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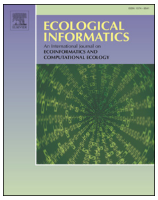

Utilization of ground-based digital photography for the evaluation of seasonal changes in the aboveground green biomass and foliage phenology in a grassland ecosystem

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ABSTRACT

We investigated the usefulness of a ground-based digital photography to evaluate seasonal changes in the aboveground green biomass and foliage phenology in a short-grass grassland in Japan. For ground-truthing purposes, the ecological variables of aboveground green biomass and spectral reflectance of aboveground plant parts were also measured monthly. Seasonal change in a camera-based index (rG: ratio of green channel) reflected the characteristic events of the foliage phenology such as the leaf-flush and leaf senescence. In addition, the seasonal pattern of the rG was similar to that of the aboveground green biomass throughout the year. Moreover, there was a positive linear relationship between rG and aboveground green biomass ($R^2 = 0.81$, $p < 0.05$), as was the case with spectra-based vegetation indices. On the basis of these results, we conclude that continuous observation using digital cameras is a useful tool that is less labor intensive than conventional methods for estimating aboveground green biomass and monitoring foliage phenology in short-grass grasslands in Japan.

1. Introduction

Grassland ecosystems, which are estimated to cover from 41 to 56 million km^2 or from 31% to 43% of the Earth's land surface, are ranked with forest ecosystems as the main terrestrial ecosystems (Scurlock and Hall, 1998; White et al., 2000). In East Asia, grassland ecosystems are widely distributed in alpine areas and semiarid regions (e.g., the Tibetan and Mongolian Plateaus [Ni, 2002; White et al., 2000; Xiao et al., 1995]). These grasslands provide livelihoods to local residents and serve as carbon sinks and/or sources in the carbon budget (Fang et al., 2007; Ni, 2002; Xiao et al., 1995). However, recent studies have reported that environmental changes such as global warming, overgrazing, and land-use change can alter vegetation and ecosystem functions (e.g., carbon cycle) in these grasslands (Cao et al., 2004; Ma et al., 2010). Because uptake of CO_2 by plants might be the only sustainable way of removing CO_2 from the atmosphere (Eisfelder et al., 2012; Trumper et al., 2008), it is important to conduct quantitative studies of the aboveground plant biomass and the length of the plants' growing seasons in order to predict the response of the carbon cycle to future environmental changes accurately. To achieve these aims, it is necessary to establish techniques for long-term and continuous in situ observations of the spatial and temporal variations in foliage phenology and plant biomass (Eisfelder et al., 2012).

Previous observations of foliage phenology and plant biomass in grasslands fall into two main classes: (1) investigations of a specific area based on conventional ground-based observations, such as clipping and weighing of aboveground plant biomass and direct observations of leaves to detect plant phenological events (e.g., Dhital et al., 2010a,b; Ma et al., 2010; Xiao et al., 1996; Zhang and Skarpe, 1996); and (2) regional or global scale investigations based on satellite remote-sensing observations (e.g., Kawamura et al., 2005; Xu et al., 2008; Yang et al., 2009). Although conventional ground-based observation is the most accurate way to collect biomass data in a fixed area, this approach is both time consuming and labor intensive (Lu, 2006). Therefore, it would be difficult to gather continuous measurements over a wide area using conventional observation techniques (Eisfelder et al., 2012; Ide and Oguma, 2010; Richardson et al., 2009). In contrast, satellite-based monitoring requires little labor and is suitable for the continuous observation of spatial and temporal changes in terrestrial ecosystem structure (e.g., foliage phenology) at regional or global scales (Akiyama and Kawamura, 2007; Eisfelder et al., 2012; Lu, 2006). However, satellite data acquisition is limited by cloud cover and atmospheric conditions (Ide and Oguma, 2010;

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Muraoka et al., 2012; Nagai et al., 2010). Thus, each approach has its strengths and weaknesses. For continuous, long-term, and accurate evaluations of spatial and temporal variations in ecosystem structure and functions at a large scale, it is important to integrate ground-truthing into the study design, that is, to combine ground-based observations and satellite remote sensing, which allows the scaling-up from a specific area to a regional or global scale (Muraoka et al., 2012).

To bridge the gap between ground-based observations and satellite remote sensing, researchers have begun to focus on near-surface remote-sensing techniques (e.g., Ahrends et al., 2008, 2009; Crimmins and Crimmins, 2008). Among these, most researchers have used the technique that utilizes the red, green, and blue channels of digital numbers (RGBs) extracted from digital repeat photographs taken by tower-mounted digital cameras (e.g., Ide and Oguma, 2010; Nagai et al., 2011; Richardson et al., 2009; Sonnentag et al., 2012). Seasonal changes in vegetation indices calculated from RGBs (camera-based vegetation indices) were closely related to seasonal changes in leaf phenology (i.e., the timing of the leaf-flush and leaf-fall [e.g., Ahrends et al., 2009; Nagai et al., 2011; Richardson et al., 2007]), gross primary production (e.g., Richardson et al., 2009; Saitoh et al., 2012), and the spectral reflectance estimated by a spectroradiometer system (Saitoh et al., 2012). Because digital cameras are relatively inexpensive and easy to use, as compared with other equipments (e.g., spectroradiometer system), they can be used as components of a worldwide network to allow continuous, large-scale, and highly precise monitoring of ecological and environmental variations in an array of ecosystems (Graham et al., 2010; Ide and Oguma, 2010; Nishida, 2007; Richardson et al., 2007). Moreover, such a system can provide ground-truthing of data gathered by satellite remote sensing (Graham et al., 2010; Nagai et al., 2011; Saitoh et al., 2012). However, most previous digital photography studies focused on forest ecosystems (e.g., Ahrends et al., 2009; Richardson et al., 2009; Sonnentag et al., 2012). Few studies have used the digital repeat photography to monitor the temporal variation in grassland structure and function (Migliavacca et al., 2011). Moreover, few such studies have examined the relationship between the plant biomass and the camera data (VanAmburg et al., 2006).

