Detection of the different characteristics of year-to-year variation in foliage phenology among deciduous broad-leaved tree species by using daily continuous canopy surface images

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ABSTRACT

Clarification of species-specific year-to-year variations of the timings of the start of leaf-expansion (S_{LE}) and the end of leaf-fall (E_{LF}) is an important and challenging task because these timings may alter spatial and temporal variations in ecosystem services such as carbon stock and climate control. Although many previous studies have applied automatically captured digital camera images to observe the timings of S_{LE} and E_{LF}, the evaluation of the long-term variation in both timings of each tree species based on image analysis has not yet been sufficiently investigated. In this study, we investigated the year-to-year variation in the timings of S_{LE} and E_{LF} for multiple deciduous broad-leaved tree species in a cool-temperate deciduous broad-leaved forest in Japan by using long-term and daily hemispherical ("fish-eye") canopy surface images from 2004 to 2013. We found that (1) differences in the characteristics of year-to-year variations in the timing of E_{LF} among the tree species were more apparent than those of the timing of S_{LE} among the tree species, (2) the threshold value of the camera-based index (green excess index) for detecting the timing of E_{LF} varied depending on the spatial and temporal distribution of understories and the visual distortion of the fish-eye images, and (3) the phenological sensitivity of the timing of E_{LF} to air temperature was lower than that of the timing of S_{LE}. Our results indicate that it might be helpful for ecologists to use daily continuous canopy surface images for monitoring of species-specific characteristics of spatial and temporal changes in foliage phenology in mixed-species deciduous broad-leaved forests.

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1. Introduction

Changes in plant phenology, such as advanced or delayed timings of the start of leaf-expansion (S_{LE}) and the end of leaf-fall (E_{LF}) (e.g., Cong et al., 2013; Jeong et al., 2011; Zeng et al., 2011), may alter ecosystem functions such as water, energy, and carbon exchanges between the land surface and the atmosphere in terrestrial ecosystems by changing physical properties (e.g., solar albedo and evapotranspiration) and biological processes (e.g., CO_2 uptake by photosynthesis) (Barford et al., 2001; Churkina et al., 2005; Lawrence and Slingo, 2004a,b; Myneni et al., 1997). Long-term trends of advanced S_{LE} and delayed E_{LF} showed different characteristics among each region at a continental scale. For example, the long-term trend of delayed E_{LF} (e.g., 2.2 days per

decade from 1986 to 2005 in China [Chen and Xu, 2012], and 1.6 days per decade from 1959 to 1993 in Europe [Menzel and Fabian, 1999]) was slower than the long-term trend of advanced S_{LE} (e.g., 4 days per decade from 1986 to 2005 in China [Chen and Xu, 2012], and 2.0 days per decade from 1959 to 1993 in Europe [Menzel and Fabian, 1999]) in temperate climate regions across Europe and China, whereas the long-term trend of delayed E_{LF} (1.6 days per decade from 1953 to 2000 [Matsumoto et al., 2003] and 2.7 days per decade from 1961 to 2011 [Nagai et al., 2013a]) was faster than the long-term trend of advanced S_{LE} (0.9 days per decade from 1953 to 2000 [Matsumoto et al., 2003]) in Japan. These local phenological changes may alter ecosystem services, such as carbon stock and climate control, on a regional to a global scale (Peñuelas et al., 2009).

Sensitivity of foliage phenology under environmental changes shows different characteristics among temperate deciduous tree species (Fu et al., 2013; Morin et al., 2010; Vitasse et al., 2009a,b). For instance, Vitasse et al. (2009a) reported that the phenological sensitivity of leaf unfolding to temperature for oak was stronger than that for beech in southern France. These differences in species-specific

phenological response to environmental changes may affect the competition for light among the tree species, and it may also therefore affect the distribution of tree species in temperate mixed-species deciduous forests (Kramer et al., 2000). Urbanski et al. (2007) suggested that the change of spatial distribution of tree species might alter the net ecosystem production in a mixed deciduous forest. These reports suggest that consideration of the differences in the species-specific phenological response to environmental change in each region would provide us with useful information to predict the response of ecosystem services to rapid environmental change.

Recently, automatically captured digital camera images have been applied to continuous phenological observations because such observations make it possible to collect automated data at high temporal resolution in multiple ecosystems with low operating costs (e.g., Alberton et al., 2014; Crimmins and Crimmins, 2008; Migliavacca et al., 2011; Richardson et al., 2007; Sonnentag et al., 2012). Temporal changes in RGB color information (the digital intensity value of red, green, and blue), which is extracted from the images, allow researchers to detect foliage phenological changes such as leaf-expansion and leaf senescence (e.g., Henneken et al., 2013; Ide and Oguma, 2010; Nagai et al., 2013b; Zhao et al., 2012). Some studies have used the greenness index for estimation of the green-up date (Ahrends et al., 2008, 2009; Ide and Oguma, 2010; Richardson et al., 2007). Although the image-analysis methods for the detection of the timing of phenological changes, such as leaf-expansion, leaf-coloring, and leaf-fall, have been developed by such previous studies (e.g., Nagai et al., 2011), the evaluation of the long-term variation in the timings of these phenological events in each deciduous tree species based on this type of image analysis has not yet been sufficiently investigated.

