Remote Sensing of Environment 177 (2016) 160–170

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Latitudinal gradient of spruce forest understory and tundra phenology in Alaska as observed from satellite and ground-based data

Hideki Kobayashi [a,*], Ali P. Yunus [a,b], Shin Nagai [a], Konosuke Sugiura [a,h], Yongwon Kim [e], Brie Van Dam [c], Hirohiko Nagano [e], Donatella Zona [g,i], Yoshinobu Harazono [d,e], M. Syndonia Bret-Harte [c], Kazuhito Ichii [a], Hiroki Ikawa [e], Hiroki Iwata [f], Walter C. Oechel [g,j], Masahito Ueyama [d], Rikie Suzuki [a]

[a] *Department of Environmental Geochemical Cycle Research, Japan Agency for Marine-Earth Science and Technology, Japan*
[b] *Department of Natural Environmental Studies, The University of Tokyo, Japan*
[c] *Toolik Field Station, Institute of Arctic Biology, University of Alaska, Fairbanks, United States*
[d] *Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Japan*
[e] *International Arctic Research Center, University of Alaska Fairbanks, Alaska, United States*
[f] *Faculty of Science, Shinshu University, Japan*
[g] *Global Change Research Group, San Diego State University, United States*
[h] *Center for Far Eastern Studies, University of Toyama, Japan*
[i] *Department of Animal and Plant Science, University of Sheffield, UK*
[j] *Department of Environment, Earth, and Ecosystems, Open University, Milton Keynes, UK*

ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form 4 February 2016
Accepted 10 February 2016
Available online xxxx

Keywords:
Autumn phenology
Satellite SOS and EOS
Radiative transfer analysis
Alaska
Time-lapse camera
Tundra
Boreal forest
Understory vegetation

ABSTRACT

The latitudinal gradient of the start of the growing season (SOS) and the end of the growing season (EOS) were quantified in Alaska (61°N to 71°N) using satellite-based and ground-based datasets. The Alaskan evergreen needleleaf forests are sparse and the understory vegetation has a substantial impact on the satellite signal. We evaluated SOS and EOS of understory and tundra vegetation using time-lapse camera images. From the comparison of three SOS algorithms for determining SOS from two satellite datasets (SPOT-VEGETATION and Terra-MODIS), we found that the satellite-based SOS timing was consistent with the leaf emergence of the forest understory and tundra vegetation. The ensemble average of SOS over all satellite algorithms can be used as a measure of spring leaf emergence for understory and tundra vegetation. In contrast, the relationship between the ground-based and satellite-based EOSs was not as strong as that of SOS both for boreal forest and tundra sites because of the large biases between those two EOSs (19 to 26 days). The satellite-based EOS was more relevant to snowfall events than the senescence of understory or tundra. The plant canopy radiative transfer simulation suggested that 84–86% of the NDVI seasonal amplitude could be a reasonable threshold for the EOS determination. The latitudinal gradients of SOS and EOS evaluated by the satellite and ground data were consistent and the satellite-derived SOS and EOS were 3.5 to 5.7 days degree^{-1} and -2.3 to -2.7 days degree^{-1}, which corresponded to the spring (May) temperature sensitivity of -2.5 to -3.9 days °C^{-1} in SOS and the autumn (August and September) temperature sensitivity of 3.0 to 4.6 days °C^{-1} in EOS. This demonstrates the possible impact of phenology in spruce forest understory and tundra ecosystems in response to climate change in the warming Artic and sub-Arctic regions.

1. Introduction

In the Arctic and sub-Arctic regions, including Alaska, warming trends have been accelerating and the increased trend in surface temperature in the region over the past decade is twofold higher than that in the whole northern hemisphere (Bekryaev, Polyakov, & Alexeev, 2010; Hinzman et al., 2013; IPCC, 2013). It is of particular interest whether the carbon uptake by terrestrial vegetation increases or decreases due to the change in phenology under climate change (Barichivich et al., 2013; Forkel et al., 2016; Goetz, Bunn, Fiske, & Houghton, 2005; Oechel, Laskowski, Burba, Gioli, & Kalhori, 2014) because the impact of earlier spring onset could be moderated by enhanced ecosystem respiration in the prolonged autumn period (Piao et al., 2008; Ueyama, Iwata, & Harazono, 2014).

