Ecology and Evolution

Patterns of shrub expansion in Alaskan arctic river corridors suggest phase transition

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Abstract

Recent increases in deciduous shrub cover are a primary focus of terrestrial Arctic research. This study examined the historic spatial patterns of shrub expansion on the North Slope of Alaska to determine the potential for a phase transition from tundra to shrubland. We examined the historic variability of landscape-scale tall shrub expansion patterns on nine sites within river valleys in the Brooks Range and North Slope uplands (BRNS) between the 1950s and circa 2010 by calculating percent cover (PCTCOV), patch density (PADENS), patch size variability (CVSIZE), mean nearest neighbor distance (MEDIST) and the multi-scale information fractal dimension (d_I) to assess spatial homogeneity for shrub cover. We also devised conceptual models for trends in these metrics before, during, and after a phase transition, and compared these to our results. By developing a regression equation between PCTCOV and d_I and using universal critical d_I values, we derived the PCTCOV required for a phase transition to occur. All nine sites exhibited increases in PCTCOV. Five of the nine sites exhibited an increase in PADENS, seven exhibited an increase in CVSIZE, and five exhibited a decrease in MEDIST. The d_I values for each site exceeded the requirements necessary for a phase transition. Although fine-scale heterogeneity is still present, landscape-scale patterns suggest our study areas are either currently in a state of phase transition from tundra to shrubland or are progressing towards spatial homogeneity for shrubland. Our results indicate that the shrub tundra in the river valleys of the north slope of Alaska has reached a tipping point. If climate trends observed in recent decades continue, the shrub tundra will continue towards homogeneity with regard to the cover of tall shrubs.

Introduction

Recent increases in productivity and shifts in tundra vegetation composition are attributable to an increase in deciduous shrub cover (e.g. *Salix, Betula,* and *Alnus* spp.) within the shrub-tundra ecotone. This shift and its resulting biotic and abiotic feedbacks are now a primary focus of terrestrial Arctic research (Sturm et al. 2001, 2005; Chapin et al. 2005; Tape et al. 2006; Loranty et al. 2011; Myers-Smith et al. 2011). Generally, studies have focused on shrub expansion and its environmental drivers at circumpolar and regional or plot-level scales (Naito and Cairns 2011a). Circumpolar or regional scale studies have utilised the normalised difference vegetation index derived from satellite data to infer changes in productivity. These increases in productivity correlate with increases in temperature (Goetz et al. 2005; Jia et al. 2006; Pouliot et al.

2008; Verbyla 2008; Beck and Goetz 2011). Recently, regional satellite-based maps of shrub cover changes using a combination of satellite products have become available (Forbes et al. 2010; Beck and Goetz 2011; Beck et al. 2011; Frost et al. 2013). Observational and experimental work at fine spatial scales suggest that shrub development is influenced by a host of interacting factors, including temperature, hydrology, biogeochemical cycling, edaphic characteristics, disturbance, and herbivory (Walker et al. 2003; Olofsson et al. 2004; DeMarco et al. 2011; Myers-Smith et al. 2011). Also, plot-level studies have revealed that warming has promoted increases in mean canopy height and shrub height (Elmendorf et al. 2012b).

Observed patterns of shrub expansion are heterogeneous (Lantz et al. 2010b; Raynolds et al. 2012, 2013; Tape et al. 2012; Walker et al. 2012). Analysis of 202 pairs of repeat photographs across the northern Brooks

Range and North Slope uplands (BRNS) of Alaska indicated increases in shrub cover ranging from 3% to 80%, with the greatest increases occurring in floodplains and along valley slopes and only minimal changes on interfluves (Tape et al. 2006). In addition, shrub expansion patterns manifest themselves as an increase in the size (areal extent and height) and number of patches, in-filling of patches, and latitudinal and altitudinal advances (Tape et al. 2006; Hallinger et al. 2010; Myers-Smith et al. 2011). Tape et al. (2012) note both expanding and stable patches are present in Northern Alaska. Expanding patches are associated with higher resource environments (e.g., floodplains, stream corridors), while stable patches are associated with low-resource environments (e.g., shallow permafrost). Naito and Cairns (2011b) suggested that shrub expansion is promoted in areas where the potential for water throughflow and accumulation is greater. These findings collectively suggest that landscape features are important considerations when predicting the future state of the Arctic vegetation cover. Interactions between climate and landscape features may also promote nonlinear ecological responses (Burkett et al. 2005).

Although we are beginning to understand some of the processes involved in the observed changes in the Arctic shrub-tundra, the patterns of shrub change are not yet well understood, especially at the landscape scale. Landscape pattern can inform us about the trajectory of shifts between vegetation types, especially when it is considered within the context of ecological phase transition theory. Loehle et al. (1996) proposed ecological phase transition theory to explain ecotone dynamics in response to environmental change. A vegetation phase refers to the state of a dominant life-form (e.g., trees, shrubs, grasslands) that is different from other possible states in the ecosystem (Uzunov 1993; Li 2002). Uzunov (1993) defines a phase transition as "a qualitative change in the state of a system under a continuous infinitesimal change in external parameters." Therefore, shifts between vegetation phases are roughly analogous to the changes that occur between different phases of matter (Milne et al. 1996; Li 2002). In a biological system, a phase is susceptible to transition if biological or environmental variability exceeds its range of self-regulation (Gillson and Ekblom 2009). Combinations of extreme events and/or biotic and abiotic factors may cause a reorganization of ecosystem structure and function, initiating a phase transition. In such a transition, interactions are reorganised, and a new phase can emerge (Gillson and Ekblom 2009). In the context of tundra ecosystems, climatic warming is a primary external forcing that could override finer-scale processes (Chapin et al. 2005; McGuire et al. 2006; Lawrence and Swenson 2011), thereby resulting in a phase transition.

Ecological phase transition theory is based on percolation processes in thermodynamic models and employs fractal analysis to characterise ecosystem heterogeneity and ecotonal dynamics (Milne et al. 1996; Li 2000; Alados et al. 2005), making it well-suited to studying plant invasion. Critical values derived from percolation theory can be used to evaluate the potential for ecotone migration (Loehle et al. 1996). These critical values can be universally applied to detect a phase transition regardless of the spatial configuration of the invading phase or scale of analysis. As a result, they can be applied to a variety of ecotones. Phase transitions have been observed in a number of ecosystems, including the North American savannas, Mediterranean scrubland, boreal forests, and alpine treeline (Rocchini et al. 2006; Zeng and Malanson 2006; Danby and Hik 2007; Alados et al. 2009; Gillson and Ekblom 2009; Scheffer et al. 2012). Phase transition theory has not yet been applied to Arctic ecosystems.

An ecotone is a transitional area between individual phases (Loehle et al. 1996; Milne et al. 1996). Ecotones are typically situated on environmental gradients that can affect key ecological processes or organism distribution or on more gradual gradients where thresholds or nonlinear responses to these gradients can lead to significant changes in ecosystem dynamics and dominant species distribution. If environmental conditions change such that it is beneficial for one of the phases, the patch size of the focal phase will increase in the ecotone system (Risser 1995). This will lead to the invasion of previously unsuitable habitats. Since many ecotones already occur at the physiological limits of species in the adjacent communities, an external forcing like climate change could promote the invasion of one species by another (Risser 1995).

