Relationships between Arctic shrub dynamics and topographically derived hydrologic characteristics

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Abstract

Shrub expansion is a global phenomenon that is gaining increased attention in the Arctic. Recent work employing the use of oblique aerial photographs suggested a consistent pattern of positive change in shrub cover across the North Slope of Alaska. The greatest amounts of change occurred in valley slopes and floodplains. We studied the association between shrub cover change and topographically derived hydrologic characteristics in five areas in northern Alaska between the 1970s and 2000s. Change in total shrub cover ranged from −0.65% to 46.56%. Change in floodplain shrub cover ranged from 3.38% to 76.22%. Shrubs are preferentially expanding into areas of higher topographic wetness index (TWI) values where the potential for moisture accumulation or drainage is greater. In addition, we found that floodplain shrub development was strongly associated with high TWI values and a decreasing average distance between shrubs and the river bank. This suggests an interacting influence of substrate removal and stabilization as a consequence of increased vegetation cover.

Keywords: shrub expansion, riparian vegetation, hydrology, topographic wetness index, Arctic, Alaska

1. Introduction

Shrub expansion is a widely documented phenomenon occurring in the grasslands and savannas of North America, South America, Africa and Australia. Livestock herding, changes in land cover and land use, and climatic warming are the most widely attributed mechanisms of this expansion (Archer et al 1995, Bisigato and Bertiller 2004, Gibbens et al 2005, Jeltsch et al 1997, Van Auken 2009, Naito and Cairns 2011). Increasingly, shrub expansion is also believed to be a pan-Arctic phenomenon (e.g., Tape et al 2006). Along with sea ice melt and permafrost decline, shrub expansion is one of the most dominant and recognized components of Arctic change (Epstein et al 2000, Sturm et al 2001, Bunn et al 2005, Serreze and Francis 2006, Sturm et al 2005, McGuire et al 2006). Mechanisms of Arctic shrub expansion have largely been attributed to increasing temperatures and subsequent productivity (e.g., Myneni et al 1997, Jia et al 2003, Goetz et al 2005, Bunn and Goetz et al 2006, Walker et al 2006, Forbes et al 2010, Hallinger et al 2010) and increased soil nutrient production by microorganisms as a consequence of snowpack retention by shrubs (Jonasson et al 1999, Sturm et al 2001, Liston et al 2002, Sturm et al 2005).

Tape et al (2006) conducted what is perhaps the most expansive examination of Arctic shrub expansion on the North Slope of Alaska. Using pairs of oblique aerial photographs taken in the 1940s and early 2000s, Tape et al (2006) assessed changes in shrub cover within four distinct geomorphic divisions (floodplains, river terraces, valley slopes and interfluves) and determined that increases in shrub cover occurred within this time period. The greatest amount of change occurred in floodplains and valley slopes. In addition, Tape et al (2006) proposed three types of shrub expansion,
Figure 1. Map of the BRNS and the five areas detailed in this study.

which include increasing shrub size, increased number of patches and in-filling of shrub patches.

Shrub expansion, however, is not occurring at uniform rates throughout the Arctic, nor even within specific Arctic regions. In addition, it is not clear what may be driving shrub expansion in geomorphic units such as the floodplains or other similar riparian areas. Vegetation is closely linked to hydrologic and geomorphologic dynamics (Seyfried and Wilcox 1995). Compared to a rich literature focused on temperate zones, Arctic hydrology, riparian ecosystems and their association with geomorphologic characteristics remains understudied (e.g., Woo et al 2008, Mann et al 2010).

Riparian vegetation development is heavily influenced by water flow dynamics (Malanson 1993). Establishment of vegetation in riparian areas is contingent on a variety of fluvial processes, such as periodic flooding (Bejarano et al 2011), flooding characteristics such as flood level, flood duration, frequency, magnitude, and seasonality (Bendix and Hupp 2000, Glenz et al 2006), channel type (whether braided or meandering) (DeWine and Cooper 2007), channelization (Hupp 1992, Poff et al 1997) and physical gradients (e.g., moisture, disturbance, drought stress, sediment size, precipitation, vegetation age) (Friedman et al 2006). Long-term measurements of these characteristics provide a basis for understanding future trends in vegetation and fluvial landform development.

Beyond floodplains, variability in hydrologic conditions like soil moisture and groundwater flow is largely controlled by topographic characteristics (Sorensen et al 2006). A topographic wetness index (TWI) provides one means for assessing and characterizing these conditions. This index can be easily derived from gridded elevation data (Sorensen et al 2006) like a digital elevation model (DEM). It has been used extensively in studies of hydrologic characteristics (e.g., Beven et al 1988) and for establishing the relationship between hydrology and vegetation (e.g., Wu and Archer 2005).

