Remote Sensing of Environment 205 (2018) 46–55

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Climate and nutrient effects on Arctic wetland plant phenology observed from phenocams

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ARTICLE INFO

Keywords:
Phenocams
Arctic wetlands
Ponds
Aquatic plants
Nutrients
Greenness
Biomass
NDVI
Time lapse
Climate variability
Carex aquatilis
Arctophila fulva

ABSTRACT

This study explores how climate and nutrients influence productivity of arctic wetland plants. The Green-excess Index (GEI) derived from Red, Green and Blue digital image brightness values from digital repeat photography (a.k.a. phenocams) was used to track the inter-annual variability in seasonal greening and above ground biomass for two dominant aquatic emergent graminoids on the Arctic Coastal Plain of northern Alaska: *Carex aquatilis* and *Arctophila fulva*. Four years of seasonal and inter-annual greening trends show strong differences in timing and intensity of greenness among species. Thawing degree-days (TDD, days above 0 °C) was a good predictor of GEI in both *A. fulva* and *C. aquatilis*. Employing regression tree analyses, we found a greening threshold of 46 TDD for *A. fulva*, after which GEI increased markedly, while *C. aquatilis* greened more gradually with a greening mid-point of 31 TDD. Based on long-term climate records and TDD thresholds, greening date has begun 16 thawing degree-days earlier over the past 70 years. To understand the effects of latitude and nutrients on seasonal greening, we compared southern sites and nutrient enriched sites with reference sites. We found statistically higher greenness in southern sites and enriched sites compare to reference sites in both plant species, supporting the role of nutrients and warmer temperatures as key factors enhancing productivity in arctic wetlands. In addition, this study provides an inexpensive, alternative method to monitor climate and nutrient effects at high frequency in arctic aquatic systems through camera-derived GEI greenness and has the potential to bridge the gap between plot level and satellite based observations given its strong relationships with biomass and NDVI.

1. Introduction

Wetlands represent a significant portion of the Arctic landscape (Lehner and Döll, 2004; Woo and Young, 2006; Avis et al., 2011; Melton et al., 2013). These systems are characterized by supporting aquatic vegetation through saturated hydrological conditions and ponding of water sustained by the shallow permafrost layer (Cowardin et al., 1979). These systems are oasis for productivity in this polar desert environment where timing, extent, and magnitude of plant primary productivity play a fundamental role in arctic hydrology, carbon fluxes and energy balance (Prowse et al., 2006; Westergaard-Nielsen et al., 2013; Andresen and Lougheed, 2015). For example, the increase in wetland plant biomass and cover in tundra ponds over recent decades (Andresen and Lougheed, 2015), has been associated with increased nutrient availability (Lougheed et al., 2011; Reyes and Lougheed, 2015) and longer thaw season, resulting in a significant rise of methane emissions to the atmosphere (Andresen et al., 2017). With the continuing and projected warming of the Arctic over the next century, there is uncertainty with respect to how changes in plant biomass and phenology in Arctic wetlands will contribute to or mitigate warming. Given the increasingly realized importance of arctic change on global processes (Hinzman et al., 2013), documenting these responses to shifts in climate is essential for assessing potential climatic feedbacks at regional and global scales.

Plot-scale phenological measurements can provide detailed observations on seasonal trends and changes at the species-level (Elmendorf et al., 2012; Oberbauer et al., 2013). However, plot-level measurements are often labor-intensive and logistically difficult in the Arctic. Spectral vegetation indices from satellite-based remote sensing, such as the Normalized Difference Vegetation Index (NDVI), have shown to be a reliable method for estimating regional and continental scale changes in Arctic greening (Bhatt et al., 2010; Epstein et al., 2012; Walker et al., 2012). However, the limited temporal coverage and persistent cloud cover in the Arctic restricts detailed seasonal satellite observations (Stow et al., 2004). Furthermore, the majority of publicly available imagery also lacks the geospatial accuracy and resolution

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https://doi.org/10.1016/j.rse.2017.11.013
Received 15 May 2017; Received in revised form 6 November 2017; Accepted 10 November 2017

required for time series analysis of discreet plant communities (Andresen et al., 2017). Defining novel technologies to advance understanding of fine-scale phenological dynamics in the highly heterogeneous and remote region of the Arctic tundra landscape is needed to address these challenges. Technological advances in sensor systems and instrument platforms to monitor phenological dynamics such as handheld spectrometers and thermal cameras, have been become increasingly popular recent years (Healey et al., 2014). However, these systems are often costly and highly technical, limiting their use in ecological studies. Therefore, there is a need to develop cost- and time-efficient mid-scale methods suitable for tracking seasonal and inter-annual plant biomass trends and bridging the gap between plot and satellite-level observations (Nijland et al., 2016).