Loehle et al. (1996) used the multi-scale information fractal dimension (d_I) to characterise spatial patterns of forest spread into prairie in eastern Kansas. The d_I is a measure of deviation from spatial homogeneity used to detect phase transitions at multiple spatial scales. The median d_I describes the state of the entire landscape, and the d_I profiles provide an interpretation of landscape heterogeneity as scale changes. The d_I values range between 0 and 2, where $d_I < 1$ indicates a fragmented landscape, $1 < d_I < 2$ indicates a heterogeneous landscape, and $d_I = 2$ indicates a homogenous landscape (Loehle and Li 1996). Loehle et al. (1996) propose that an ecotone is present on a landscape for critical values $1.56 \leq d_I \leq 1.8958$; at $1.7951 \leq d_I \leq 1.8285$, the invading phase can spread to the entire landscape and initiate a phase transition. These critical values used in interpreting landscapes are based on percolation theory and can be related to percent cover using linear regression to derive critical forest percent cover values needed to initiate a

phase transition (Loehle et al. 1996). In the Kansas case, forest cover could spread to the entire landscape after reaching a critical value of 18.5%. Since their data indicated that forest cover was approaching 20%, Loehle et al. (1996) argued that their landscape was undergoing a phase transition. Our goal, here, is to apply phase transition theory to an Arctic tundra landscape to evaluate if a phase transition is occurring.

In this study, we characterised landscape patterns of Arctic shrub expansion throughout the BRNS of northern Alaska and evaluated the potential of a local-scale phase transition from tundra to shrubland. Specifically, we examined the historic variability of tall (*Alnus*, *Betula*, and *Salix* spp.) shrub expansion patterns in nine river valleys using vertical imagery at two or three dates between the 1950s and c. 2010 using pattern metric analysis and the d_I. We sought sites that encompassed both floodplains and upslope areas that include valley slopes and higher elevation interfluves. This provided an opportunity to examine previously reported patterns of expansion (Tape et al. 2006; Myers-Smith et al. 2011) within the context of phase transition theory. We focused on transition areas between shrub tundra and other tundra types on hillslopes believed to be sensitive to environmental changes (e.g., Epstein et al. 2004) and therefore susceptible to phase transition.

Methods

Study area

The BRNS comprise approximately 220,000 km^2 of land area in northern Alaska. Broad river valleys separated by interfluves are a key constituent of this landscape. The mean summer (June, July, August) temperature at Bettles Airport, Alaska is 8.02°C (SD 0.99), while the mean annual precipitation is 311 mm (National Climatic Data Center, 1955–2010 observations; available online). Vegetation assemblages are characteristic of the Arctic Bioclimate Subzone E (Walker et al. 2005). Dominant species include *Alnus* spp., *Betula glandulosa, B. nana,* and *Salix* spp. (Viereck et al. 1992; Walker et al. 2005; Tape et al. 2006). We focused on nine river valleys in the BRNS (Ayiyak, Chandler, Colville, Killik, Kurupa, Nanushuk, Nigu, and Nimiuktuk) (Fig. 1). Five of these sites correspond to ones examined in a previous study (Naito and Cairns 2011b); however, that study investigated the influence of river dynamics and topographic controls on hydrology on general patterns of shrub development.

We calculated mean annual summer air temperature values for the 55-year period for Bettles from the NCDC data air temperature values for the 55-year period for Bettles from the NCDC data and used least-squares regression to develop a linear temperature trend line. We then calculated air temperature anomalies from this trend line (Fig. 2). This trend line indicated an annual temperature increase of 0.013°C.

Image processing and vegetation mapping

We acquired digital scans of historic vertical aerial photographs (true colour, colour infrared, and panchromatic) of the BRNS sites from the United States Geological Survey Earth Resources Observation and Science (USGS EROS) website. These images were taken in the mid-1950s, 1970s, and 1980s (Table 1). These are the best data
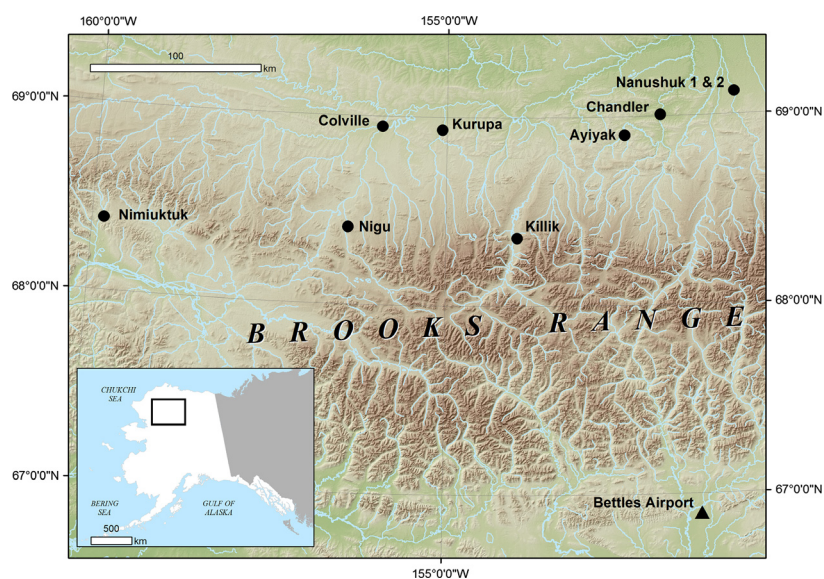

Figure 1. Location of the nine landscapes used in this study across the Brooks Range and North Slope uplands (indicated with a black circle) and the location of Bettles Airport weather station which served as the source of climate data in this study (indicated with a black triangle).
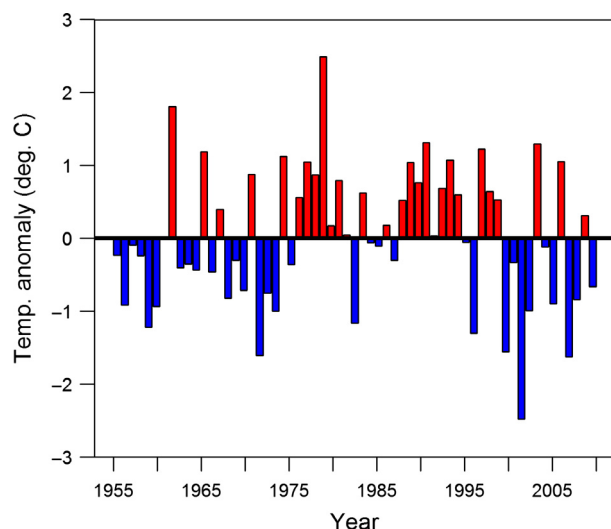
Figure 2. Anomalies from least squares trend line for averaged June-July-August (JJA) mean monthly temperatures from Bettles Airport, Alaska from 1955 to 2010. Blue bars indicate negative temperature anomalies and red bars indicated positive temperature anomalies.

available over the period of known changes in shrub cover. We also acquired nine geographically referenced and terrain-corrected archival Quick Bird-2 (QB), World-View-1 (WV), GeoEye-1 (GE), and IKONOS 2 (IK) images of these areas dating from the late 2000s (Table 1). The QB and GE images were pan-sharpened to a horizontal resolution of 0.5 m prior to purchase. The panchromatic (0.8 m native resolution) and multispectral (3.2 m native resolution) bands of the IK products were delivered separately. We pan-sharpened the IK images using the Gram-Schmidt transformation algorithm in ENVI 4.7 (Exelis Visual Information Solutions, Boulder, Colorado, USA 2009). We then co-registered the EROS imagery to the QB/WV/GE/IK imagery (satellite imagery) using ENVI 4.7. All imagery was then resampled to a common pixel resolution of 1 m.