We explored the relationship between Arctic shrubs and fluvial characteristics at five sites throughout the northern Brooks Range and North Slope uplands (hereafter referred to as BRNS) of Alaska previously studied by Tape et al (2006) (figure 1). Our objectives were to determine: (1) changes in area of shrubs using aerial photography, with particular focus on the floodplains, (2) the existence of an association between topographically derived hydrologic characteristics (using the TWI as a proxy) and shrub expansion within each of the four geomorphic units proposed by Tape et al (2006), and (3) develop a relationship between fluvial characteristics derived from aerial photography and vegetation dynamics. In the case of objective 2, we sought to objectively determine whether frequency distributions of TWI values differed among geomorphic unit types. Fluvial characteristics that we assessed included channel width and the average distance between areas undergoing shrub cover change and the river bank.

2. Methods

2.1. Study area

The BRNS occupies approximately 220,000 km² in northern Alaska. The basin is bound by the Arctic coastal plain in the north, the Brooks Range in the south, the Noatak and Kokolik Rivers in the west, and the Jago River in the east. Several river valleys separated by higher elevation interfluvies are key characteristics of this landscape. The basin lies largely within the low Arctic, a vegetation zone dominated by dwarf shrubs (Walker et al 2005). Typical shrub species include Alnus viridis (Chaix) ssp. crispa (Aiton) Turrill, Betula nana L., Salix glauca L., and S. pulchra Cham. (Walker 2000, Tape et al 2006, USDA NRCS 2011). Streams, floodplains, and associated riparian areas are a key constituent of Arctic terrestrial ecosystems. We examined five areas in the BRNS
2.2. Aerial photograph acquisition and processing

Digital scans (14 \( \mu \)m scanning resolution) of 9\(^\circ\) × 9\(^\circ\) historic vertical aerial photographs for the five sites were acquired from the United States Geological Survey Earth Resources Observation and Science (USGS EROS) (table 1). QuickBird/Worldview (QB-02) (0.5 m resolution), GeoEye-1, and IKONOS-2 (0.5–0.8 m resolution) (GE-1 and IK-2) imagery for each site was also acquired from archives at DigitalGlobe, Inc and the GeoEye Foundation (table 1). The QB-02 imagery is a pan-sharpened multispectral product. In the case of the GE-1 and IK-2 products, the panchromatic and multispectral bands were acquired separately. The multispectral bands for GE-1 and IK-2 were pan-sharpened in ENVI 4.7 (ITT Visual Information Solutions 2009) using the Gram–Schmidt transformation. These high-resolution images are preferred because they facilitate visual interpretation of landscape characteristics and can serve as a source for spatially referencing other imagery (e.g., Lantz et al 2010). Ancillary information from ground control point networks and high-resolution elevation data sets are not available in northern Alaska.

The USGS EROS photographs from the 1970s were processed and georeferenced to the QB-02/GE-1/IK-2 imagery using 80–100 ground control points and the Delaunay triangulation transformation (figure 2(a)). The USGS and QB-02/GE-1/IK-2 images were then resampled to a pixel resolution of 1 m. Shrub patches were identified and delineated on both sets of imagery using the Iterative self-organizing data analysis (ISODATA) unsupervised classification algorithm in ENVI 4.7 with a maximum of 20 classes and 20 iterations (figure 2(b)). Spectral classes most closely resembling shrubs were isolated and converted to polygons using a minimum mapping unit of 1 m (figure 2(c)). Errors in classification were corrected manually using visual interpretation by overlaying the polygons on the images within a Geographic Information System developed using ArcGIS 9.3.1 (ESRI 2009) and checked for correspondence. Shrub polygons in each map were then classified as present (1) or absent (0) (figure 2(d)). This procedure was then repeated for the next available image at each site. The process of converting the shrub spectral classes to polygons was used only to aid in the correction process, and polygons were not simplified in order to preserve the original raster boundaries. We did not distinguish among shrub genera because of similarities in their spectral characteristics as apparent on the aerial photographs (e.g., Robinson et al 2008). Change detection between the two final raster maps for each site was facilitated by using map algebra to ‘subtract’ the 2000s map from the 1970s map. The resulting maps classified pixels into one of three categories (1, 0, and −1), representing gain, no change, and loss, respectively (figure 2(e)).