Repeat photography has become a well-sourced tool for documenting long-term changes in Arctic vegetation (Sturm et al., 2001; Tape et al., 2006; Callaghan et al., 2011; Villarreal et al., 2012), including aquatic systems (Smol and Douglas, 2007; Andresen and Lougheed, 2015; Andresen et al., 2017). However, these camera systems have not yet been used to assess seasonal dynamics. Mostly outside the Arctic, analysis of digital time-lapse photography (phenocam imagery) has developed as a favored method for near-surface remote sensing and generally provides high spatial and temporal resolution for the characterization of plant phenophase development and greenness as proxies of plant biomass (Richardson et al., 2009; Brown et al., 2016). Previous studies have employed commercial phenocams to assess seasonal and inter-annual greening trends in a wide range of ecosystems including desert scrublands (Kurc and Benton, 2010), subalpine grassland (Migliavacca et al., 2011), low Arctic fen (Westergaard-Nielsen et al., 2013) and forests (Richardson et al., 2009; Elmore et al., 2012; Keenan et al., 2014; Nagai et al., 2016). Greenness indices derived from Red-Green-Blue (RGB) color space such as the green excess index (GEI) and the green chromatic coordinate (G%) have proven to be good indicators of gross primary production (GPP) and leaf area index (LAI) (Ahrends et al., 2009; Richardson et al., 2009; Saitoh et al., 2012; Keenan et al., 2014). To our knowledge, no studies have directly linked RGB indices to aboveground biomass nor tested its potential in vegetated aquatic systems. Additionally, this technology appears to not have been used for assessing plant phenological responses to different environmental conditions, such as gradients of temperature and nutrients, which are key determinants of ecosystem carbon balance in arctic tundra plant communities (Walker et al., 2006; Epstein et al., 2012). Nutrients in particular, have been increasing over the past four decades in tundra ponds (Lougheed et al., 2011) boosting plant growth and methane emissions (Andresen and Lougheed, 2015; Andresen et al., 2017). However, little is known about how nutrients affect seasonal changes in timing and intensity of greening and senescing in Arctic tundra wetlands. Therefore, it is imperative to understand and characterize nutrient effects in aquatic plant phenology and develop novel methods to identify and monitor these effects.

In this multi-year study, focused on wetlands in the northern Arctic Coastal Plain of Alaska, we evaluate the effectiveness of time-lapse digital photography as a novel automated and cost-effective method to assess:

(i) Seasonal and inter-annual greening patterns of aquatic emergent graminoids,
(ii) The effects of latitude and nutrient gradients on the timing and magnitude of wetland plant greenness, and
(iii) The relationship between phenocam-derived greenness, biomass and NDVI derived from a hyperspectral spectrometer.

2. Methods

2.1. Research site

This study was located on the Arctic Coastal Plain area near Utqiaġvik (formerly known as Barrow) and Atqasuk, Alaska. The region is characterized by its low-relief, deep permafrost, shallow thaw depth, and the dominance of thaw lakes and basins that contain numerous wetlands and ponds (Hinkel et al., 2003; Lougheed et al., 2011; Andresen and Lougheed, 2015). This Arctic landscape (~71° latitude) is known for its short snow-free growing season lasting approximately three months from early June to the beginning of September with an average summer temperature of 4 °C. The annual vegetation growing cycle starts with warmer temperatures and 24 h of light in late May-early June triggering snow melt, and thawing of the active layer, suitable conditions for plant growth. Peak growing season is usually reached in late July–early August followed by senescence and decreasing temperature and daylight hours (Gamon et al., 2013). In late September, snow starts covering the vegetated areas and ice develops gradually freezing shallow ponds and wetlands systems throughout the water column.

Aquatic vegetation communities in the Arctic Coastal Plain are dominated by two emergent graminoids: *Arctophila fulva* and *Carex aquatilis*. *A. fulva* has a wide distribution across Arctic and Boreal regions, and is common in inundated landscapes where competition from other species is lacking (Dobson, 1989). *Carex aquatilis* is known for its wide distribution across northern hemisphere wetland habitats. These perennial species usually grow in pure stands with depth preference of 16.2 cm for *A. fulva* and 4.5 cm for *C. aquatilis* and (Andresen and Lougheed, 2015) and are the most important primary producers in Utqiaġvik tundra ponds (McRoy and Leue, 1973). Both species have been noted to be increasing in both areal cover and tiller density in the Utqiaġvik area (Andresen et al., 2017).

For the purpose of this study, we monitored nine tundra pond sites (Table 1), including five sites that were representative reference sites for Utqiaġvik, AK (IBP-J, IBP-C, IBP-10, ITEX-N, WL03), one nutrient enriched thermokarst pond (TK3), one nutrient enriched urban pond (BOXER) and two ponds located approximately 100 km south of Utqiaġvik near the village of Atqasuk, AK (ATQ-E, ATQ-W). Given that Utqiaġvik air temperature is expected to continue its upward trajectory over the next century and air temperature in Atqasuk is ~4 °C warmer than Utqiaġvik (http://climate.gi.alaska.edu/), we used sites in Atqasuk as a proxy for the future state of Utqiaġvik ponds. All ponds in this study contained *A. fulva* and *C. aquatilis*, except for ponds IBP-C and TK3, which contained only *C. aquatilis*. Three representative sites (IBP-C, J, 10) were monitored for three or four consecutive years, while the remaining sites were only monitored in 2013.

2.2. Nutrient enriched sites

Enriched urban ponds (e.g. Boxer) are located within the town of Barrow, AK and their source of nutrients is mainly from urban runoff. Enriched thermokarst ponds (e.g. TK3) were situated within the Barrow Environmental Observatory (BEO), and their nutrient inputs originate

Table 1
Location and classification of sites sampled in this study. Plant types include *Arctophila fulva* (A) and *Carex aquatilis* (C).

Site	Type	Latitude	Longitude	Plant type	Years
IBP-10	Reference	71.293500	− 156.704330	A, C	2011–2013
IBP-J*	Reference	71.293630	− 156.701440	A, C	2010–2013
IBP-C*	Reference	71.294600	− 156.702100	C	2010–2013
ITEX-N	Reference	71.318140	− 156.583220	A, C	2013
WL03	Reference	71.282300	− 156.616250	A, C	2013
TK3	Enriched Thermokarst	71.273980	− 156.636431	C	2013
BOXER	Enriched Urban	71.303620	− 156.752594	A, C	2013
ATQ-E	Lower Latitude	70.447892	− 157.362756	A, C	2013
ATQ-W	Lower Latitude	70.457525	− 157.401083	A, C	2013

*Sites with Wingscapes BirdCam; all others sites used TimeLapseCam.