We identified tall (>0.5 m in height) shrub patches by applying a semi-automated image classification approach to the resampled satellite imagery. Each processed image was classified using the ISODATA algorithm in ENVI 4.7 using a maximum of 20 classes and 20 iterations (*cf.* Naito and Cairns 2011b). The spectral classes in the resulting image were reclassified to informational classes designated as either 1 ("shrub") or 0 ("not-shrub"). This new classified image was overlaid on the original imagery using ArcGIS 10.1 (ESRI, 2012). Classes that most closely match shrub patches were isolated and converted to polygons that maintained the original raster boundaries at the 1 m resolution. This conversion process facilitated editing of the resulting information classes. Using visual interpretation of the original aerial image, polygons were checked

for agreement with shrubs. This was particularly important because the ISODATA procedure usually identified dark shrubs and water bodies as the same spectral class. Individual polygons representing shadows and water could then be removed. *In situ* field observations to validate the classification of the satellite imagery were not possible. However, the repeat oblique aerial photographs from Tape et al.'s (2006) study were used as a substitute for ground validation for the most recent imagery. This process was repeated for all available imagery at each site, resulting in 26 maps of shrub cover (Fig. 3).

Development of a conceptual model

We conceptualised two possible cases of landscape configurations undergoing phase transition in a 512 × 512 m quadrat (Fig. 4). These conceptual landscapes help illustrate changes in d_I and pattern metrics over time and provide a basis for comparison with the observed landscapes.

Four pattern metrics provide a means for assessing the presence and trends of the types of shrub expansion at landscape scales. These include PCTCOV (percent area covered by shrubs), PADENS (shrub patch density per ha), CVSIZE (coefficient of variation of patch size expressed as a percent), and MEDIST (mean Euclidean nearest neighbour distance between patches). CVSIZE is an indicator of variability about the mean patch size and facilitates greater comparability of patch size between landscapes of different sizes over mean patch size alone (McGarigal and Marks 1995). Based upon our results from the conceptual landscapes and previously published descriptions of shrub expansion patterns (Tape et al. 2006; Myers-Smith et al. 2011), we expected to observe an increase in PCTCOV, a variety of PADENS responses, a continual decrease in MEDIST, and an inflection of the trend in CVSIZE sometime during or after a local-scale phase transition.

Pattern metric and d_I analysis of shrub expansion maps

We rasterised the shrub maps of both the observed and conceptual landscapes to a resolution of 1 m and used FRAGSTATS 4.1 (McGarigal et al. 2012) to calculate PCTCOV, PADENS, CVSIZE, and MEDIST. We also calculated the median d_I and d_I profiles for each landscape by generating grids containing equal-sized square cells using Geospatial Modelling Environment 0.7.2.1 (Beyer 2012) and overlaying them on each landscape. Each grid consists of successively larger cell sizes, and sizes are based on a geometric sequence (e.g., 1, 2, 4, 8, ...). Each pixel in the landscape is assigned a 0 or 1 for absence or presence of the invading shrub phase. These values are divided by the total number of shrub pixels in the entire

Table 1. Description and source of the images used for study sites Ayiyak, Chandler, Colville, Killik, Kurupa, Nanushuk 1, Nanushuk 2, and Nimiuktuk.

Site specifications				Image specification			
Site	Location	Dimensions (m)	Area (ha)	Source	Type	Acquisition date	Native resolution
Ayiyak	68° 54′ 33″ N 152° 27′ 59″ W	1534 × 2048	314	USGS[1]	CIR[2]	13 Jul, 1979	0.92
				USGS	CIR	2 Aug, 1985	0.93
				GE[3]	Pan[4]	2 Jul, 2010	0.50
Chandler	69° 0′ 53″ N 151° 56′ 5″ W	2500 × 2560	640	USGS	CIR	28 Jun, 1978	0.91
				USGS	CIR	19 Aug, 1985	0.90
				WV[5]	Pan	7 Jul, 2010	0.50
Colville	68° 57′ 17″ N 155° 57′ 20″ W	2048 × 4068	944	USGS	Pan	19 Jul, 1977	0.96
				USGS	CIR	19 Aug, 1985	0.91
				QB[6]	Pan MS[7]	17 Aug, 2008	0.50
Killik	68° 22′ 15″ N 154° 0′ 54″ W	7168 × 2048	1468	USGS	CIR	1 Jun, 1978	0.88
				USGS	CIR	1 Aug, 1982	0.88
				IK2[8]	Pan MS	20 May, 2009	0.50
Kurupa	68° 55′ 53″ N 155° 4′ 56″ W	3000 × 5100	1530	USGS	CIR	26 Jul, 1977	1.00
				USGS	CIR	2 Aug, 1985	0.91
				USGS	CIR	6 Jul, 2007	0.56
Nanushuk 1	69° 9′ 12″ N 150° 52′ 50″ W	1024 × 1536	157	USGS	Pan	1 Jun, 1955	0.70
				USGS	CIR	28 Jun, 1978	0.91
				GE	Pan MS	14 Aug, 2010	0.50
Nanushuk 2	69° 7′ 21″ N 150° 51′ 29″ W	1997 × 1536	306	USGS	Pan	1 Jun, 1955	0.70
				USGS	CIR	28 Jun, 1978	0.91
				GE	Pan MS	14 Aug, 2010	0.50
Nigu	68° 25′ 38″ N 156° 25′ 27″ W	3072 × 2048	629	USGS	CIR	19 Jul, 1977	3.19
				USGS	CIR	19 Aug, 1985	1.60
				QB	Pan	5 Sep, 2008	0.50
Nimiuktuk	68° 23′ 37″ N 159° 51′ 12″ W	2560 × 2560	655	USGS	Pan	19 Jul, 1977	0.94
				GE	Pan	27 Jun, 2010	0.80

[1]USGS Earth Explorer archive image.
[2]Colour infrared image.
[3]GeoEye-1 image.
[4]Panchromatic image.
[5]WorldView 01 image.
[6]QuickBird 02 image.
[7]Panchromatic multispectral image.
[8]IKONOS 2 image.

landscape, resulting in a probability value of occupation. These probabilities are then summed for each overlying cell in an individual grid. Cells with a higher number of shrub pixels and/or have larger dimensions will therefore have a higher probability of occupation. This calculation is repeated for each grid. The d_I is then calculated by using Equation 1:

$$d_1(\varepsilon) = \frac{\Sigma_{i=1}^{K(\varepsilon)} P_i(\varepsilon)\log P_i(\varepsilon) - \Sigma_{i=1}^{K(\gamma)} P_j(\gamma)\log P_j(\gamma)}{\log\left[\frac{1}{\varepsilon}\right] - \log\left[\frac{1}{\gamma}\right]} \quad (1)$$

where P represents the probability of occupation, $K(\varepsilon)$ is the number of cells of width ε, and $K(\gamma)$ is the number of cells of the next larger cell size to ε in the geometric sequence.

We then developed a linear regression model between the median d_I value for all grids in a landscape and its corresponding PCTCOV determined from the pattern metric analysis. The Shapiro-Wilk test was used to verify normality for both the d_I and PCTCOV datasets ($P > 0.05$). This regression model was used to predict percent shrub cover required to initiate phase transition using the critical d_I values of Loehle et al. (1996).

