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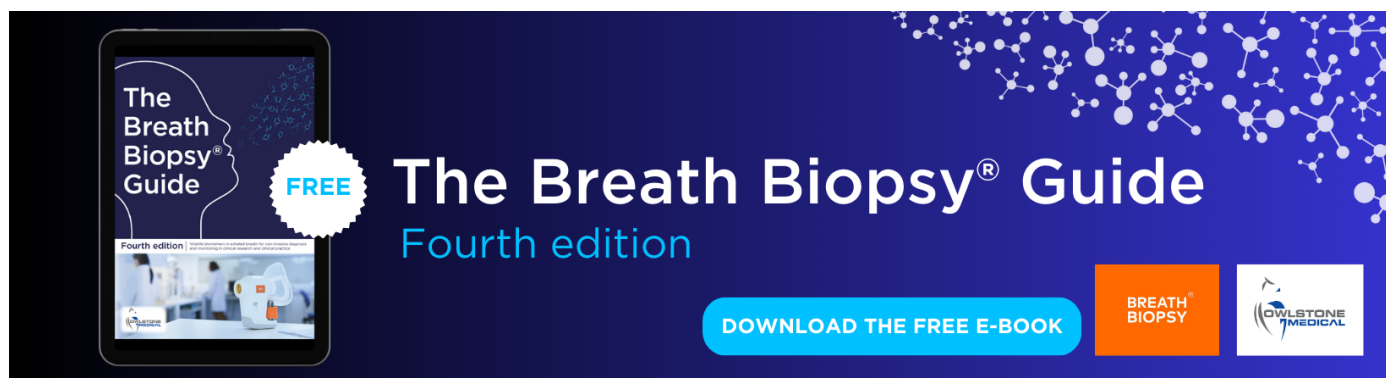
High spatial resolution decade-time scale land cover change at multiple locations in the Beringian Arctic (1948–2000s)

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High spatial resolution decade-time scale land cover change at multiple locations in the Beringian Arctic (1948–2000s)

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Abstract

Analysis of time series imagery from satellite and aircraft platforms is useful for detecting land cover change at plot to regional scales. In this study, we created multi-temporal high spatial resolution land cover maps for seven locations in the Beringian Arctic and assessed the change in land cover over time. Land cover classifications were site specific and mostly aligned with a soil moisture gradient. Time series varied between 60 and 21 years. Four of the five landscapes studied in Alaska underwent an expansion of drier land cover classes while the two landscapes studies in Chukotka, Russia showed an expansion of wetter land cover types. While a range of land cover types was present across the landscapes studied, the extent of shrubs (in Chukotka) and open water (in Alaska) increased in all landscapes where these land cover types were present. The results support trends documented for regional change in NDVI (a measure of vegetation greenness and productivity) as well as a host of other long term, experimental and modeling studies. Using historic change trends for each land cover type at each landscape, we use a simple probabilistic vegetation model to establish hypotheses of future change trajectories for different land cover types at each of the landscapes investigated. This study is a contribution to the International Polar Year Back to the Future project (IPY-BTF).

Keywords: Beringia, land cover change (LCC), Arctic change, vegetation change, arctic tundra, remote sensing, International Polar Year

 Online supplementary data available from stacks.iop.org/ERL/7/025502/mmedia

1. Introduction

Rates of recent climate warming in the Arctic have been approximately twice the global average (IPCC 2007, Kaufman *et al* 2009). Increasingly, widespread and, in some cases, dramatic changes in arctic ecosystem structure and function are being reported and linked to climatic warming (ACIA 2005, Hinzman *et al* 2005, Post *et al* 2009). While there have been many recent studies documenting vegetation change over decadal time scales (Tape *et al* 2006, Callaghan *et al* 2011a, Hill and Henry 2011), most have focused on either plot level

change (e.g. Villarreal *et al* 2012) or large scale regional change derived from satellite remote sensing (e.g. Bhatt *et al* 2010). Few studies have linked decade-time scale changes observed at the plot level to those observed at the landscape or regional scale (*sensu* Silapaswan *et al* 2001, Johansson *et al* 2006). A remaining challenge pertains to understanding how changes at small spatial scales (e.g. plot and landscape level) manifest to affect change at larger spatial scales, and how changes at larger spatial scales constrain change at small spatial scales.

Recent changes (1982–2008) in NDVI (normalized difference vegetation index) documented across the pan-arctic from low-spatial resolution satellite imagery indicate a general greening trend, which suggests there has been an increase in terrestrial ecosystem productivity (Bhatt *et al* 2010). Bhatt *et al* (2010) largely link this trend to warming of coastal landscapes adjacent to areas of the Arctic Ocean where declines in the extent of sea ice and summer warming have been greatest. However, increases in NDVI values in this study were not always consistent with warming trends in some areas of the Arctic. In Beringia, for example, warming occurred in both Chukotkan and Alaskan sectors but greening was documented only in Alaska. Such discrepancies are difficult to explain without more detailed studies that assess ecosystem change at higher spatial resolutions. In Alaska, and elsewhere in the low Arctic, shrub expansion has been shown to be an underlying cause of landscape greening (Forbes *et al* 2009) with strong implications on ecosystem function (Sturm *et al* 2005, Chapin *et al* 2005). However, underlying causes of greening in non-shrub dominated landscapes, typical of the coastal margins where Bhatt *et al* (2010) documented greening, remain poorly studied.

At comparatively small spatial scales, experimental studies (Johnson *et al* 2011a, Oberbauer *et al* 2007, Hollister *et al* 2005), some long term observations (Hill and Henry 2011, Hudson *et al* 2011) and retrospective studies (Johansson *et al* 2006, Verbyla 2008, Lara *et al* 2012, Villarreal *et al* 2012) suggest arctic plant communities can respond differently to warming and other environmental changes. Already, expansion in shrubs (Sturm *et al* 2001, Tape *et al* 2006), increase in biomass (Epstein *et al* 2012, Hudson and Henry 2009), and changes in plant community structure and species richness (Callaghan *et al* 2011a) have been observed across the Arctic. Moreover, plant communities in a given landscape can have markedly different functional properties such as land–atmosphere carbon exchange (Lara *et al* 2012, Oberbauer *et al* 2007), energy balance (Chapin *et al* 2005), and nutrient cycling (Hobbie 1992, Hobbie *et al* 2002, Edwards and Jefferies 2010). Thus, assessment of likely feedbacks to the climate and other subsystems from landscape level ecosystem change (*sensu* Chapin *et al* 2005) require the integration of specific landscape units to account for differences in their dynamic response to change and functional importance (*sensu* Johansson *et al* 2006, Lara *et al* 2012).

