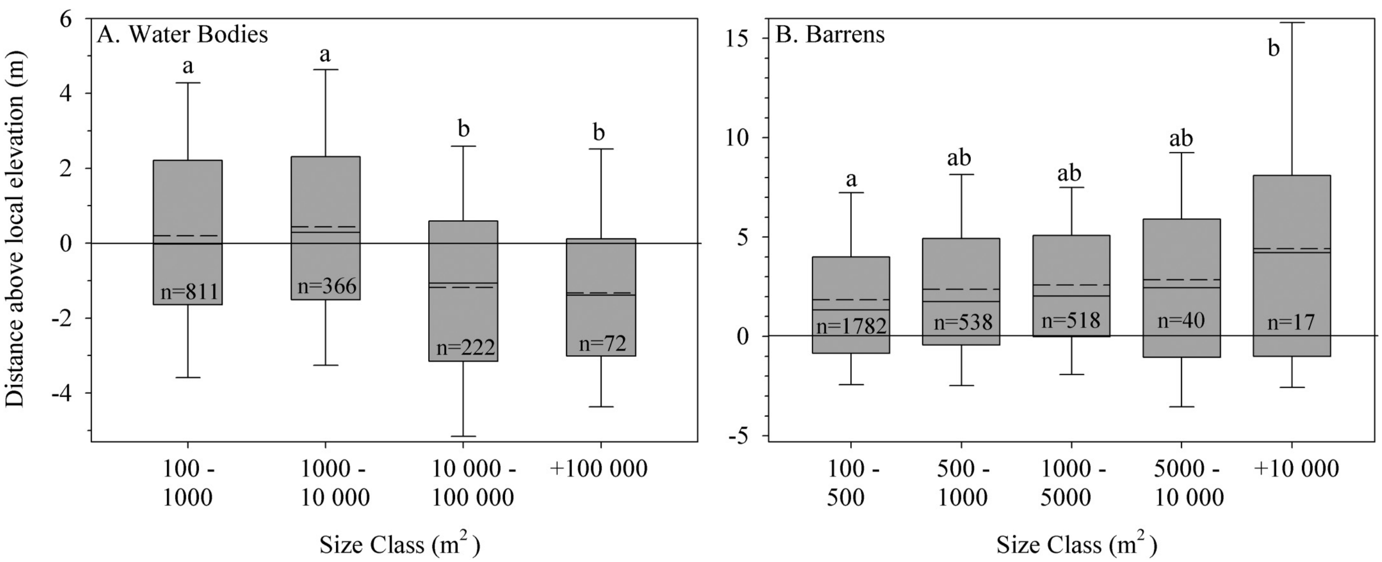
From 1956 to modern, the total number of barrens decreased by an average of 55% (t = 3.99, df = 7, p = 0.005) across the eight study sites (Table 2). There was a significant 67% decrease in total area (t = 5.15, df = 7, p = 0.001) of barrens across the eight sites.

Table 3. Characteristics of water and barrens that disappear, persist, or appear between 1956 and 2008–2011 (modern). Areas for water and barrens that disappear or persist given based on delineations of 1956 imagery. Differences in relative elevation were tested for the three types of water bodies and barrens using Kruskal–Wallis rank sum tests with results given below.

	Mean area (m²)	Median area (m²)[a]	Relative (±1 SD) elevation (m)[b,c]	Connected[d]	n[e]
(A) Water					
Disappear	534	227 (145, 445)	0.24 (3.70)	133	456
Persist	33955	1830 (509, 15 285)	–0.14 (3.22)	679	1015
Appear	318	209 (137 330)	–0.10 (2.86)	14	147
			(K = 4.77, df = 2, p = 0.09)		
(B) Barrens					
Disappear	471	258 (163, 4480)	1.63 (8.37)[a]	—	1348
Persist	1491	719 (370, 1453)	2.61 (4.39)[b]	—	2115
Appear	208	151 (122, 215)	1.42 (4.18)[a]	—	233
			(K = 28.90, df = 3, p < 0.001)		

[a]Values in parentheses show 25th and 75th percentiles.
[b]Relative elevation is the distance of individual water bodies or barrens above or below average elevation for surrounding area in a 1 km radius.
[c]Relative elevations with different symbols are statistically different at the p < 0.01 significance level based on post-hoc pairwise Wilcoxon comparisons. See text for details.
[d]Connected indicates that a water body intersected a drainage network stream as identified in the Canadian National Hydro Network data set (downloaded from GeoBase).
[e]n, number of sites.