Results

Pattern analysis of the conceptual landscapes

In the "ecotone" and "phase transition" stages for Case 1 (Fig. 5), the landscape is highly fragmented for invading shrubs at fine spatial scales (cell sizes ≤4 m). At coarser spatial scales, the landscape transitions towards spatial homogeneity. At the coarsest scales, d_I then declines as
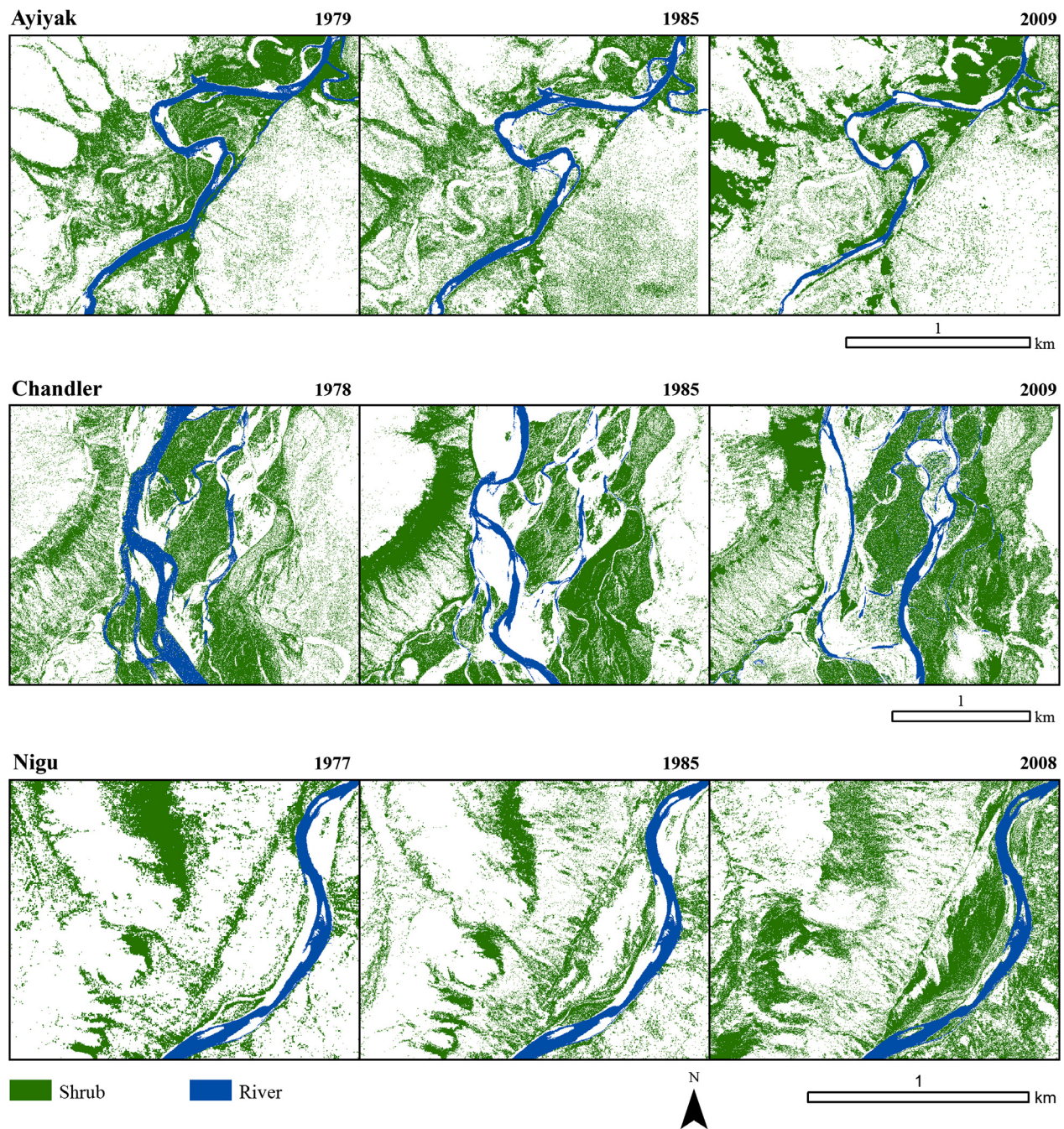
Figure 3. Shrub cover change maps for the Ayiyak, Chandler, and Nigu sites from the 1970s, 1980s and late 2000s.

the irregular distribution of shrubs is sampled (Fig. 5). In the "ecotone" and "phase transition" stages for Case 2, the landscapes are in a state of phase transition at fine spatial scales due to their clumped pattern. At coarser scales, the landscape becomes heterogeneous before transitioning towards spatial homogeneity (Fig. 5). In Case 1, PADENS peaks just before the phase transition period and CVSIZE peaks just after. MEDIST declines through-

out the time period, with the greatest decreases occurring as the landscape transitions from "fragmented" to "heterogeneous" and between the phase transition period and "spatial homogeneity" (Fig. 6). In Case 2, PADENS decreases throughout the time period. CVSIZE increases towards the phase transition period and then decreases afterwards. MEDIST also decreases throughout, with the greatest decreases occurring during the transition from
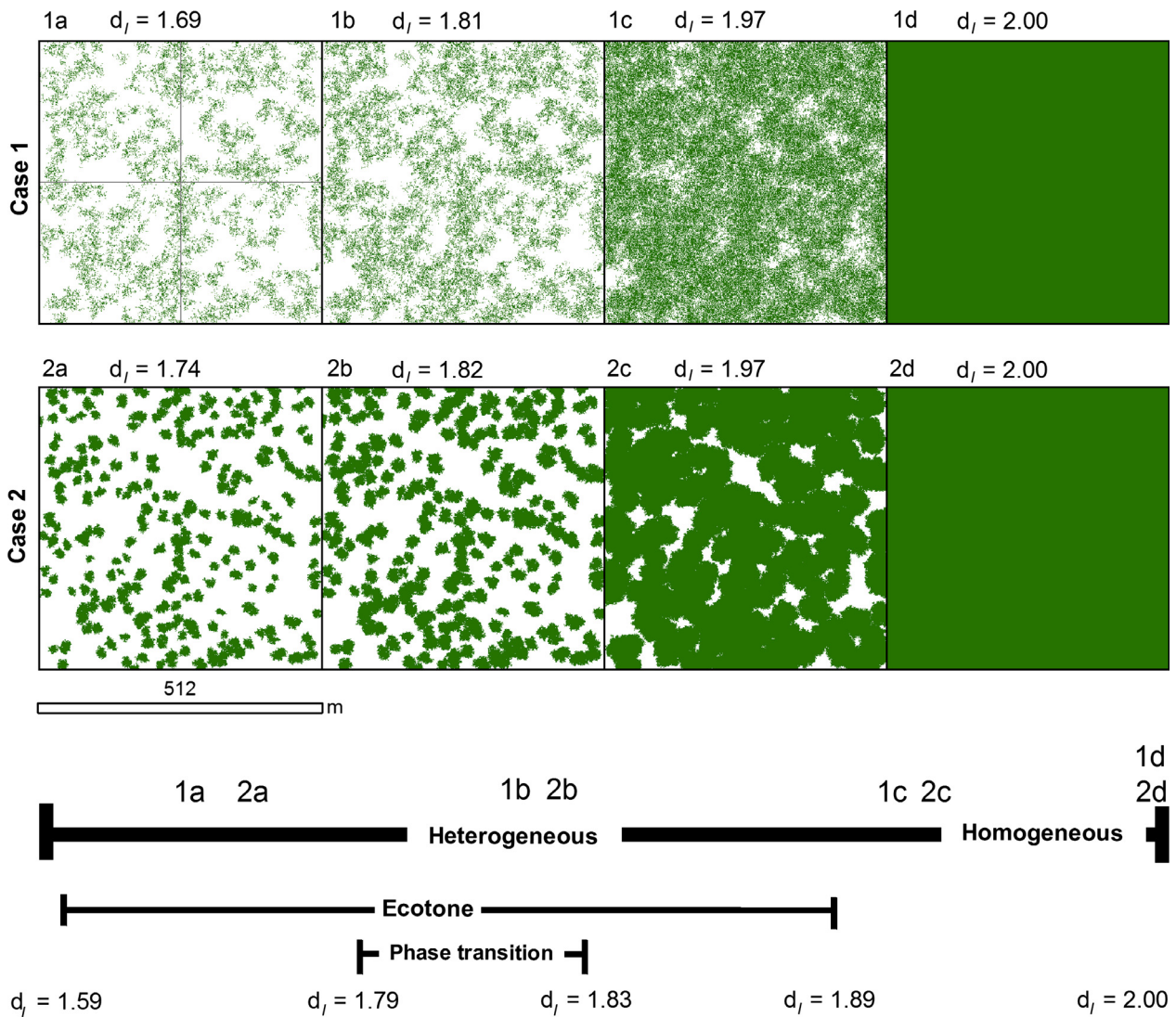
Figure 4. Conceptual maps of shrub patch dynamics at two landscapes (Case 1 and Case 2) categorized as ecotones with different configurations of the invading phase (gray pixels). As time increases from Step a to Step d, the median information fractal dimension (d_I) increases to a value of 2.00. 1a and 2a are representative of landscapes in an ecotone. 1b and 2b are representative of the landscapes in an ecological phase transition. 1c and 2c represent landscapes approaching spatial homogeneity for the invading phase. 1d and 2d represent landscapes completely homogenous for the invading phase.