Improved multi-scale understanding of ecosystem change in arctic landscapes is likely to contribute to improved understanding of how ecosystem function has also changed and how, for example, altered land–atmosphere carbon exchange and other feedbacks affect different components of the Arctic System such as climate. Landscapes at high northern latitudes have historically functioned as a carbon sink, accumulating a large pool of soil organic carbon (Tarnocai *et al* 2009), which is largely stored in permafrost (Schuur *et al* 2008). With arctic warming, concern surrounds the future fate and transport of this carbon store (Mack *et al* 2004, Dutta *et al* 2006, Schuur *et al* 2006, Hollesen *et al* 2011). If historic soil carbon is metabolized and mobilized to the atmosphere as a greenhouse gas, and if the forecast

increase in photosynthetic uptake of CO₂ (Euskirchen *et al* 2006) does not offset this loss, greenhouse warming could be positively enhanced (Schuur *et al* 2008, Koven *et al* 2011). The lack of sustained observations and a relatively poor knowledge of linkages between land cover change dynamics and ecosystem structural and functional properties pose a challenge to understanding the likely impact of decade-time scale land cover change on land–atmosphere greenhouse warming potential. Several studies to date have demonstrated the propensity of multi-temporal high spatial resolution imagery to document landscape level change and determine the differential response of various landscape subunits (Sturm *et al* 2001, Johansson *et al* 2006, Malmer *et al* 2005, Tape *et al* 2006). In this study, we employ a similar approach to explore the spatio-temporal land cover change dynamics at seven landscapes in the Beringian Arctic, which appear to be warming but demonstrate different greening responses (Bhatt *et al* 2010). Historical high-resolution single-band aerial photography and historic declassified military imagery were used in combination with modern multi-band satellite imagery to create retrospective and modern land cover maps using classification algorithms trained on ground-based data. Following a normalizing and modeling procedure that accounts for the different capacities for change and standardization of the temporal period over which change was assessed at each landscape, we determine shifts in coverage of extant land cover types. Our objective is to determine the direction and magnitude of decadal time scale land cover change and compare the dynamics of change between landscapes and with trends documented at larger spatial scales. This study is a contribution to the International Polar Year Back to the Future (IPY-BTF) project (IPY #512, Callaghan *et al* 2011b).

2. Methods

2.1. Study area

Land cover change was analyzed for seven landscapes (about 6–20 km²) within the Beringia region (table 1). These landscapes span arctic bioclimate subzones B through E (*sensu* CAVM Team 2003), see figure 1. Each landscape contained a range of vegetation types associated with different surface hydrologic conditions. Barrow, Midway and Atkasuk are landscapes located on the Arctic Coastal Plain on the North Slope of Alaska where average July temperatures range from 3.7 to 9 °C and summer precipitation is approximately 55–57 mm (Oberbauer *et al* 2007). Ivotuk is a gently sloping moist tussock-graminoid/dwarf shrub tundra landscape in the northern foothills of the Brooks range with a mean July temperature of 11.3 °C and summer precipitation of 181.5 mm (Hinzman *et al* 2003). The Kougarok landscape is a tussock-graminoid/dwarf shrub tundra landscape located on the Seward Peninsula where the mean July temperature is 11.0 °C and summer precipitation is 102.1 mm (Hinzman *et al* 2003). Yanrakinot and Penkigney Bay are gently sloping graminoid dominant landscapes with occasional stands of shrubs situated at the base of the mountainous

Table 1. Landscape name, location, circumpolar Arctic vegetation map bioclimate subzone and floristic province (*sensu* CAVM Team 2003), land cover classes present, and image acquisition dates used for land cover classifications.

Site name	Lat	Long	Bioclimate subzone	Floristic province	Land cover classes ^a	Imagery dates
Barrow, Alaska	71.28	−156.59	C	Northern Alaska	D, M, W, A, O	1/8/1948 ^b 14/8/1955 ^b 15/7/1979 ^d 27/7/2008 ^c
Midway, Alaska	70.86	−156.99	C	Northern Alaska	D, M, W, A, O	13/8/1955 ^b , 2/9/2002 ^c
Atkasuk, Alaska	70.46	−157.41	D	Northern Alaska	D, M, W, A, O	25/7/1955 ^b , 2/8/2005 ^c
Ivotuk, Alaska	68.48	−155.77	E	Northern Alaska	D, M, W, A, O	19/7/1977 ^d , 19/8/1985 ^d 17/8/2008 ^c
Kougarok, Alaska	65.39	−164.65	E	Beringian Alaska	D, M, W, A, O	3/8/1985 ^d , 27/8/2006 ^c
Penkigney Bay, Chukotka	64.83	−173.07	D	East Chukotka	B, D, S, M, W	19/7/1963 ^c 18/8/2005 ^c
Yanrakinot, Chukotka	64.88	−172.66	E	East Chukotka	B, D, S, M, W	19/7/1963 ^d 15/7/2008 ^c

^a B—Bare. D—Dry. M—Moist. W—Wet. A—Aquatic. O—Open Water. S—Shrub.

^b Historic black and white aerial photography.

^c Quickbird—4 band standard image product.

^d Historic color-infrared photography.

^e CORONA declassified military imagery.

^f USGS Digital orthophoto quadrangle.

coastal region of east Chukotka, Russia. The Yanrakinot and Penkigney Bay study locations are located approximately 50 km northeast of Provideniya, where the mean July temperature is approximately 8.6 °C and summer precipitation is 173 mm (Meteorologisk Institutt 2007–2012). To aid image classification and functional ecological studies associated with this work, ground-based data from Chukotka were collected in July of 2005 during the Swedish Beringia Expedition (Tweedie *et al* 2006), and in Northern Alaska and the Seward Peninsula in 2006 and 2007. The selection of landscapes included in this study were largely limited by the availability of both modern and historic high spatial resolution imagery, and logistic constraints associated with site access and ground-based sampling.

2.2. Image analysis

For each landscape, a land cover classification derived from a high spatial resolution modern Quickbird satellite image was compared to classifications derived from historic color-infrared or grayscale imagery as outlined below. Quickbird imagery for all locations was acquired between 2002 and 2008. Historic imagery was acquired between 1948 and 1977 (table 1). For consistency, all images analyzed for this study were restricted to seasonal acquisitions between mid-July and mid-August, close to peak growing season. For the majority of sites, only two images (historic and modern) were found to be suitable, but for the Barrow and Ivotuk sites, four and three images were found to be suitable respectively (see table 1).

2.2.1. Image preprocessing. All image analysis was performed with the software Environment for Visual Images V4.2 (ENVI). For each landscape, historic images were registered to the geometrically corrected and standard product Quickbird image (table 1) using a nearest neighbor second degree polynomial transformation method with >30 ground control points evenly distributed across a given landscape. Registration was improved iteratively until a root mean squared error (RMSE) of <0.75 was attained.