Fig. 5. Comparison of relative elevation (m) for (A) water bodies and (B) barrens in 1956 by size. Solid line in each box is median, and dashed line is mean. Upper bound of box is 75th percentile while lower bound is 25th percentile; whiskers represent 90th and 10th percentiles, respectively. Size classes (water bodies or barrens compared separately) with same letter ("a" or "b") were not significantly different based on Tukey HSD (honestly significant difference; α < 0.01). Relative elevation is the difference (m) between the elevation of a water body or barren and mean elevation for the surrounding area based on a 1 km radius.



Significant decreases in the number and area of barrens were observed for all five size classes but were greatest for barrens ranging in size from 500 to 5000 m² (Fig. 4). More barrens split (190 to 497) into sections from 1956 to modern than coalesced (84 to 36) over the same time period.

Approximately eight times as many barrens disappeared than appeared (1831 versus 233) from 1956 to modern. Barrens that disappeared were twice as large as those that appeared (t = 12.01, df = 412.70, p < 0.001). Larger barrens were located ~2 m higher in the landscape than small barrens in 1956 (linear model, F = 5.7, df = 4, 2890, p < 0.001) (Fig. 5), and barrens that persisted from 1956 to modern were found ~0.5–1 m higher in the landscape than those that disappeared or appeared (Kruskal–Wallis, K = 28.90, df = 3, p < 0.001) (Table 3).

Discussion

Climate warming in the Arctic has resulted in major changes in terrestrial and aquatic ecosystems, with broad implications for the planet, ranging from the balance of greenhouse gases (Stieglitz et al. 2000; Sitch et al. 2007) to discharges of freshwater to the Arctic Ocean (MacLean et al. 1999; McClelland et al. 2006). The climate of low-Arctic northern Manitoba has likely gotten warmer and wetter over the past 60 years (Plummer et al. 2006; Callaghan et al. 2011; Sannel and Kuhry 2011). Our data indicate that these climatic changes may not always translate into clear shifts on the landscape. A significant decline in number (55%) and area (67%) of barrens is consistent with the notion of warmer–wetter conditions (Table 2). However, we also observed a 20%–30%

drop in number of small water bodies despite little or no change overall in area of water occupied by water. Local elevation and permafrost ice content in particular may mediate landscape responses to climate change.

Water bodies

Sannel and Kuhry (2011) reported a 5.4% increase in water area for a Hudson Bay lowland site ~290 km southeast of our sites, but they did not observe any significant change in number of water bodies. This differs from our results of a drop in number of small water bodies but no overall change in area, which may simply reflect the fact that we did not limit ourselves to peat plateaus and, instead, identified samples from a much larger, more heterogeneous area. Our results also contrast with (*i*) a 5%–15% increase in number and area of lakes reported for a continuous permafrost areas in Siberia (Smith et al. 2005), (*ii*) a 10.7% increase in number but 14.9% decrease in area reported for Alaska's Seward Peninsula (Jones et al. 2011), and (*iii*) a 5%–54% decline in number and coincident 4%–34% drop in total surface area in subarctic Alaska (Riordan et al. 2006). Coalescence of water bodies could cause a decrease in number but not area, but we observed only 80 water bodies that coalesced, versus 27 that split, representing <5% of the 1471 total recorded in 1956 for the eight sites (Tables 2, 3).

Variation among studies, especially for numbers of water bodies, may simply be due to differences in image resolution and choice of minimum size of water body to be included in a study. Our minimum cutoff was 0.01 ha compared with 40 ha (Smith et al. 2005), 0.1 ha (Jones et al. 2011), 0.0027 ha (Sannel and Kuhry 2011). Differences in minimum cutoff size are unlikely to impact estimates of change in total area, however, since large lakes likely dominated total area of water in all study areas.

Differences among studies may also result from contrasting topography, soils, and permafrost which affect surface, subsurface, and groundwater movements of water (Woo 1986; Woo and Carey 1998; Essery and Pomeroy 2004; Woo et al. 2008; Wright et al. 2008; Wright et al. 2009; Wolfe et al. 2011; Bosson et al. 2012). In some permafrost-dominated landscapes, as much as 40%–70% of melt water may be delivered to lakes and ponds, and surface flows are especially critical to recharge of shallow lakes and ponds (Woo et al. 1981; Spence 2000; Bowling et al. 2003; Young et al. 2013). Increasing active layer depths under the water body or in the surrounding area may reduce these surface flows as will soils that are drier in autumn (Woo et al. 2008; Avis et al. 2011; Quinton et al. 2011).