"fragmented" and "heterogeneous" categories and from "phase transition" to "spatial homogeneity" (Fig. 6). Our observed landscapes and their pattern metrics should more closely match that of Case 1 due to its more heterogeneous configuration.

Pattern analysis of the observed landscapes

Net increases in PCTCOV occurred at all nine sites (Fig. 7, Table 2, Appendix 1 and 2). The average PCTCOV for the two sites in the 1950s was 32.28%. The average PCTCOV in the 1970s was 28.32%, while it was 27.32% in the 1980s. By the 2000s, the average PCTCOV was 37.44%. The greatest percent change in PCTCOV for the two landscapes with maps dating from the 1950s onwards occurred at Nanushuk 2 (+79.50%), while the smallest percent change in PCTCOV occurred at Nanushuk 1 (+51.08%). The greatest percent change in PCTCOV for the seven landscapes with maps dating from the 1970s onwards occurred at Kurupa (+85.03%), while the smallest percent change in PCTCOV occurred at Nigu (+22.51%). The average
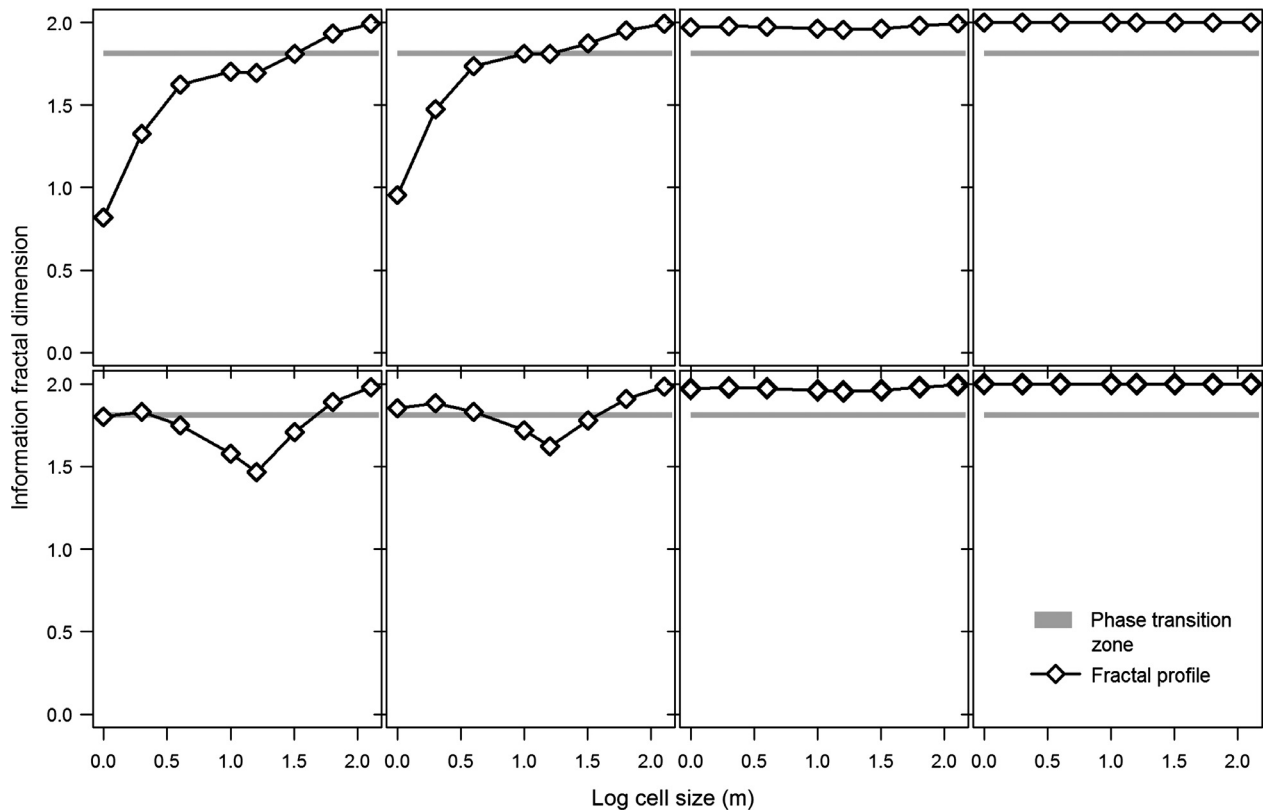
Figure 5. Information fractal dimension (d_I) profiles for the conceptual shrub patch dynamics of landscapes Case 1 and Case 2.

annual percent change in shrub cover for the sites dating from the 1950s was 1.21%/year. The average annual percent change in shrub cover for the sites dating from the 1970s was 1.29%/year.

Four sites (Killik, Nanushuk 1 and 2, and Nimiuktuk) exhibited an overall decline in PADENS ranging from −25.0 to −51.7%. The other five sites (Ayiyak, Chandler, Colville, Kurupa, and Nigu) exhibited an increase ranging from 1.8 to 59.7%. Seven sites (Ayiyak, Chandler, Colville, Killik, Kurupa, Nigu, and Nimiuktuk) exhibited an overall increase in CVSIZE, ranging from 14.8 to 518.3%. In addition, five of the sites (Ayiyak, Chandler, Colville, Killik, Nanushuk 2, and Nigu) exhibited a decrease in MEDIST, ranging from −0.3 to −3.4 m (Fig. 7, Appendix S1 and S2).

With the exception of Colville, the d_I profiles indicate that heterogeneous landscapes are present at fine spatial scales (cell size ≤2 m). As the cell size increases to the landscape-scale, the d_I becomes relatively consistent and generally exceeds the critical value for phase transition to occur (Fig. 8 and Appendix S3).