Because of differences in view angles, pixel resolution, and spectral properties between historic and modern imagery for each landscape, the following techniques were used to standardize image time series for each landscape. The pixel size of the modern Quickbird image was resampled to match the pixel size of the historic image, which ranged from 1.4 m in Barrow, Alaska to 5 m at both landscapes in Chukotka. To compare historic grayscale images with modern multi-band color images, color images were converted to grayscale by averaging the red, green, and blue bands to a single band. Following the color to grayscale conversion, modern image histograms were then matched to those of the corresponding historic grayscale image. Radiometric corrections of historic images were made using the ‘cross-track illumination correction’ function in ENVI. These corrections resulted in image time series for each landscape that were co-registered to within 0.75 m, were of the same pixel resolution, and had similar intensity ranges within a scene (supplementary figures S1–S7 available at stacks.iop.org/ERL/7/025502/mmedia). The preprocessing procedures followed here were similar to those used in another study for correcting high-resolution historic imagery (Rigina 2003). Major inconsistencies were then masked from all images, including clouds, man-made

structures, and large hills/mountains and river banks that resulted in shadowing in some images.

2.2.2. Image classification. All image classifications were completed using ENVI (V4.2). Based on field surveys and plot level data collected to describe vegetation composition and cover and physical site attributes such as soil moisture, five broad land cover classes were identified for each landscape. The classification schemes were defined to describe discrete plant community associations, which appeared to correspond with a relative surface soil moisture gradient at all sites. Thus, the classification used refers to a combined discrete vegetation class and soil moisture regime. This classification scheme is similar to that used in other tundra landscapes (Silapaswan *et al* 2001, Rees *et al* 2003, Schneider *et al* 2009, Olthof *et al* 2008). For Alaskan landscapes, dominated by graminoid tundra, we classified land cover into dry, moist, wet and aquatic tundra, and open water (non-vegetated) classes. For Chukotkan landscapes, which were dominated by mixed graminoid tundra and occasional stands of shrubs, we classified land cover into dry, moist, wet and shrub tundra, and bare ground (non-vegetated) classes. The classification scheme for Chukotkan landscapes reflected the more mountainous, sloping landscape of the region where little to no standing water was present, unlike the landscapes sampled in Alaska. Land cover classes, while named according to relative moisture levels in each landscape, reflect markedly different plant community assemblages at each site. Contrary to the naming convention, shrubs were present at all landscapes studied but were not dominant and in most cases consisted of prostrate or dwarf shrub species in most landscapes and land cover types within these landscapes. The relative cover of plant functional types within each land cover type and landscape is given in supplementary figure S8 (available at stacks.iop.org/ERL/7/025502/mmedia). At each of the landscapes studied, we collected a range of biophysical and spectral reflectance properties for three 0.25 m² plots in each vegetated land cover type within a given landscape. Spectral properties of these landcover classes have been appended to the Vegetation Spectral Library (<http://spectrallibrary.utep.edu>). The only exception was for large shrub stands (>0.5 m) in Chukotka, which were not sampled at this spatial scale. Plot level data, in combination with ground-level photographs of the study area and surrounding landscape, were used to identify training classes for a minimum-distance classification of the image derived from Quickbird satellite imagery. In our analysis of ground truthed modern imagery, areas of open water and dry vegetation represented the lowest and highest grayscale pixel values respectively. Pixel values for aquatic, wet, moist and dry tundra fell between these two spectral endpoints and followed a gradient from lower to higher pixel values respectively. There were no standing water/aquatic classes present in the Chukotkan landscapes, where the darkest/lowest pixel values corresponded with shrub cover.

To test the adequacy of the classification method utilizing grayscale imagery, the classification derived for the modern image of the spatially heterogeneous Barrow landscape was

compared to classifications derived from the same satellite image using multiple spectral bands. The latter classification derived from the multispectral image has been shown to have a high level of accuracy compared to similar studies in the arctic (Muller *et al* 1999, Jorgenson *et al* 1994, Noyle 1999, Stine *et al* 2010, Chaudhuri 2008) with an overall user and producer accuracy of 74% and 88% respectively (Tweedie *et al* 2012). When we compared the classification derived from the grayscale classification described above with the classification derived from the same but multispectral image, the grayscale classification had an overall accuracy of 98.58% and a Kappa coefficient of 0.97, suggesting it adequately represented the extant land cover of the landscape and that this is an acceptable method for classifying spatially heterogeneous tundra landscapes such as those in this study.

To develop classifications for historic imagery, classifications derived from modern imagery had to be used as a baseline because of the lack of appropriate data suitable for ground truthing historic classifications. As such, classification of historic imagery conservatively assumes (1) state-level change at the landscape level (complete loss or gain of a land cover class) has not occurred; (2) at some locations within a landscape, land cover change has not occurred and that the spectral properties of these locations on historic imagery match that for modern imagery, thereby making these locations appropriate training sites for classification of the historic imagery; (3) areas of change can be detected from shifts in the boundaries of discrete land cover types (LCT) (e.g. draining and subsequent re-vegetation of ponds, expansion of shrub clumps); and (4) shifts in vegetation communities detected at the m² scale occur as a result of persistent environmental change over decadal time scales. Based on these assumptions, we selected the same location for classification training sites in homogeneous areas in the historic/modern images where change was not obvious and where we had a high degree of confidence in the classification of a particular land cover type based on field studies. Resulting classifications generated a time series (for Barrow and Ivotuk) of modern and historic land cover classifications (supplementary figures S9–S15 available at stacks.iop.org/ERL/7/025502/mmedia) for each of the seven landscapes (about 6–20 km²).

2.3. Change analysis and prediction

To quantify land cover change between the historic and modern image classifications, the change in pixel classes was calculated for each pixel within the oldest and most recent classifications in each landscape. Change was characterized as one of five categories based on the direction and magnitude of the change along a land cover–soil moisture gradient. Moisture rankings were based on measurements of volumetric water content made during field campaigns in each land cover class at each landscape. Pixels that remained the same land cover class in both classifications were assigned ‘no change’. Pixels that changed to an adjacent moisture class were assigned ‘wet+’ and ‘dry+’ based on the direction of the respective change along a soil moisture gradient, and