We used digital copies of the oblique photograph pairs used in Tape et al (2006) to assess the accuracy of our classification of shrubs in the 2000s. In this situation, oblique aerial photographs provided the best source for ground information as shrub patches depicted in these photographs are clearly distinguishable from the underlying tundra matrix. The area covered by shrubs in each raster map was calculated using FRAGSTATS 3.3 (McGarigal et al 2002).

2.3. TWI preparation and analysis

The association between the presence of shrubs and hydrological characteristics as a function of topography was investigated using the TWI proposed by Beven and Kirkby (1979). This index is defined as the natural log of the ratio between the upslope contributing area (\( a \)) and slope per cent (\( b \)), and is represented as an equation by:

\[
\text{TWI} = \ln(a/\tan b). \tag{1}
\]

Pixels possessing larger TWI values are located in areas with a greater upslope catchment area (large value of \( a \)), and have more potential to be wetter than surrounding areas (Wu and Archer 2005). Specifically, areas of high values can either be well-drained (high value of \( a \) and \( b \)) or relatively stagnant due to a minimal slope gradation (small value of \( b \)) (Zinke et al 2005). In the context of the BRNS, valley

| Site | Location | Source | Date of acquisition | Type | Native pixel resolution (m) |
|------|----------|--------|---------------------|------|-----------------------------|
| A    | 68° 23′ 37.238″N | USGS AP\(^a\) | 19 July, 1977 | CIR\(^b\) | 0.94 |
|      | 159° 51′ 12.340″W | GE-1\(^c\) | 21 May, 2010 | Pan MS\(^d\) | 0.80/3.22 |
| B    | 68° 57′ 17.027″N | USGS AP | 22 June, 1974 | Pan\(^e\) | 1.9 |
|      | 155° 57′ 19.575″W | QB-02\(^f\) | 17 August, 2008 | Pan MS | 0.5 |
| C    | 68° 22′ 15.233″N | USGS AP | 1 June, 1978 | CIR | 0.88 |
|      | 154° 0′ 54.060″W | GE-1 | 20 May, 2009 | Pan MS | 0.50/2.00 |
| D    | 69° 9′ 12.244″N | IK-2\(^g\) | 28 June, 1978 | CIR | 0.91 |
|      | 150° 52′ 49.995″W | USGS AP | 14 August, 2010 | Pan MS | 0.50/2.00 |
| E    | 69° 7′ 21.369″N | IK-2 | 28 June, 1978 | CIR | 0.91 |
|      | 150° 51′ 28.544″W | USGS AP | 14 August, 2010 | Pan MS | 0.50/2.00 |

\(^a\) United States Geological Survey aerial photograph. \(^b\) Color infrared image. \(^c\) GeoEye-1 satellite. \(^d\) Panchromatic-sharpened multispectral image. \(^e\) Panchromatic (black and white) image. \(^f\) QuickBird 02 satellite. \(^g\) IKONOS-2 satellite.
Figure 2. Procedure for processing and classifying digital images, and associating classified shrubs with the TWI. (a) Panchromatic aerial photograph of Colville River from 1977 georectified to pan-sharpened color QuickBird image from 2008. (b) Spectral classes on 2008 image identified by ISODATA classification algorithm. (c) Isolated spectral classes from (b) most closely representing shrubs. (d) Corrected polygons from (c) converted to presence (green) and absence (white). (e) Difference map identifying gain (blue), loss (red), or no change (yellow) in shrub cover between 1977 and 2008. (f) Calculated TWI index from digital elevation model of same area. Lighter shades are representative of progressively higher TWI values.

Mosaics of 1 arc-s, 30.88 m resolution ASTER GDEM of the North Slope were acquired from the Alaska Mapped Statewide Digital Mapping Initiative. The TWI index was calculated using the TauDEM 5.0 (Terrain Analysis Using Digital Elevation Models) software suite (Tarboton 2010) using the Dinf flow direction calculation method (Tarboton 1997). TWI values were then binned into integer categories ranging from 0–21 (figure 2(f)).

The Geospatial Modeling Environment (GME) (Beyer 2009) software was used to generate 2000 randomly selected points within each study area. Each point was then spatially associated to its corresponding pixel values for the difference map (1, 0, −1) and TWI map. Points from each site were then merged into one dataset.

Statistical tests were carried out using S-PLUS 8.1 (TIBCO 2008). Because the data were not normally distributed, non-parametric Kruskal–Wallis and Wilcoxon rank-sum tests were used to determine the significance of shifts in the frequency distribution of TWI values within each change category.