Observation and modeling of start of growing season (SOS), end of growing season (EOS), and growing season length provide essential information on how terrestrial vegetation responds to climate changes (Buermann et al., 2014; Keenan et al., 2014; Nagai et al., 2013b; Piao

---

[*] Corresponding author at: 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan.
E-mail address: hkoba@jamstec.go.jp (H. Kobayashi).

http://dx.doi.org/10.1016/j.rse.2016.02.020

et al., 2011; Richardson et al., 2013b; Schwartz, Ault, & Betancourt, 2013; Verbyla, 2008; Xu et al., 2013). In the Arctic and sub-Arctic regions, the earlier SOS trends were found in previous studies (Buermann et al., 2014; Delbart et al., 2008; Hogda, Tommervik, & Karlsen, 2013; Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; Piao et al., 2011). On the other hand, a relatively limited amount of information is available on large-scale EOS variations and its long-term trends (Jeong & Medvigy, 2014). Recent studies have found a trend for later EOS in many zones in Europe (Garonna et al., 2014), North America (Zhu et al., 2012), and for temperate vegetation over the northern hemisphere (Jeong, Ho, Gim, & Brown, 2011), suggesting that rising temperature could affect the phenological events. However, the environmental factors (e.g. photoperiods and temperature changes) that control the changes in EOS are not clearly understood (Delpierre et al., 2009; Jeong & Medvigy, 2014; Richardson et al., 2013a).

The estimation of SOS and EOS utilizes the seasonal patterns in satellite vegetation indices (VIs). In the Arctic and sub-Arctic regions, an increase in the normalized difference vegetation index (NDVI) (green-up) in spring is partially affected by the timing of snowmelt (Dye & Tucker, 2003; Jonsson, Eklundh, Hellstrom, Barring, & Jonsson, 2010; Kobayashi, Delbart, Suzuki, & Kushida, 2010; Kobayashi, Suzuki, & Kobayashi, 2007; Suzuki, Kobayashi, Delbart, Asanuma, & Hiyama, 2011). A systematic bias has also been found at EOS, and snow is thought to affect the satellite-based EOS estimation (Zhu et al., 2012); however, it has not been investigated quantitatively.

Because boreal forests in Alaska are sparser than forests in lower latitudes (Canada and the U.S.), the seasonality of understory plants has a substantial impact on satellite signals (Pisek & Chen, 2009; Rautiainen & Heiskanen, 2013; Yang, Kobayashi, Suzuki, & Nasahara, 2014). In interior Alaska, black and white spruce are the dominant species. The spectral reflectance of these species with evergreen needles is relatively unchanged throughout the growing season (Nagai et al., 2012), while it is likely that satellite phenology metrics should be greatly influenced by understory plant phenology. However, how the satellite-based phenology metrics are influenced by the forest overstory status, understory plant phenology and other factors such as snow and observation conditions remains less investigated in Alaska. Thus, comparisons with ground-based datasets are essential. Time-lapse camera images provide the seasonal information on surface conditions and have been used widely for the detection of phenological events at ground level (Richardson et al., 2007; Woebbecke, Meyer, Vonbargen, & Mortensen, 1995).

In this study, we quantified the latitudinal gradient of SOS, EOS, and the timing of snow cover in Alaska using ground-based time-lapse digital camera images, and then compared these events with SOS and EOS determined using the satellite data. In the ground-based analysis, we used firsthand time-lapse camera images obtained at 17 sites (six tundra sites and eleven boreal evergreen forest sites) along a latitudinal transect through the state of Alaska, USA (61°N to 71°N), which covers the boreal forest and tundra ecosystems (Fig. 1). We evaluated SOS and EOS by the three phenology algorithms using two satellite datasets (Terra-moderate resolution imaging spectroradiometer (MODIS) and SPOT-VEGETATION). Through the comparison, we investigated the discrepancies in satellite phenology metrics and the influence of snow and understory phenology in tundra and boreal forests. To quantitatively evaluate those impacts, we performed a detailed radiative transfer simulation.