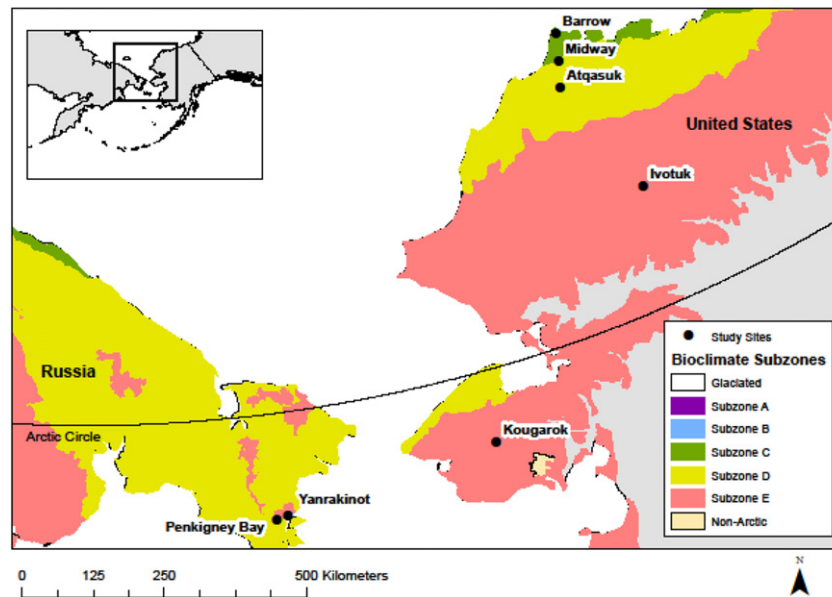


Figure 1. Location of the seven Beringian landscapes included in this study overlaid on a map of bioclimate subzones (derived from CAVM Team 2003).

pixel changes to classes that were 2 or more ranks apart were assigned ‘wet2+’ and ‘dry2+’ based on the respective direction of change. For each landscape, the percentage of pixels that fell into each class was normalized by the total number of pixels that could undergo each respective change after which the ratio of pixels that became drier relative to those that became wetter was calculated. A non-metric multidimensional scaling (NMDS) ordination was performed on resulting values using PC-Ord V5.0 (McCune and Grace 2002) to determine the similarity of change between the landscapes studied.

For each of the historic and modern land cover classifications used, the change detection tool in ENVI was used to create a matrix of pixel counts for every permutation of initial and final land cover class. Using this matrix, the probabilities of one land cover type changing to another within a given landscape were calculated. Resulting probabilities were then divided by the time period between image acquisitions to normalize for differences in the time period over which change was assessed for the different landscapes. Probabilities were used to formulate a probabilistic model forecasting land cover change 100 years into the future (*sensu* Johnson *et al* 2011a). This model assumes that (1) the direction and magnitude of change from one land cover type to another within a landscape will be consistent over the forecast time interval; and (2) new land cover types will not appear. The model is based on the following equation where V_i is the number of pixels classified for land cover type $i, j, k, \dots$, at time t , C_{ji} is probability of subtracting one pixel from V_j and adding it to V_i , and C_{ij} is the probability of subtracting one plot from V_i and adding it to V_j :

$$\frac{dV_i}{dt} = V_i(t-1) + C_{ji}, C_{ki}, \dots, C_{ni} - C_{ij}, C_{ik}, \dots, C_{in}.(1)$$

Here, each model iteration ($t, t+1, \dots$) represented 1 yr and we ran the respective landscape-specific model for 100 iterations using a fourth order Runge–Kutta method for integrating equations (Wilson 2000). To add stochasticity to each iteration (Sabo and Post 2008), the probability of change was compared against a randomly generated number and a transition between land cover types was programmed to occur if the random number was below the probability of change (table 2). Each model was simulated 100 times to calculate a mean and confidence interval over the simulation period. Thus, the number of pixels in each land cover type for a given iteration is a function of the number of pixels at the end of the prior iteration plus the net exchange among the other four land cover types. Such probability models are typically used by population ecologists to trace the impacts of different population demographics and sex ratios on multi-temporal population dynamics (e.g. Crouse *et al* 1987, figure 2) but have recently been used to hypothesize future change scenarios for different plant communities in alpine tundra (Johnson *et al* 2011a). Modeling was performed using the software Stella (V9.0).

3. Results

Land cover change has occurred at each of the landscapes studied. Interestingly, there was no consistent trend in the direction or magnitude of change across all landscapes studied. Some landscapes demonstrated overall drying while others indicate overall wetting (table 3). Here we describe changes as ‘directional’ when referring to the ratio of pixels becoming drier to those becoming wetter (table 3, ‘D/W ratio’), and refer to ‘absolute change’ when referring to the sum of all pixels undergoing change, regardless of direction (table 3, ‘absolute change’). The two coastal Chukotkan landscapes, Penkigney Bay, and Yanrakinot, had the greatest

Table 2. Land cover change statistics derived from comparison of historic and modern image classifications. *H*—historic per cent cover, *P*—Present per cent cover, Δ —total change, N/Δ —rate of change; all values are normalized to 1 yr.

Site name	Time period	Bare			Dry			Shrub			Moist			Wet			Aquatic			Open water							
		H	P	Δ	N/Δ	H	P	Δ	N/Δ	H	P	Δ	N/Δ	H	P	Δ	N/Δ	H	P	Δ	N/Δ						
Barrow	1948–2008	n/a	n/a	n/a	n/a	9.20	15.60	6.40	0.11	n/a	46.66	51.84	5.18	0.09	35.48	25.18	–10.30	–0.17	5.72	3.86	–1.86	–0.03	2.94	3.52	0.58	0.01	
Atkasuk	1955–2008	n/a	n/a	n/a	n/a	10.07	6.44	–3.63	–0.07	n/a	44.46	52.33	7.87	0.15	21.52	16.92	4.60	–0.09	11.99	10.11	–1.88	–0.04	11.95	14.20	2.25	0.04	
Midway	1955–2008	n/a	n/a	n/a	n/a	21.60	24.25	2.65	0.05	n/a	43.51	40.08	–3.43	–0.06	17.68	15.67	–2.01	–0.04	3.37	6.00	2.63	0.05	13.84	13.99	0.15	0.00	
Ivotuk	1977–2008	n/a	n/a	n/a	n/a	12.21	21.08	8.87	0.29	n/a	52.18	47.61	–4.57	–0.15	30.72	23.20	–7.52	–0.24	4.66	7.80	3.14	0.10	0.24	0.31	0.07	0.00	
Kougarok	1985–2006	n/a	n/a	n/a	n/a	10.54	6.59	–3.95	0.19	n/a	55.00	69.52	14.52	0.69	30.23	21.02	–9.21	–0.44	3.70	2.24	–1.46	–0.07	0.53	0.62	0.09	0.00	
Penikigne Bay	1963–2005	2.97	3.53	0.56	0.01	22.65	14.56	–8.09	–0.19	2.88	54.67	64.15	9.48	0.23	15.67	13.97	–1.70	–0.04	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Yunraknot	1963–2008	9.33	8.44	–0.89	–0.02	18.88	24.19	5.31	0.12	1.58	2.43	0.85	0.02	54.30	39.46	–14.84	–0.33	15.88	25.48	9.60	0.21	n/a	n/a	n/a	n/a	n/a	
Average		6.15	5.99	–0.16	0.00	15.02	16.10	1.08	0.02	2.23	3.11	0.88	0.02	50.11	52.14	2.03	0.09	23.89	20.21	–3.68	–0.12	5.89	6.00	5.90	6.53	0.63	0.01