2.4. Regression analysis

Spectral classes created by the ISODATA process most closely matching the river channels were isolated and converted to polygons. These polygon features were collapsed into single centerlines that extended the longitudinal length of the main channel of the river. GME was used to generate points at 5 m intervals along the centerlines. These served as the origins for lines perpendicular to the center that extended to the banks of the river. The lengths of these lines were then calculated within the GIS to determine channel width at each point along the centerline. Distance from the river bank was determined by generating raster layers representing straight-line Euclidean distance from the river polygon boundaries using the ArcGIS Spatial Analyst (ESRI 2009).

Sample points from the TWI analysis were subset to those present only in the floodplains. Points associated with no change in shrub cover were removed from this subset. The remaining points were then spatially associated with the distance raster layers. Floodplain sample points were matched with their closest river centerline point to determine the distance to a river and the width of the river at that point. Each floodplain sample point therefore contained attributes representing binomial change in shrub cover, TWI value, distance from the river bank in the 1970s and 2000s, and river channel width. Additional attributes were created for bank distance and channel width differences between the two decades. These attributes were used to create a binomial generalized linear model using logistic regression in S-PLUS 8.1 (TIBCO 2008).
3. Results

3.1. Changes in shrub cover

Four out of the five sites we examined experienced an increase in shrub cover, while one site experienced a subtle decrease. An increase in shrub cover within floodplains also occurred within all five areas, and ranged from +3.38% (site D) to +76.22% (site A) (table 2 and figure 3).

3.2. Association between shrub cover changes and TWI

Of the 10000 total sampled points from the five areas we examined, 14.9% underwent an increase in shrub cover (conversion from tundra to shrub), 12.42% underwent a decrease (conversion from shrub to tundra), and 72.68% experienced no change (10.76% in shrub to shrub, and 61.92% tundra to tundra). All frequency distributions of TWI values in each study area were non-normally distributed ($K = 0.1655$, $p < 0.01$). The Kruskal–Wallis rank-sum test highlighted statistically significant differences among the categories ($\chi^2 = 17.07, p = 0.0002$). Wilcoxon rank-sum tests determined that TWI frequency distributions for sampled points that gained shrub cover were significantly higher than those that lost cover ($Z = 2.1006, p = 0.0178$) as well as those experiencing no change ($Z = 4.1085, p < 0.01$) (figure 2).

3.3. Association between floodplain shrub dynamics and fluvial characteristics

Binomial logistic regression of variables related to shrub cover, TWI values and river channel characteristics suggests a relationship between the development of floodplain shrubs and migration of the river channel. The model statistics are described in table 3. The difference in distance between

Table 2. Change in area of shrub patches between years. Per cent of change and annual per cent rate of change in cover between years is provided in the bold columns.

| Study area | Total area of shrubs (ha) | Area of floodplain shrubs (ha) |
|------------|--------------------------|--------------------------------|
|            | 1970s | 2000s | % change | Annual % rate of change | 1970s | 2000s | % change | Annual % rate of change |
| A          | 252.89 | 287.25 | 13.59 | 0.41 | 62.29 | 109.77 | 76.22 | 2.31 |
| B          | 274.17 | 361.59 | 31.89 | 0.94 | 188.28 | 224.04 | 19 | 0.56 |
| C          | 241.14 | 353.43 | 46.56 | 1.50 | 29.34 | 42.89 | 46.17 | 1.49 |
| D          | 103.26 | 102.59 | 0.65 | -0.02 | 52.92 | 54.71 | 3.38 | 0.12 |
| E          | 129.79 | 166.65 | 28.4 | 0.89 | 60.8 | 93.09 | 53.1 | 1.66 |

Figure 3. Maps of each of the five study areas detailing TWI values in relation to change in shrub cover between the 1970s and 2000s. Note the areas classified as ‘gain’ are generally spatially associated with areas of high TWI values. Such values typically occur in drainage channels or flatlands.
Table 3. Model statistics for the generalized linear model using logistic regression. The GLM formula is indicated by: GLNC ~ DIFF.DIST + TWI + WIDTH.1970 + DIFF.WID, where GLNC represents the value for shrub cover change (−1, 0, 1), DIFF.DIST represents the difference in the distance between shrubs and the river bank between the 1970s and 2000s, TWI is the topographic wetness index value, WIDTH.1970 is the width of the river bank in 1970, and DIFF.WID is the difference in the width of the river channel between the 1970s and 2000s. SE represents standard error, and df represents degrees of freedom.