The linear relationship between d_I and PCTCOV is represented in Eq. 2:

$$d_I = 1.7853 + 0.0025(\text{PCTCOV}) \qquad (2)$$

$$R^2 = 0.5406, P < 0.001$$

Using the critical d_I values noted by Loehle et al. (1996) and Eq. 2, we calculated critical PCTCOV for each landscape (Fig. 9 and Table 2). The upper critical d_I value of 1.8286 corresponded to a PCTCOV of 17.62%. Therefore, the PCTCOV value for each landscapes at each observed date exceeded the upper critical value.

Discussion

Implications of an Arctic ecological phase transition

In this study, we applied fractal analysis of spatial pattern in a theoretical context to determine the potential for an ecological phase transition in the shrub-tundra ecotone within river valleys in northern Alaska. This type of analysis has not yet been applied to Arctic ecosystems. Based upon the median d_I values for each landscape, the results of the linear regression, and the comparison of the
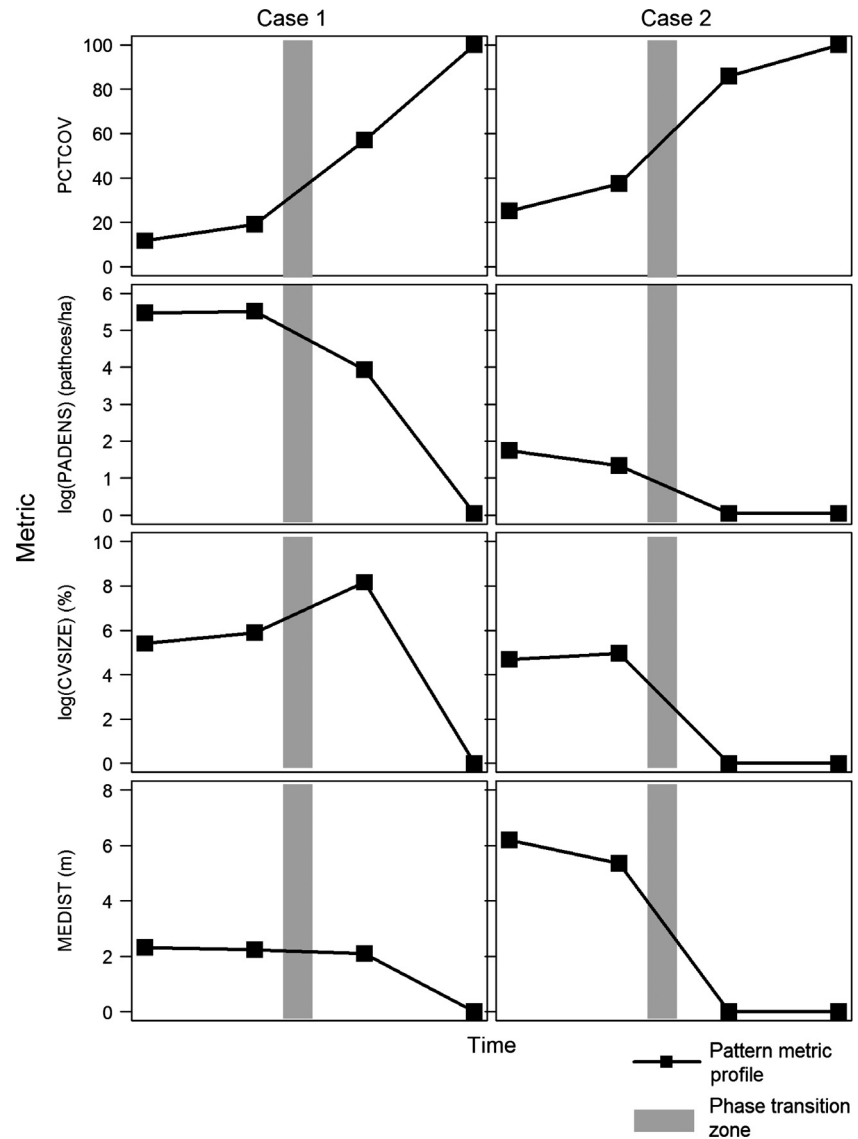
Figure 6. Changes in the pattern metrics of each of the two conceptual landscapes (Case 1 and Case 2) for percent cover (PCTCOV), patch density (PADENS), coefficient of variation of size (CVSIZE), and mean Euclidean nearest neighbor distance between patches (MEDIST). The shaded box approximates a possible phase transition period whereby the d_I ranges from 1.7951 to 1.8286.

historic pattern metric curves with the conceptual metric curves, we argue that the shrub-tundra ecotone within river valleys of the BRNS is in a state of phase transition from tundra to shrubland. Our objective in this work was not to determine or infer the mechanism of this phase transition at a landscape-scale. However, our analysis can be contextualized with recent literature examining the processes of shrub expansion and will inform future work to identify cross-scale processes and the interaction of positive and negative feedbacks (e.g., Myers-Smith et al. 2011).

The implications of this phase transition are important because the conversion of tundra to tall, canopy-forming deciduous shrub cover (e.g., *Alnus, Betula*, and *Salix* spp.) have considerable consequences for Arctic ecosystem processes and their associated feedbacks. For example, tall

shrub cover alters local nutrient availability (Cornelissen et al. 2007; Elmendorf et al. 2012a; Vankoughnett and Grogan 2014), reduces surface albedo (Bonfils et al. 2012), and promotes an increase in atmospheric heating, evapotranspiration, soil active layer depth, and permafrost degradation (Chapin et al. 2000). The expansion of shrubs is also thought to reduce erosion (Tape et al. 2011) and can shift the landscape's geomorphic threshold for change (Mann et al. 2010).

The d_I profiles suggest that the landscapes we examined are highly heterogeneous at fine spatial scales. Recent findings suggest that microsite differences (e.g., soil or permafrost conditions, snow regime, etc.) contribute to this fine-scale heterogeneity (e.g., Tape et al. 2012; Raynolds et al. 2013). Recent work (Bokhorst et al. 2010; Blok et al. 2011; Myers-Smith and Hik 2013; Vankoughnett

Table 2. Median information fractal dimension (d_I) and percent shrub cover (PCTCOV) values for each landscape for each date of observation. By the most recent date of observation, all landscapes have passed through the phase transition zone (d_I = 1.7951–1.8285) and are now progressing towards a state of homogeneity.

Landscape	Year	Median d_I	PCTCOV	Total Δ PCTCOV	Total %Δ PCTCOV
Ayiyak	1977	1.84	27.13	11.21	41.32
	1985	1.85	29.22		
	2009	1.88	38.34		
Chandler	1977	1.84	30.29	9.49	31.33
	1985	1.84	35.68		
	2009	1.96	39.78		
Colville	1975	1.84	24.56	8.56	34.85
	1985	1.86	31.79		
	2008	1.86	33.12		
Killik	1977	1.87	14.11	6.50	46.07
	1982	1.87	13.38		
	2009	1.84	20.61		
Kurupa	1977	1.8	17.3	14.71	85.03
	1985	1.88	32.41		
	2009	1.9	32.01		
Nanushuk 1	1955	1.86	30.66	51.08	51.07
	1978	1.88	38.03		
	2009	1.9	46.32		
Nanushuk 2	1955	1.87	33.9	79.50	79.50
	1978	1.92	50.64		
	2009	1.94	60.85		
Nigu	1977	1.81	25.45	22.51	22.51
	1985	1.81	21.44		
	2008	1.87	31.18		
Nimiuktuk	1977	1.86	27.35	27.09	27.10
	2009	1.91	34.76		
			Mean 1950s PCTCOV		32.28
			Mean 1970s PCTCOV		28.32
			Mean 1980s PCTCOV		27.32
			Mean 2000s PCTCOV		37.44

and Grogan 2014) has also suggested that abiotic influences of tall shrub canopy (e.g., increased shading and below-canopy snow accumulation) on nutrient dynamics and permafrost thaw is less than previously suggested (e.g., Sturm et al. 2005).