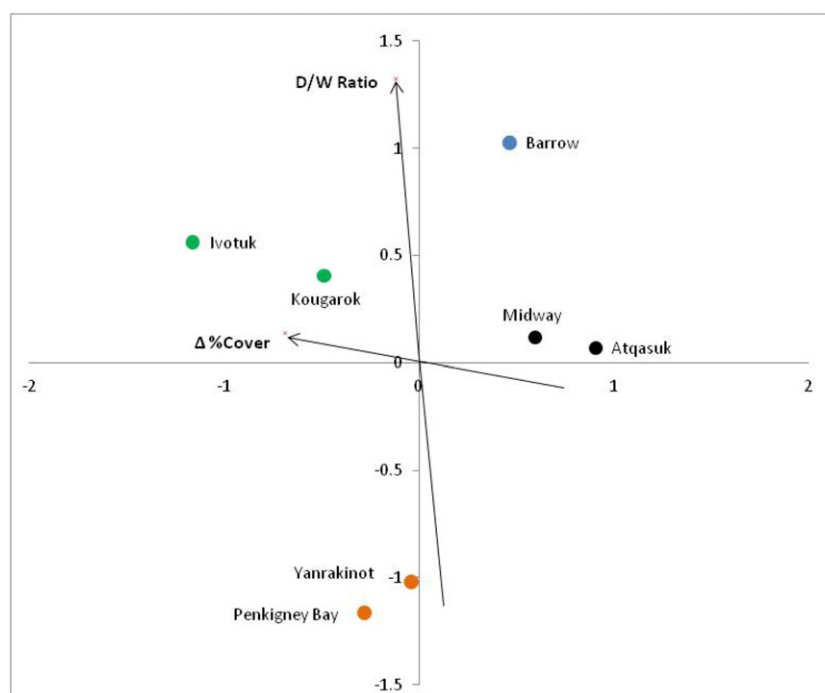


Figure 2. Ordination of raw, non-normalized land cover change parameters for the seven landscapes examined. Vectors have been multiplied by three and extended across the origin, for improved visualization. D/W ratio = direction of change along a soil moisture gradient (% pixels drier/% pixels wetter within a landscape). $\Delta\%Cover$ = magnitude of change (% of pixels in the historic classification that were classified as a different LCT in the modern classification). Sites are color coded according to their cluster analysis groupings.

Table 3. Land cover change for each landscape study area expressed as the percentage of drying and wetting documented at each landscape. All values are normalized by year. The first two columns represent the percentage land area changing per year. D/W ratio is the % area drier/% area wetter (i.e. values >1 indicate overall landscape has become drier, while values <1 indicate overall landscape has become wetter. Absolute change indicates the change observed at each site regardless of the direction of change.

Site name	%Cover wetter	%Cover drier	D/W ratio	Absolute change
Barrow	0.27	0.69	2.53	0.97
Atqasuk	0.48	0.45	0.94	0.93
Midway	0.53	0.59	1.12	1.12
Ivotuk	0.91	1.63	1.79	2.54
Kougarak	0.70	1.26	1.79	1.96
Penkigney Bay	2.17	0.63	0.29	2.79
Yanrakinot	1.93	0.61	0.31	2.53

directional shift toward wetter land cover types. The absolute change measured in Penkigney Bay and Yanrakinot was also the largest and third largest of all landscapes respectively. The two inland landscapes, Ivotuk and Kougarak, had the highest percentage of pixels become drier classes (1.63% and 1.26% per year respectively). With respect to directional change, four of the five Alaskan landscapes became drier, with the Atqasuk landscape being the only Alaskan landscape to become slightly wetter (table 3). The change estimated for the Barrow landscape had the greatest directional drying trend; however the absolute change was among the lowest observed. The greatest absolute change in Alaskan landscapes

was recorded at Ivotuk (table 3). Shrub and open water classes were the only land cover classes which had a net increase in all sites where present (figure 3). At Barrow, Alaska results from the analysis of multiple time series images show an overall increase in extent of dry and moist land cover and decrease in wet, aquatic, and open water land cover types, however trends of increasing/decreasing extent of land cover types from image to image were not consistent within the time series (figure 4). Results from a three image time series analysis at Ivotuk, Alaska indicate a consistent increase in the extent of dry and aquatic land cover that corresponds to a loss in moist and wet land cover classes over all three images (figure 5).

3.1. Ordination results

Cluster analysis (nearest neighbor linkage method and Sorensen distance measure) of land cover change data derived from the historic and modern land cover classifications grouped the seven landscapes into four clusters with 82.5% of the information remaining. The four groups had strong geographic tendencies suggesting landscapes in close proximity to one another had similar change responses irrespective of the time interval over which change was assessed. The four landscape groupings identified through cluster analysis were: (1) Penkigney Bay and Yanrakinot in Chukotka; (2) Atqasuk and Midway situated inland on the North Slope of Alaska; (3) the continental landscapes in Alaska at Ivotuk and Kougarak; and (4) Barrow on the Arctic coast of northernmost Alaska.

The NMDS ordination selected a two-dimensional solution following 500 iterations. This solution had a final