To validate the usefulness of the ground-based digital photography approach in grasslands, we performed 2 years of continuous monitoring with a digital camera and gathered monthly measurements of ecological variables (aboveground green biomass and spectral reflectance of aboveground plant parts) throughout a single year in a short-grass grassland in central Japan. We investigated the relationships between a camera-based vegetation index and these ecological variables. The objectives of this study were (1) to test how well the seasonal changes in each RGB channel obtained from the digital repeat photography or a camera-based vegetation index reflect the temporal variations in ecosystem structure (foliage phenology and aboveground green biomass) in the grassland; and (2) to validate the usefulness of the ground-based digital photography for continuous observations of grassland ecosystems.

2. Methods

2.1. Site description and study period

Our study site is a short-grass grassland located in the central mountain region of Japan (36°08′N, 137°26′E, 1340 m a.s.l.). The grassland is maintained by cattle grazing from May to October. The vegetation consisted primarily of *Zoysia japonica*, but *Ranunculus japonicus* and *Trifolium repens* were also common (Dhital et al., 2010a). The grass height can range from 5 to 10 cm. The annual mean air temperature and annual cumulative precipitation from 1997 to 2006 were 7.2 °C and 2151 mm, respectively (Inoue and Koizumi, 2012). The snow season usually begins in late December and ends in early April. More information about this site is provided by Dhital et al. (2010a,b) and Inoue and Koizumi (2012).

We established a 20 m × 20 m experimental area on a south-facing slope (about 16°) of the study site. The present study was conducted from early May 2010 to early December 2011 (except during the snow season, which extended from late December 2010 to mid-April 2011).

2.2. Observation of foliage phenology using a digital camera system

To observe the foliage phenology, we mounted a digital camera system (Nishida, 2007) on a stand at the site, facing east and providing a view of the whole experimental area. The placement of the system was fixed during the study period. The camera system consisted of a digital camera (Coolpix 4500; Nikon, Tokyo, Japan), a recording controller (SPC31A; Hayasaka Rikoh, Sapporo, Japan), and a lithium-ion battery (Y00-00250, Enax Inc., Tokyo, Japan). Image size was set to 2272 × 1704 pixels. All images were captured with automatic exposure, and the white balance set to “auto.” The images were saved in JPEG format. The observation periods were from 6 May (day of year: DOY 126) to 21 December (DOY 355) in 2010 and from 27 April (DOY 117) to 7 December (DOY 341) in 2011. The images were captured at 4-hour intervals between 00:00 and 24:00 h (Japan Standard Time: JST) each day. The timing of the start of leaf-flush (S_{LF}), end of leaf-flush (E_{LF}), start of leaf senescence (S_{LS}), and end of leaf senescence (E_{LS}) was detected by visual inspection of the images. We defined the timings of S_{LF}, E_{LF}, S_{LS}, and E_{LS} as the first day when 10% of leaves had flushed, the first day when 90% of leaves had flushed, the first day when 10% of leaves were withered, and the first day when 90% of leaves were withered, respectively.

2.3. Calculation of the camera-based vegetation indices

We selected one photo that was captured around noon (between 10:30 and 15:30 h JST) per day for the image analysis (see Appendix A for a detailed description). As determined by visual inspection, the images obtained on rainy or foggy days were removed because of noise in the RGB channels. Moreover, some images were also removed from the analysis because of dirt on the camera housing window. In the end, we used 127 and 151 images for the analysis in 2010 and 2011, respectively.

The red, green, and blue channels of digital numbers (DN_R, DN_G, and DN_B, respectively) were extracted from each pixel of an image. We then calculated the averages of DN_R, DN_G, and DN_B within the regions of interest, an example of which is demarcated in white in Fig. 1. These analyses were conducted with the free geographic information system software GRASS GIS (http://grass.osgeo.org). Because both weather conditions (i.e., sunny or cloudy) and solar altitude vary during a day and over each season, the illumination conditions at around noon at the site may not always be equal (Saitoh et al., 2012). To avoid the effects of these variations on the RGBs, we calculated the normalized RGBs (ratios of DN_R, DN_G, and DN_B as percentages of total DN) by using Eqs. (1) to (3). In addition, we used Eq. (4) to calculate the green excess index (GEI), which has been reported as a useful index to evaluate the variation in foliage phenology (e.g., timing of leaf flush) more precisely than the individual RGB channels (Richardson et al., 2007).

$$rR = DN_R/(DN_R + DN_G + DN_B) \tag{1}$$

$$rG = DN_G/(DN_R + DN_G + DN_B) \tag{2}$$