The median d_I values and general consistency of the d_I values in the fractal profiles of each landscape at coarser spatial scales (Fig. 8, Appendix S3) suggests that these landscapes can be characterized as approaching spatial homogeneity. Climatic warming is a primary driver of expansion at these scales, so continued warming will facilitate a shift towards spatial homogeneity for shrub cover. In addition, this warming trend is

thought to be an overriding factor of these finer-scale processes (Lawrence and Swenson 2011; Bonfils et al. 2012).

While the growth of low shrubs are responsive to increases in temperature, their impacts on ecosystem functioning are not as extensive. However, it is possible that pixels categorized as tall shrub cover in our study do include some low shrubs. Some of the best imagery was also panchromatic for some of our areas. Tall shrubs often appears as dark patches, but differentiating low shrub from tussock tundra can be more difficult on these images because only textural characteristics are available. The phase transition theory as proposed by Loehle et al. (1996), however, is predicated on the treatment of landscapes as binary in terms of vegetation composition. In the context of this paper, we must treat each pixel in each landscape as "shrub" and "not-shrub." We propose that this study be considered as a preliminary application of phase transition theory to an Arctic ecosystem to determine its applicability and understanding the implications for the local ecosystems.

Changes in shrub area

We observed net increases in shrub cover at all sites, and this is consistent with previous studies in the region. Loehle et al. (1996) noted that percent cover would increase dramatically during and after the phase transition. Since a transition already appears to have occurred, we could expect continued increases in shrub cover within river corridors as conditions continue to warm (Tape et al. 2006; Walker et al. 2006; Lantz et al. 2010a). Tape et al. (2006) and Lantz et al. (2010b) reported areal increases of shrub patches in the western Arctic between 1 and 6% per decade. Our decadal rates are higher likely due to a smaller total area of investigation.

It is possible that the increase in PCTCOV from the 1970s to the 1980s is a response to the positive temperature anomalies in the late 1970s. Likewise, the stabilization or slight decrease in PCTCOV from the 1980s to the late 2000s is partially a response to the fluctuations in temperature anomalies in the early 2000s (Fig. 2). However, shrub data from additional river valleys and climate data from other nearby stations will be required to more firmly establish a correlative link between temperature variability and PCTCOV.

Trends in the spatial characteristics of shrub expansion

Based upon the established types of shrub expansion (Tape et al. 2006; Myers-Smith et al. 2011), we expected to observe consistent increases in PADENS and CVSIZE,
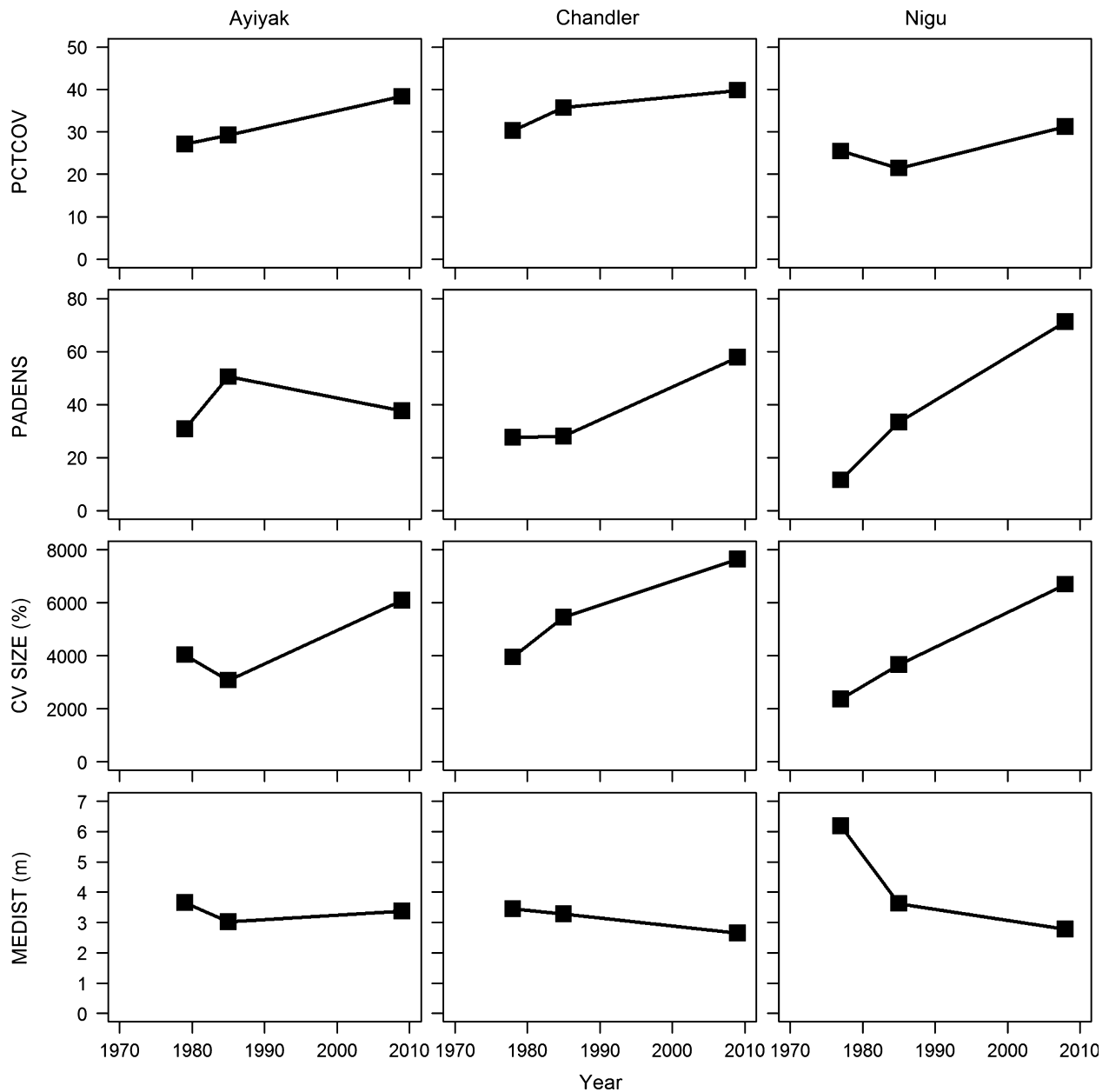
Figure 7. Observed trends in (from top to bottom) percent shrub cover (PCTCOV), patch density (PADENS), coefficient of variation of patch size (CVSIZE), and mean Euclidean nearest neighbor distance (MEDIST) for the Ayiyak, Chandler, and Nigu sites.