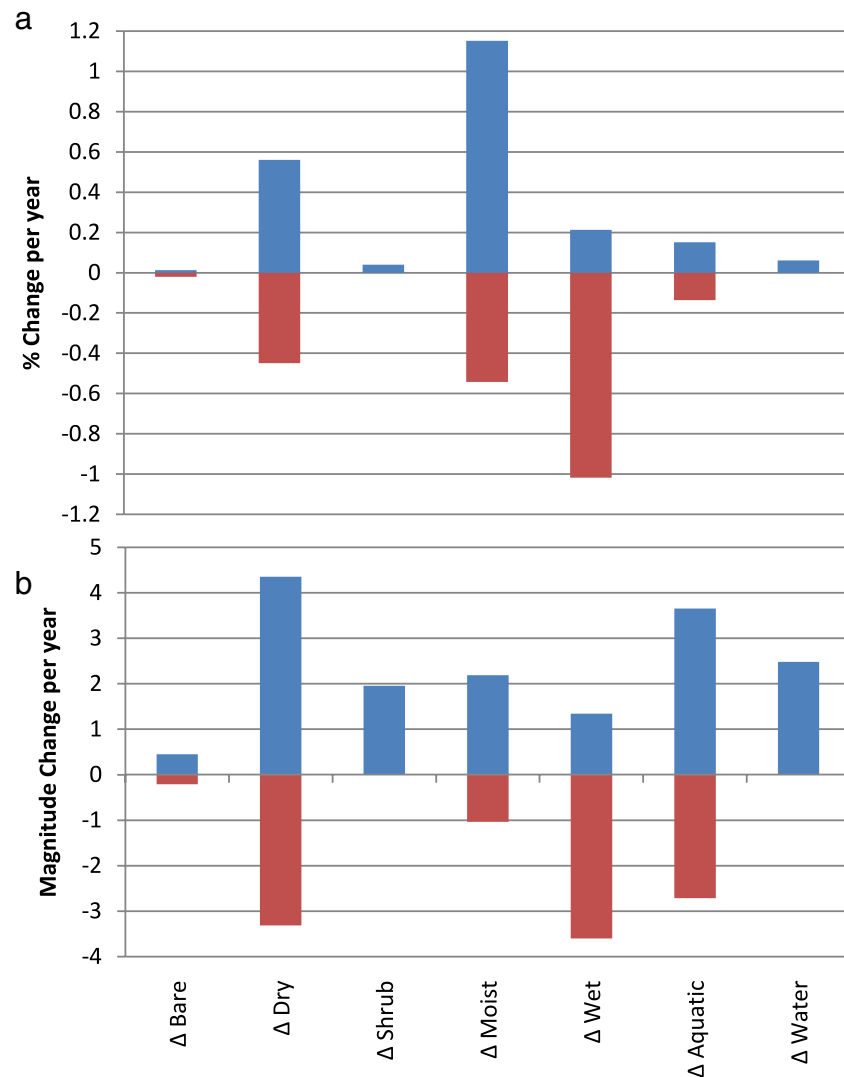


Figure 3. (a) (Top) net gain and loss of land cover types over all landscapes. (b) (Bottom) net gain and loss of land cover types over all landscapes, (relative to historical land cover type area).

stress <0.1314 and instability of 0.0034. Together, axis 1 and 2 account for 91% of the variability in ordination space, with individual r^2 values of 0.459 and 0.453 for axis 1 and 2 respectively (figure 2). The two landscape attributes that demonstrated the strongest correlation with ordination axis scores were the % drier/% wetter pixel ratio (directional change) and the absolute land cover change (figure 2; $n = 7$, $r^2 = 0.878$ and 0.835 respectively). The Ivotuk and Kougarok landscapes, which have the lowest latitude of the Alaskan landscapes and the most continental setting, demonstrated greater absolute change than the other Alaskan landscapes, with a directional shift toward drier land cover types. The Barrow landscape had a relatively low absolute change but the greatest proportional change toward drier land cover types. The two landscapes in Chukotka fell on the opposite side of the ordination to the Alaskan sites and were associated with the greatest absolute and directional change toward wetter land cover types (table 3).

3.2. Modeling results

The 100 year forecasts of change generated from the probability modeling suggest that Penkigney Bay was the most dynamic landscape and is likely to have the greatest absolute landscape change while Atqasuk will have the least (table 3). In all Chukotkan landscapes, clear increases in the shrub land cover class were observed and in all Alaskan landscapes, open water land cover class increased. Forecasts for all Alaskan landscapes suggest there will be a decreased extent of wet land cover classes in the future and an increased extent of open water. Within the Alaskan landscapes, the Barrow landscape is forecast to undergo the greatest loss of combined wet and aquatic land cover. The models for the Midway and Ivotuk landscapes forecast similar changes with a decreased extent of wet and moist land cover classes and an increased extent of dry, aquatic, and open water land cover classes. Models for the two Chukotkan landscapes forecast increases in shrub cover and a decreased extent of bare ground (figure 6). Both the overall extent of initial and final shrub

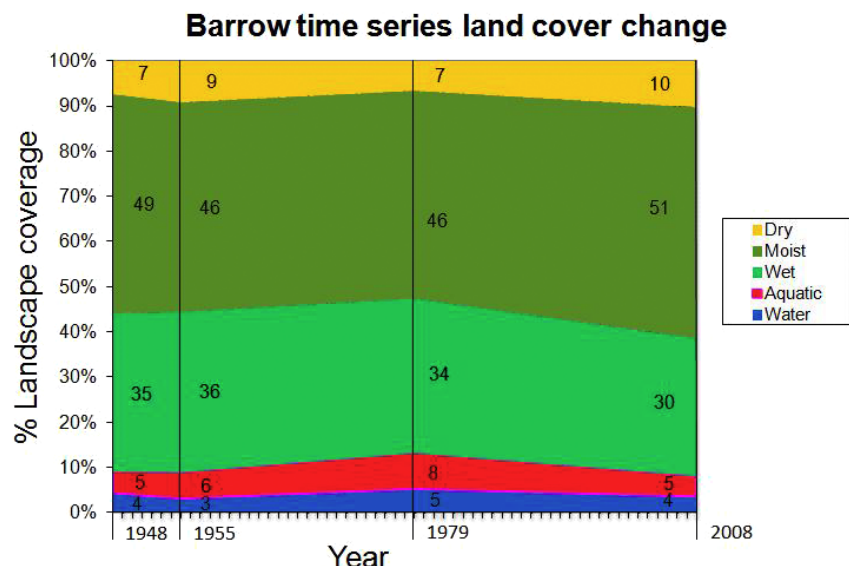


Figure 4. Change in relative cover of vegetation types at Barrow, Alaska during the period of 1948–2008 derived from a set of four historic land cover classifications.

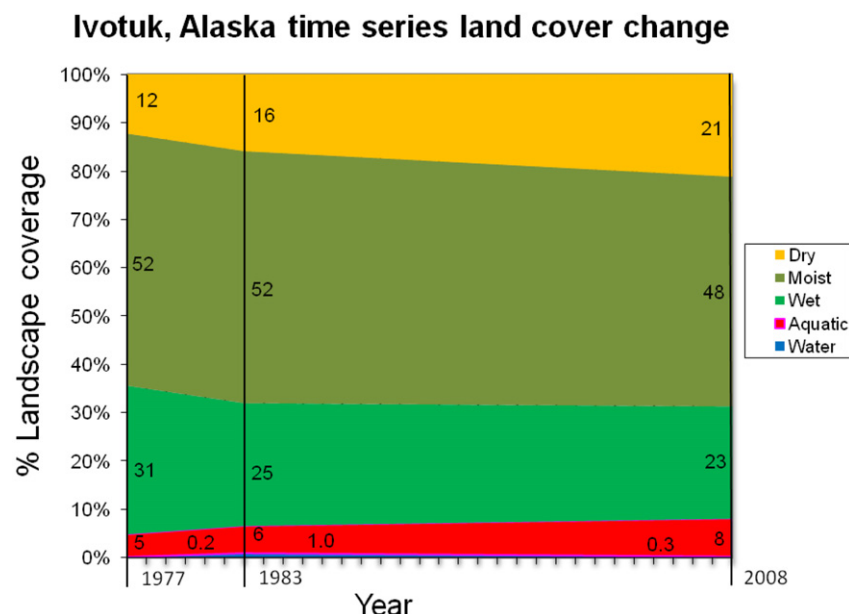


Figure 5. Change in relative cover of vegetation types at Ivotuk, Alaska during the period of 1973–2008 derived from a set of three historic land cover classifications.

coverage at the Chukotkan landscapes was relatively low ($<3\%$), however the relative increase (figure 6(b)) was large, indicating that this land cover type may change at a faster rate than others in the future. At Penkigney Bay, the extent of moist land cover is forecast to increase while those of dry and wet land cover classes are forecast to decrease in extent. Opposite trends are forecast for the Yanrakinot landscape.