Compared with other regions, the Nejanilini Lake region of northern Manitoba exhibits low topographic relief, coarse and rocky tills, low-ice-content permafrost, and the presence of outcropping bedrock, which combine to suggest the potential for shallow hydrologic flow paths during the growing season and potentially more connections to surface groundwater, streams, and lakes. Small water bodies were located relatively higher in the landscape than larger water bodies (Fig. 5; Table 3) and so may be recharged less frequently by either surface or subsurface flows even as annual precipitation increases (Rains 2011). Similarly, water bodies located higher in the landscape may be less likely to be connected to drainage inlets. Increased evaporation due to warmer temperatures in combination with high surface area to depth ratios (Smol and Douglas 2007) or disproportionately smaller catchments may also explain the greater loss of small ponds. Larger lakes and ponds have lower surface area to depth ratios, and higher evaporation rates could be balanced by greater recharge from deeper groundwater sources given the lower position in the landscape (Fig. 5). Low-ice-content permafrost in our region, and resulting limited thermokarst and thermal erosion, may explain why so few new ponds appeared in the modern imagery compared to more ice-rich regions of the Arctic (Brown et al. 1998 (revised 2001); Jorgenson and Osterkamp 2005; Smith et al. 2007; Roach et al. 2011). Hinkel et al. (2012) recently underscored the importance of substrate, including ice content, in determining the morphometry of thermokarst lakes in Alaska.

Terrestrialization, possibly due to enhanced plant growth in response to warming (Roach et al. 2011), was suggested for the 44% of our small water bodies that appeared to be vegetated in the modern imagery. The degree to which this terrestrialization is aided or impeded by loss of water is unclear. The remaining water bodies classified as lost between 1956 and modern (56%) appeared to have bare sediments or rocks and so likely are subject to annual flooding and drying. Earlier, more frequent annual drying appears likely with warming, but it is not possible for us to assess changes in annual drying since 1956 directly with only two sets of imagery. Our data may exaggerate the amount of annual drying since the 1956 imagery was taken in early July and the modern images (7 of 8 sites) were from August or September. For the one image from June (Site F) ~10% of water bodies were dry compared with an average of 22% percent for the later August–September images (Table 1). However, the decrease in number and area of small water bodies (100–1000 m^2) was still significant even if annual drying was excluded from analysis.

Barrens

Barrens decreased in number and area by ~60% over the last ~50 years. The apparent rapid vegetating of these barrens is consistent with widespread increases in terrestrial biomass and productivity of 20% or more for vascular plants across the Arctic at both a regional and landscape level (Walker et al. 2006; Fraser et al. 2011; Elmendorf et al. 2012; Epstein et al. 2012).

Climate warming may be expected to increase plant growth on barrens as well as terrestrialization in or adjacent to ponds and lakes (Roach et al. 2011; Elmendorf et al. 2012). Higher average soil and ground temperatures will extend the growing season and directly increase plant growth and may also result in greater nutrient availability (Natali et al. 2012). With warming, low-growing, evergreen shrubs, commonly adjacent to barrens, have been shown to increase in cover and height in dry heath tundra (Wahren et al. 2005; Hudson and Henry 2009). Buizer et al. (2012) documented increased vegetative growth and berry production in the dwarf shrub *Empetrum nigrum* L. associated with increased summer warmth, and added nitrogen may also enhance growth (Aerts 2010). Working at a dune site in subarctic Quebec, Boudreau et al. (2010) observed rates of expansion for *Empetrum* of 200 m in 50 years. Rapid expansion of *Empetrum* was attributed to effective seed dispersal, which may, in part, explain why size of barrens was not an important factor in explaining barrens disappearance. Colonization of barrens may also be facilitated by low ice content of soils in our region (Jorgenson et al. 2010).

Shrub expansion has been documented to occur more in valley bottoms and slopes than on hilltops (Stow et al. 2004; Tape et al. 2006). Naito and Cairns (2011) found that shrub expansion was greater in wetter portions of five different areas in Alaska. Soil moisture also has significant impacts, direct and indirect, on plant colonization in high Arctic (Bliss et al. 1984; Gold and Bliss 1995). Differences in soil moisture may explain why barrens located relatively higher in the local Nejanilini landscape were most likely to persist (Table 3).

Increased winter precipitation and snow cover, in particular, can enhance plant colonization in dry tundra areas such as barrens. Plants, including *Empetrum* and other shrubs, can be damaged during the winter due to a lack of snow cover, especially in combination with extreme warming events (Aerts 2010; Bokhorst et al. 2011). Less snow also suggests less moisture due to the spring thaw. Winter precipitation did increase by 19% from 1954 to 2005 at Churchill (nearest recording station) (Sannel and Kuhry 2011). Greater snow cover would reduce scouring and other exposure-related damage and may also result in greater soil temperatures and microbial cycling of N which would lead to enhanced colonization of barrens (Wahren et al. 2005; Natali et al. 2012). Increasing shrub cover in and around barrens would result in strong feedbacks due to enhanced trapping of snow (Myers-Smith et al. 2011; Bonfils et al. 2012).