In this study, (1) we investigated the year-to-year variation in the timings of S_{LE} and E_{LF} for four tree species (redvein maple: *Acer rufinerve*, Erman's birch: *Betula ermanii*, Miyama cherry: *Prunus maximowiczii*, and white oak: *Quercus crispula*) in a cool-temperate deciduous broad-leaved forest in Japan by using daily continuous canopy surface images from 2004 to 2013, (2) we also investigated the differences of the phenological sensitivity in the timings of S_{LE} and E_{LF} to air temperature among the tree species, and (3) we discussed the usefulness and problems of using canopy surface images for phenological observations in a forest ecosystem. Our aim was to provide robust evidence of the usefulness of daily continuous canopy surface images for continuous observation of the interannual variation in foliage phenology among various tree species within a deciduous broad-leaved forest.

2. Methods

2.1. Study site

The study site is located in a cool-temperate deciduous broad-leaved forest in Takayama, Japan (TKY site; 36°08′46″N, 137°25′23″E, 1420 m above sea level; Nagai et al., 2013a). The dominant tree species are 50–60-year-old *Q. crispula* and *B. ermanii* (Ohtsuka et al., 2009). The height of the dominant trees ranges from 13 to 20 m (Nasahara et al., 2008). An evergreen dwarf bamboo species (*Sasa senanensis*) covers the forest floor, and its height is about 1.5 m (Ohtsuka et al., 2009). The annual mean air temperature and annual mean precipitation are 7.2 °C and 2151 mm, respectively (Inoue et al., 2012). The snow season begins in late December and ends in early April. Snow depth is usually 1–2 m during the snow season (Ohtsuka et al., 2005). A more detailed description of the TKY site is provided by Ohtsuka et al. (2005, 2009). The present study was conducted from 29 March 2004 (day of year [DOY] 89) to 31 December 2013 (DOY 365). The monthly mean air temperatures from our study period are shown in Appendix A. Detailed description of the meteorological data at the TKY site was described in Nagai et al. (2013a).

2.2. Canopy surface images

We have installed a downward-facing automatic-capturing digital fish-eye camera system at the top of a tower at the study site (18 m above ground level) (Nagai et al., 2011). The camera system consists of a commercial digital camera (Coolpix 4500, Nikon Corporation, Tokyo, Japan), a fish-eye lens (FC-E8, Nikon Corporation; field of view 180°), and a controller (SPC31A; Hayasaka Rikoh, Sapporo, Japan). The camera system captured hemispherical images of the forest canopy every 90 min during the daytime every day during the study period. Image size, stored format, and exposure were set to 2272 × 1704 pixels, JPEG, and "automatic", respectively. The white balance of images was set to "Sunny", "Auto", and "Sunny" during the periods from 29 May 2004 to 31 July 2008, from 1 August 2008 to 18 June 2009, and from 19 June 2009 to 31 December 2013, respectively (Saitoh et al., 2012). We replaced the original camera with another (Coolpix 4300, Nikon Corporation) on 26 March 2013 because of a malfunction with the original camera. The observations were supported by the Phenological Eyes Network (PEN: Nishida, 2007), and the canopy surface images are publicly available on the Internet (http://www.pheno-eye.org).

2.3. Detection of the timings of S_{LE} and E_{LF}

The images taken at 12:00 Japan Standard Time were used for our analysis to remove the effect of the diurnal cycle of solar altitude on the images (Saitoh et al., 2012). The images taken on rainy or foggy days were eliminated. Moreover, some images were also eliminated because of dirt on the camera housing window. We set the regions of interest (ROIs) for the whole forest canopy (Fig. 1a), one individual of *A. rufinerve* (Ar_1; Fig. 1b), two individuals of *B. ermanii* (Be_1 and Be_2; Fig. 1c and d, respectively), one individual of *P. maximowiczii* (Pm_1; Fig. 1e), and three individuals of *Q. crispula* (Qc_1–Qc_3; Fig. 1f–h, respectively). The timings of S_{LE} and E_{LF} were detected by visual inspection using the canopy surface images. The timings of S_{LE} and E_{LF} were defined as the first day when 20% of leaves had flushed and the first day when 80% of leaves had fallen in the given ROI, respectively.

2.4. Image analysis

First, we extracted the digital numbers of the RGB channels (DN_R, DN_G, and DN_B, respectively) in each pixel for each image. We then calculated the average digital numbers of the RGB channels for each ROI. After that, we calculated the percentage of DN_R, DN_G, and DN_B to the total DN (%R, %G, and %B, respectively) and the Green Excess Index (GEI; Richardson et al., 2007) for each ROI by using the following equations:

$$\%R = 100 \times \{DN_R/(DN_R + DN_G + DN_B)\} \tag{1}$$

$$\%G = 100 \times \{DN_G/(DN_R + DN_G + DN_B)\} \tag{2}$$

$$\%B = 100 \times \{DN_B/(DN_R + DN_G + DN_B)\} \tag{3}$$

$$GEI = 2 \times DN_G - (DN_R + DN_B). \tag{4}$$

GEI shows seasonal patterns that largely mirrored those in %G and it has been reported as a useful index to evaluate the variation in foliage phenology (e.g., timing of S_{LE}) more accurately than the individual RGB channels (e.g., Richardson et al., 2009). Missing data in the time-series of GEI were filled linearly. In addition, we applied a 5-day moving average of the GEI values to smooth fluctuations. We detected the first