2. Materials and methods

2.1. Study area

The study sites are distributed on a north–south transect across Alaska between a latitudinal range of 61°N to 71°N (Fig. 1). All ground observation sites are within a longitudinal band between 144°W to 157°W. These sites contain two distinct ecosystems: evergreen needleleaf forest and tundra. Evergreen needleleaf forests are found in the south of the Brooks Range (68°N), while the tundra ecosystem is typical of the north. The dominant overstory tree species in interior Alaska is black spruce (*Picea mariana*). Most of the understory layer is covered with rusty peat moss (*Sphagnum fuscum*) and splendid feather moss (*Hylocomium splendens*). The colors of rusty peat moss and splendid feather moss vary spatially and seasonally (brown to green). The understory layer is also partly covered with tussocks formed by herbaceous perennial cotton-grass (*Eriophorum vaginatum*) (Kim, Kodama, Shim, & Kushida, 2014; Nakai et al., 2013). The dominant vascular plants of the understory are low shrubs and herbs such as Labrador tea (*Ledum groenlandicum*), bog bilberry (*Vaccinium uliginosum*), dwarf birch (*Betula nana*), and cloudberry (*Rubus chamaemorus*) (Kim et al., 2014; Nakai et al., 2013). These vascular plants are deciduous. The camera observation sites in the tundra are located in heath tundra and moist acidic tundra areas. The moist acidic tussock tundra is dominated by tussock sedge (*Eriophorum vaginatum*), and dwarf shrubs (*Betura nana*, *Carex bigelowii*, *Vaccinium vitis-idaea*, and *Ledum palustre*) (Euskirchen, Bret-Harte, Scott, Edgar, & Shaver, 2012; Kim et al., 2014; Oechel et al., 2014). The dry heath tundra is dominated by *Dryas* spp., lichen, and dwarf shrubs (Environmental Data Center Team, 2014; Euskirchen et al., 2012).

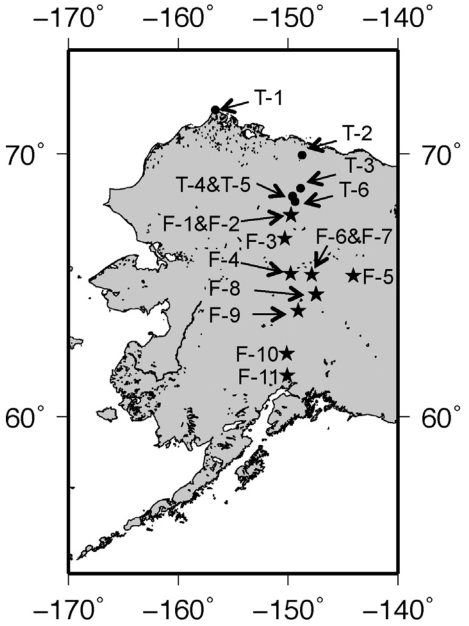

Fig. 1. Geographical distribution of the time-lapse camera locations. Black circles are tundra sites and the stars are forest sites. Full site names are provided in Table 1. Some camera images for individual sites are provided in the supplemental figure.

2.2. Datasets

2.2.1. Time-lapse photography

We used time-lapse camera images obtained from 17 sites across Alaska (Table 1 & Fig. 1). The 6 northern sites (denoted as T-1 to T-6) are located in tundra and the other 11 sites are in boreal forests (denoted as F-1 to F-11). At these sites, there are three different time-lapse camera systems: GardenWatchCams (Brinno Inc., Taiwan), webcams, and a fish-eye camera (Nikon Coolpix 4500 with an FC-E8 fisheye lens) (Table 1). These camera systems took the images of tundra and forest understory vegetation at a nadir or horizontal view. The sampling interval was from 15 min to 6 h depending on the camera setting. Images that were bright enough to obtain color information and in which there were no distinct sunlit or shade variations were selected.