| Coefficients | Analysis of deviance | p |
|--------------|----------------------|---|
| Variable     | Value                | t-value | df  | Deviance | Residual df | Residual deviance |
| DIFF.DIST    | 0.0015                | 3.1813  | 1   | 14.6035  | 1044        | 1425.498          | 0.0001 |
| TWI          | 0.0717                | 2.4938  | 1   | 7.6162   | 1043        | 1417.882          | 0.0058 |
| WIDTH.1970   | 0.0009                | 0.4951  | 1   | 1.6617   | 1042        | 1416.22           | 0.1974 |
| DIFF.WID     | −0.0001               | −0.0659 | 1   | 0.0043   | 1041        | 1416.216          | 0.9474 |

sampled shrubs and the location of the nearest river bank (Wald \( \chi^2 = 10.12, p = 0.0001 \)) and the TWI value (Wald \( \chi^2 = 6.22, p = 0.005 \)) provide the greatest explanatory power. The floodplain TWI values ranged from 4 to 18, with a median value of 8. The median distance between river bank and shrub cover decreased from 54.47 m in the 1970s to 37.71 m in the late 2000s. Differences in river channel width were not significant.

4. Discussion

4.1. Changes in shrub cover

Our results regarding shrub expansion characteristics on the North Slope largely agree with the findings of Tape et al. (2006). Their visual analysis of repeat oblique aerial photographs revealed that shrub cover change across the North Slope between the late 1940s and early 2000s ranged from +3 to +80%. With the exception of site D, total shrub cover change in our study falls well within this range. Total shrub cover figures for the 2000s in sites A and C are likely to be underestimates. These images were acquired in May, and snow patches were still visible on the ground, particularly on valley slopes and interfluvies. Snow covers 2.23% of the 2010 image in site A and 1.3% of the 2009 image in site C.

4.2. Associations between shrub dynamics and fluvial characteristics on valley slopes

The TWI index was useful for inferring relationships between vegetation, hydrology, and geomorphology. Our non-parametric statistical testing suggests a significant association between shrub development and topographically derived hydrologic characteristics. Since the 1970s, shrubs have generally expanded into areas of greater TWI values. This means that shrubs are preferentially developing in areas that have a greater potential for accumulating moisture. Visual inspection of the aerial images confirms that valley slope shrubs are expanding upslope along hill slope water tracks (sensu McNamara et al. 1999). These drainages are typically shallower than the neighboring hill slopes and serve as the primary route for downhill water migration. The TWI captures these features by representing them with higher index values. Future studies incorporating the use of a TWI in conjunction with modeling and field measurements will help to assess potential impacts on the hydrology of the Arctic system.

4.3. Association between shrub expansion/development and floodplain characteristics

The binomial logistic regression shows that positive change in floodplain shrub cover is associated with: (1) a decreasing distance between shrubs and the river bank, and (2) preferential expansion onto areas with high TWI values. Given that we observed a net increase in shrub cover, we conclude that the overall median distance between shrubs and the river banks will continue to decrease as expansion continues.

Visual inspection of the aerial photographs suggests that, while unvegetated sediment bars are visible along the river course in the 1970s, many of these have disappeared by the 2000s. This could be attributed to deposits providing a substrate for primary succession of shrubs (e.g., Douglas 1989), erosion of these deposits by the river channels, or channel migration (e.g., Konrad et al. 2011). Since the two mass-wasting events during the Pleistocene–Holocene transition (Mann et al. 2010), rivers in northern Alaska have become increasingly decoupled from valley slope sediment inputs. While deposition and erosion of sediment still occur, the rivers have transported much of the sediment input from those events (Mann et al. 2010). This suggests that overall sediment input has decreased over time, thereby reducing overall sediment loads in the channels. The presence of vegetation can stabilize otherwise ephemeral features like sediment bars, reducing their susceptibility to erosion (Konrad et al. 2011). This has the effect of restricting channel migration.

Warming Arctic temperatures will lead to earlier river ice break up and later freeze-up, thereby increasing evapotranspiration. Prowse et al. (2006) argue that this will lead to diminished surface water and will be compounded by increased infiltration as a result of permafrost loss. The consequence of this will be reduced spring peak flows (Prowse et al. 2006) and potentially less flood-induced disturbance. This would likely improve survivorship of floodplain shrubs.

5. Conclusion

Shrubs are preferentially expanding into areas with greater potential for high drainage or moisture accumulation. Positive change in shrub cover is associated with both higher TWI values and a decrease in the distance to the river bank. Considering the rapid terrestrial changes occurring as a result...
of climatic warming, refining our understanding of the linkages between vegetation development and hydrology is critical to predicting the future state of the Arctic.

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