4. Discussion

In this study, we retrospectively assessed the direction and magnitude of land cover change at multiple landscapes in the Beringian Arctic using land cover classifications derived from

historic and modern high spatial resolution aerial and satellite imagery. We also employed a probabilistic modeling approach to enhance landscape inter-comparison by normalizing for the capacity of change in a landscape and the time period over which land cover change was assessed. Land cover change was observed at all locations studied with landscapes in Chukotka, and Alaska showing contrasting tendencies toward wetter and drier land cover types respectively. The extent of shrub tundra and open water expanded at all landscapes where these land cover types were present. Overall, dry tundra land cover underwent the greatest expansion across all landscapes and the more southern landscapes showed greater magnitudes

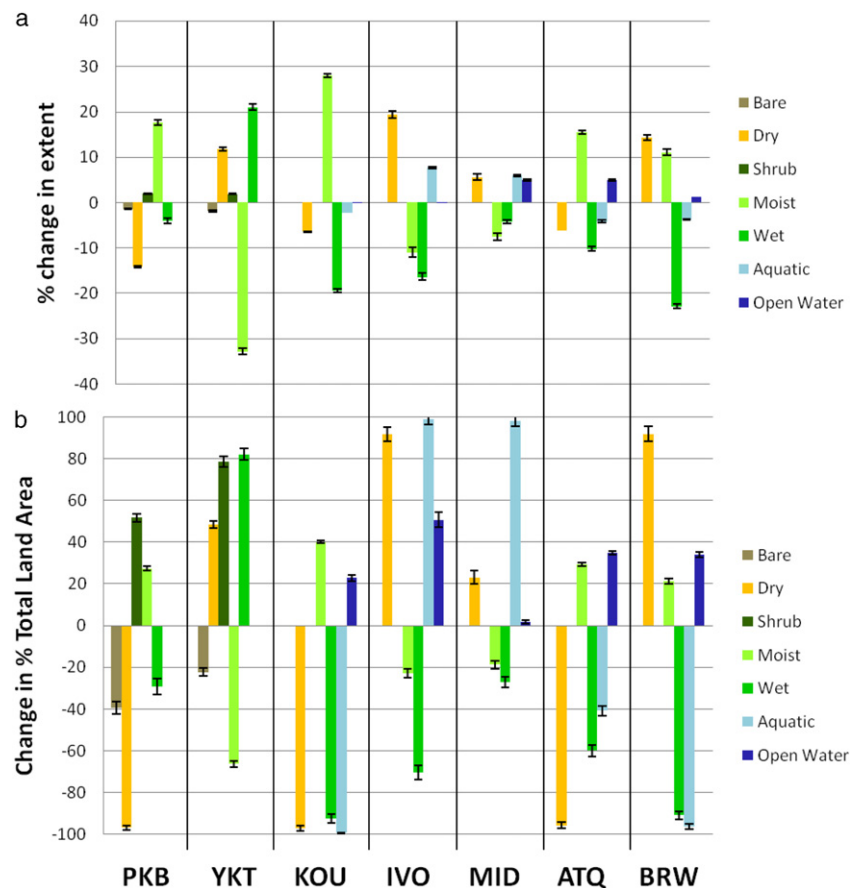


Figure 6. (a) (Top) 100 yr forecast of change in the extent of each land cover type and landscape examined. Change is relative to the total area examined. Error bars represent the 95% confidence intervals calculated from 100 model runs. (b) (Bottom) per cent change in each land cover type relative to the extent of the identical land cover type documented in the historic classification—i.e. the forecast magnitude of change for each land cover type in a given landscape. Error bars represent 95% confidence intervals calculated from 100 model runs. PKB—Penkigney Bay (Chukotka, Russia). YKT—Yanraknot (Chukotka, Russia). KOU—Kougarok (Alaska, USA). IVO—Ivotuk (Alaska, USA). ATQ—Atkasuk (Alaska, USA). MID—Midway (Alaska, USA). BRW—Barrow (Alaska, USA).

of change compared to more northern landscapes on the North Slope of Alaska.

Conducting any form of retrospective ecosystem change assessment is challenging (Washington-Allen *et al* 2006, Luo *et al* 2011). Such research demands the use of historical data or research sites for which analysis of decade-time scale change detection was not necessarily intended (*sensu* Sturm *et al* 2001, Johnson *et al* 2011a, Villarreal *et al* 2012), or from which uncertainty in findings are difficult to resolve (Lara *et al* 2012)—hence the need for conservatism when interpreting and extrapolating results from such studies. Considering the absence of long term monitoring at spatio-temporal scales suitable for linking and understanding plot to satellite measurements of ecosystem properties throughout much of the Arctic (Callaghan *et al* 2011a, NRC 2006, ACIA 2005), we maintain that although not optimal, retrogressive analyses such as that performed in this study can contribute an important and new understanding of ecosystem change. Such information is likely to be most powerful when synthesized with findings from paleoecological, experimental, remote sensing and/or modeling studies to seek multiple lines of agreement. Here, we frame the interpretation of land cover change dynamics at our study landscapes as hypotheses of

both past and likely future changes in these landscapes, which have received little focus at similar spatial and temporal scales, yet display intriguingly different greening responses to regional warming (Bhatt *et al* 2010). A key challenge for studies that use retrospective analysis to predict future land cover states, is predicting future states that did not exist previously (the last few decades). This is particularly relevant in this study where large expanses of erect shrubs are at present and/or historically have been rare or absent as a discrete landscape unit in the landscapes examined, but appear to be expanding dramatically in nearby areas (e.g. Sturm *et al* 2001, Tape *et al* 2006).

This study was based on several strict assumptions pertaining to how historic and modern images were used as well as the methods by which land cover was defined and quantified. Overall, we feel our approach is conservative and may in some instances underestimate the magnitude of change but not the direction of change given the way change was classified. While we made all reasonable efforts to minimize error and misclassification of historic landscapes in this study, historic classification accuracy is impossible to determine directly, and is strongly limited by the quality and availability of historic imagery. Imagery from landscapes with greater

topographic variation (the Chukotkan landscapes and Ivotuk) may have a lower classification accuracy compared to images from relatively flat landscapes, which are likely to have lower associated error and exhibit a greater degree of accuracy following the application of standard radiometric corrections described above.