and a reduction in MEDIST. Our conceptual landscape results, however, suggest a reduction in PADENS during or after a phase transition, and an increase followed by a decrease in CVSIZE just after the phase transition. These conceptual models, however, do not account for environmental heterogeneity. Our results suggest that the response of PADENS, CVSIZE, and MEDIST vary from site to site, and correspond with previous findings that patterns of shrub development are heterogeneous (Tape et al. 2012). Sites for which the median d_I indicated that

a phase transition recently occurred or was in progress during the observation period generally exhibited increases in PADENS and CVSIZE (e.g., Ayiyak, Chandler, and Nigu), suggesting the acceleration of recruitment as shrubs begin to expand across the landscape. For sites with higher d_I values at the beginning of the observation period (e.g., Killik and Nimiuktuk), however, we noted better correspondence with Case 2 through reduction in PADENS and CVSIZE. This suggests that the phase transition at these sites is completing, leading to spatial
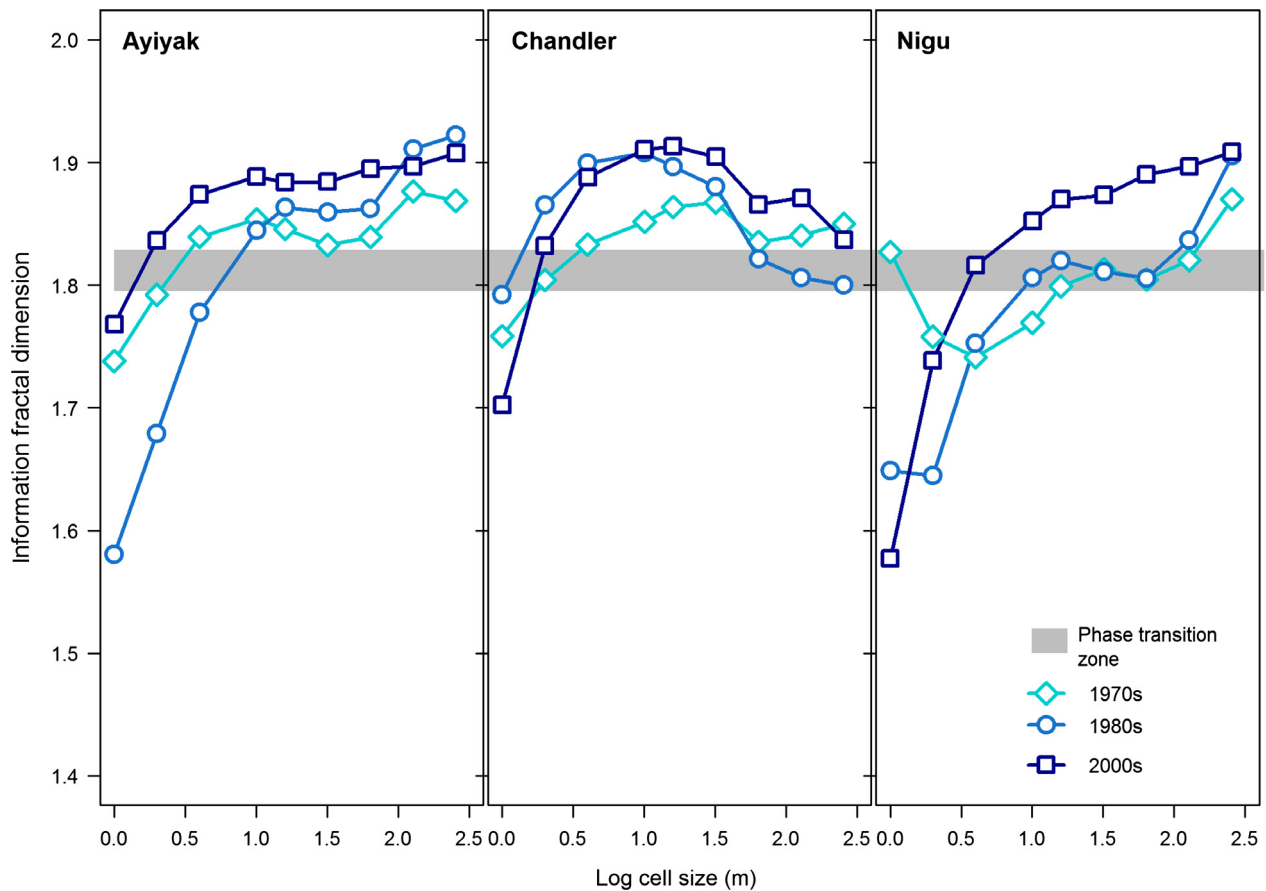
Figure 8. Information fractal dimension (d_I) profiles for the Ayiyak, Chandler, and Nigu sites.

homogeneity. Any other variability in these trends is likely due to the irregular distribution and recruitment of shrubs along the floodplains and valley slope drainage channels in response to local hydrological characteristics (e.g., Naito and Cairns 2011b). Over the period of analysis, alterations in the stream channel and the creation of sediment banks that provide new surfaces for shrub recruitment likely introduce additional variability in these trends. Although half the sites exhibited an increase in MEDIST, these increases are very small (<1 m). The unusual trend in pattern metrics at the Nigu site are attributable to the fact that the native resolution of the historical images for the Nigu site were larger than other images used in this study. We opted to present results from this work to ensure good geographic coverage across the BRNS.

Conclusion

Although fine-scale heterogeneity is still present, landscape-scale patterns suggest that our study areas are either currently in a state of phase transition from tundra to shrubland or are progressing towards spatial homogeneity for shrubland. The shrub tundra in the river valleys of the BRNS has reached a tipping point. If climate trends observed in recent decades continue, the shrub tundra within river valleys will continue towards homogeneity with regard to the cover of tall shrubs. Given current understanding of the local-scale implications for hydrology, surface energy balances, and carbon and nutrient cycling as a result of enhanced shrub cover, the completion of this phase transition will alter tundra ecosystem structure and function. Such transitions and ecosystem processes are currently being observed in other biomes.
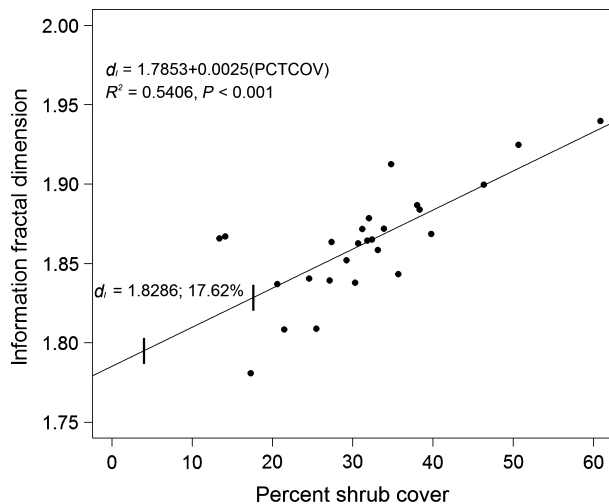
Acknowledgments

Figure 9. Scatterplot demonstrating the relationship of the information fractal dimension (d_I) for each site at each observed year with their corresponding percent shrub cover (PCTCOV). The regression line equation is $d_I = 1.7853 + 0.0025(PCTCOV)$. The vertical lines superimposed on the regression line represent the coordinates of the critical d_I values, with the upper critical value of 1.8286 and its corresponding PCTCOV labeled. All sites at all years meet or exceed this upper critical value.

Conflict of Interest

None declared.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Change in pattern metrics PCTCOV (percent shrub cover), PADENS (patch density), CVSIZE (coefficient of variation of patch size), and MEDIST (mean Euclidean nearest neighbor distance) of the Ayiyak, Chandler, Colville, Killik, and Kurupa sites.

Appendix S2. Change in pattern metrics PCTCOV (percent shrub cover), PADENS (patch density), CVSIZE (coefficient of variation of patch size), and MEDIST (mean Euclidean nearest neighbor distance) of the Nanushuk 1, Nanushuk 2, Nigu, and Nimiuktuk sites.

Appendix S3. Information fractal dimension (*dI*) profiles for all nine sites examined in this study.