An alternative explanation for decreasing area and number of barrens may be reduced herbivory or trampling by caribou. Caribou grazing may significantly reduce vegetation cover (Henry and Gunn 1991; Manseau et al. 1996; Boudreau and Payette 2004). Our site is part of the migratory route of the Qamanirjuaq caribou herd. Reliable quantitative estimates for herd size are not available for the entire period represented by our imagery, but the data that do exist (CircumArctic Rangifer Monitoring and Assessment Network, http://www.caff.is/carma) suggest large increases from the 1970s to the 1990s, with subsequent decline. Data for adjacent herds also suggest recent decline (Vors and Boyce 2009). If caribou numbers have decreased significantly, then this might result in our overestimating the direct impacts of climate on barrens revegetation.

The unvegetated soils in barrens are highly reflective and, like water, contrast strongly with adjacent vegetated areas (Fig. 1), but several factors may complicate our analysis of barrens. First, differences in the month and year of acquisition may affect our estimates of the modern number or area of barrens, but this seems unlikely since the majority of plants growing in and around barrens are perennial, evergreens or, if deciduous, both green and fall-colored leaves contrast markedly with bare soil. Differences in soil moisture due to month of image acquisition (June versus August or September) could also influence our results because wet soils generally have greater reflectivity, although the relationship between moisture and reflectivity is curvilinear (Liu et al. 2002). Second, greater spatial and spectral resolution (RGB color) of modern images might result in easier identification of smaller barrens in the modern imagery — and by extension water bodies. This would cause us to underestimate the loss of smaller barrens, and the barrens and water bodies that "appear" in the modern imagery (Table 3) may in part be an artifact of the shift in resolution. We chose the 10 m² minimum area threshold as a way of mitigating this bias. Third, the dark lichen mats present in and around many barrens likely may represent another source of error since they are clearly visible in the modern but not the historic imagery. While dark, the lichens mats do not contrast as strongly with bare soils as do *Empetrum*, *Betula*, and other shrubs and lichens. Less contrast in combination with lower resolution could result in delineation of lichen-dominated areas as barrens in the 1956 imagery, while excluding these same areas in the modern imagery which would result in an inflated estimate of barrens loss. Unfortunately, we have no way to directly ground truth either the modern or 1956 imagery.

Conclusions

In this study, we documented significant declines in number and area of barrens and small water bodies over the past 60 years in an unstudied subarctic landscape located near Nejanilini Lake, Manitoba. The changes we observed are broadly consistent with a greening of the Arctic due to warming and increased precipitation (Fraser et al. 2011; Roach et al. 2011; Epstein et al. 2012; Walker et al. 2012). Our work suggests that analysis of barrens may provide an important way of extending the utility of historical photographs in understanding long-term change in the Arctic. The use of barrens may be especially valuable in upland areas where poor quality or low spatial and spectral resolution make it difficult to detect shrubs in vertical aerial photographs (Stow et al. 2004).

The rapid loss of barrens, in particular, highlights the possible importance of changes in winter conditions (Bokhorst et al. 2011; Callaghan et al. 2011; Bonfils et al. 2012). If snow cover is critical to plant success in barrens, then projected future decreases in snow cover (Callaghan et al. 2011) could result in the re-expansion of barrens especially as summer temperatures also increase.

Substrate and terrain are important in determining landscape responses to climate change (Devito et al. 2005; Jorgenson and Osterkamp 2005; Hinkel et al. 2012). Low permafrost ice content, in particular, may explain why so few new water bodies appeared in our study area, and low ice content may facilitate plant colonization of barrens. Over 60% of Arctic permafrost is classified as low ice content (Brown et al. 1998 (revised 2001)), and there is likely a need to separate ice content from extent of permafrost as a way of understanding regional differences in pond and lake response to climate change.

The changes we observed in area and number of small water bodies may be of direct interest (Smol and Douglas 2007; Zona et al. 2012) but may be more important as proxies for changes in surrounding lowland areas. Over 40% of our study sites are classified as lowland, which includes extensive areas of sedge fens and peatlands (Table 1). Small water bodies can be linked hydrologically to their surroundings (Ferone and Devito 2004), and the significant loss of small water bodies we observed (Fig. 4) suggests that wet tundra areas may be drying especially at relatively higher elevations in the landscape. Any offset in carbon uptake due to terrestrialization of these water bodies (Roach et al. 2011) may be more than offset by increased rates of soil respiration in the surrounding area due to drying (Dagg and Lafleur 2011). It is not yet clear why small water bodies are drying, and additional field work is needed to distinguish among higher evaporation rates (Smol and Douglas 2007), changes in surface or subsurface movements of water due to increasing active layer depth (Woo 1986; Woo and Marsh 2005; Wright et al. 2008; Avis et al. 2011), and even the potential for trapping of snow by shrubs in upland areas (Myers-Smith et al. 2011).

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