Some landscapes spanned areas that have anthropogenic disturbance such as roads, runways, buildings and other structures. These areas comprised a relatively small percentage of the affected landscapes (<2%) and were masked with a 5 m buffer in Barrow where a small boardwalk approximately 1 m wide was installed 3 yr before the most recent image, and a 100 m buffer for the road and landing strip at Kougarok and Ivotuk. However, it is possible that the construction and ongoing use of these structures have influenced the direction and magnitude of change in these landscapes. The Barrow landscape in particular, contains an active (at the time of acquisition) large scale flooding and draining manipulation of a vegetated drained thaw lake basin. While the source and destination of flooding and draining were all contained within the scene, it is likely that the flooding treatment, which was larger in area than the drained treatment, resulted in an increased area of wetter land cover types, which under represents the degree of overall drying noted for this landscape (supplementary figure S7 available at stacks.iop.org/ERL/7/025502/mmedia). Nonetheless, change trends reported in this study are being used for the scaling of ecosystem processes in studies related to this work (Tweedie *et al* 2006), and many landscape scenes (Ivotuk, Kougarok, Atqasuk, Barrow) were selected to cover areas of historic and/or current research activity to aid this process. At this time, attribution of other drivers of change is difficult. High lemming populations at the time the modern Quickbird scene for Barrow was acquired could have affected vegetation cover across this landscape based on recent findings reported for the Barrow area using plot level studies focused on plant community change (Johnson *et al* 2011b, Villarreal *et al* 2012) and ecosystem function (Lara *et al* 2012). For the other landscapes investigated, climate change (Bhatt *et al* 2010) successional change associated with the thaw lake cycle (Britton 1957) and colonization of bare ground, and to a lesser extent historic off road vehicle disturbance (Barrow only) are likely to be the dominant drivers of change. These are extremely difficult to isolate without more detailed multi-temporal analysis from which the nonlinearity of change can be assessed.

It is difficult to determine whether these landscapes are regionally representative, as the study landscapes were chosen for their ease of access and relevance to historical research activity. However, the analyses were designed to normalize change relative to the time frame of investigation and the capacity for change in the historic landscapes. This is evident in our results, which show that while landscape composition was different between landscapes, and the dynamics of change was different for separate land cover classes, trends of change were similar among landscapes that were relatively close to each other. This suggests that the number and size of the landscapes studied are indicative of larger scale

change in the vicinity of the landscapes studied. Nonetheless, we are strongly supportive of additional decade-time scale land cover change research in the region at similar spatial scales so further indicators of regional representation can be addressed and the scaling of ecosystem properties and change documented at larger spatial scales can be validated. Similarly, we are strongly supportive of additional studies that examine land cover change trends at higher temporal frequencies. Analysis of multiple images at Barrow and Ivotuk showed some inconsistencies in the pattern of gain/loss of land cover types over time. With the limited resources available to make inferences about the past, it is difficult to determine the amount of change that can be attributed to interannual variability as a result of variable surface hydrological conditions or lemming population cycles for example (see Goswami 2011, Villarreal *et al* 2012). Land cover change studies at a higher temporal frequency than that used in this study are needed to isolate such factors.

Given the sensitivity of Beringian tundra to change, demonstrated through other retrospective studies (e.g. Sturm *et al* 2001, Tape *et al* 2006), long term observations (e.g. Villarreal *et al* 2012), experimental manipulations (Hollister *et al* 2005, Johnson *et al* 2011b), remote sensing (Bhatt *et al* 2010, Jia *et al* 2003), and modeling (Euskirchen *et al* 2009), it is not surprising that land cover change was documented in all of the landscapes investigated. The general trends in land cover change found here largely corroborate other change trends documented for the region. In Chukotka, for example, increases in shrub cover are similar to observations of comparable landscapes in arctic Alaska (Sturm *et al* 2001, Tape *et al* 2006). Additionally, trends in land cover change documented in this study suggest that the Chukotkan landscapes are transitioning to wetter land cover types while those in Alaska are transitioning to drier land cover types agree with the measured changes in maximum NDVI documented by Bhatt *et al* (2010). Spectrally, Goswami *et al* (2011) have shown that the presence of surface water absorbs light in the near infrared (Goswami 2011), thereby causing a reduction in NDVI. Vice versa, if there is a loss of surface water in association with general landscape drying, NDVI is likely to increase. Such patterns of landscape wetting (Chukotka) and drying (Alaska) documented in this study match, therefore, decreases and increases in NDVI documented by Bhatt *et al* (2010) for Chukotka and Alaska respectively. Drying of other landscapes on the Seward Peninsula has also been documented by Lloyd *et al* (2003) and Silapaswan *et al* (2001). Near Barrow, other studies have shown that there has been a slightly negative but non-significant trend in precipitation–evapotranspiration (P-ET) over the past few decades (Liljedahl *et al* 2011, Oechel *et al* 2000), and that aquatic and wet plant community types have been the most sensitive to change over the past four decades (Villarreal *et al* 2012).

Although some studies have inferred plant community and land cover change as possible drivers of change in ecosystem function (e.g. Oechel *et al* 2000, Chapin *et al* 2000, Wookey *et al* 2009), the impact of land cover change on ecosystem function is not well understood

in arctic landscapes, largely because historic records of ecosystem function are not available over decadal time scales. Nonetheless, multi-temporal land cover maps have been used to scale ecosystem processes spatially and temporally to interpolate likely changes in ecosystem function over such time scales (Johansson *et al* 2006). Ecosystem function can differ markedly between land cover types (Lara *et al* 2012, Oberbauer *et al* 2007), suggesting that the patterns of land cover change observed in this study could be coupled to changes in ecosystem function across the Beringia region. Such lines of investigation are beyond the scope of this immediate study but could provide new and valuable insight into landscape to regional shifts in ecosystem function and interactions between landscapes and other components of the Arctic System such as climate, and further complement larger scale modeling and remote sensing studies in the region.

5. Conclusion

This study explored the spatial and temporal dynamics of land cover change at seven locations in the Beringian Arctic using land cover classifications derived from historic high spatial resolution aerial photography, declassified military imagery, and modern Quickbird satellite imagery. Overall, Chukotkan and Alaskan landscapes appeared to be transitioning toward wetter and drier landscapes respectively, and the extent of shrub tundra and open water land cover types expanded wherever this land cover type was present. Results corroborate those from other retrospective, observational, experimental and modeling studies, and large scale change in vegetation greenness derived from satellite remote sensing. The drivers of change are difficult to attribute at this time but the changes observed suggest future change is likely and that these changes will impact ecosystem function.

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