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Relationship between leaf physiologic traits and canopy color indices during the leaf expansion period in an oak forest

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Abstract. Plant phenology has a significant impact on the forest ecosystem carbon balance. Detecting plant phenology by capturing the time-series canopy images through digital camera has become popular in recent years. However, the relationship between color indices derived from camera images and plant physiological characters are elusive during the growing season in temperate ecosystems. We collected continuous images of forest canopy, leaf size, leaf area index (LAI) and leaf chlorophyll measured by a soil plant analysis development (SPAD) analyzer in a northern subtropical oak forest in China. Our results show that (1) the spring peak of color indices, Gcc (Green Chromatic Coordinates) and ExG (Excess Green), was 18 days earlier than the 90% maximum SPAD value; (2) the 90% maximum SPAD value coincided with the change point of Gcc and ExG immediately after their spring peak; and (3) the spring curves of Gcc and ExG before their peaks were highly synchronous with the expansion of leaf size and the development of LAI value. We suggest it needs to be adjusted if camera-derived Gcc or ExG is used as a proxy of chlorophyll or gross primary productivity, and images observation should be complemented with field phenological and physiological information to interpret the physiological meaning of leaf seasonality.

Key words: chlorophyll; greenness indices; leaf area index; leaf sizes; phenology; plant images.

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Introduction

Plant phenological observation has played a significant role in studying the response of forest ecosystems to climate change (Penuelas and Filella 2001, Menzel 2002, Morisette et al. 2009). Previous research on plant phenological observation has detected the advancement of the date of leaf-expanding and gradual increase in the growing season length over the last decades from middle to high latitudes in the northern hemisphere(Linderholm 2006, Cleland et al. 2007, Piao et al. 2008, 2011, Yang et al. 2012). Especially, earlier leaf development increases the carbon gain in spring and likely has greater influence for the whole year of ecosystem carbon budget (Niemand et al. 2005, Barr et al. 2007, Richardson et al. 2007).

To obtain high-resolution phenological information and overcome the limitation of manual observation and satellite remote sensing, an increasing amount of commercial digital cameras have been installed on research towers to capture plant canopy images on a daily basis (Richardson et al. 2007, Graham et al. 2010, Nagai et al. 2011, Sonnentag et al. 2012). Digital number of red, green, and blue were extracted in the region of interest (ROI) from images, and then several greenness indexes, such as green chromatic coordinates (Gcc) and excess green (ExG), were used to quantify the timing of the start and end of phenological phase throughout the year (Gillespie et al. 1987, Woebbecke et al. 1995, Richardson et al. 2009*a*, Mizunuma et al. 2011, Henneken et al. 2013, Nagai et al. 2013). It has been concluded that plant phenological phase can be detected by the continuous canopy images based on the quantitative analysis of color indexes (Richardson et al. 2009*a*, Ide and Oguma 2010, Morris et al. 2013).

Although the index of RGB (red, green, blue) values could indicate the timing of canopy phenological phases, for example, of green-up or color change, these phases may not definitely refer to phenological and physiological characteristics, such as the stage of leaf-expansion or the dynamic level of chlorophyll contents (Richardson et al. 2009*a*, Henneken et al. 2013, Morris et al. 2013, Yang et al. 2014). Ahrends et al. (2009) have showed that there was a delay between maximum gross primary production (GPP) and the time of maximum Gcc, but how to mathematically adjust Gcc to match GPP is unresolved. Nagai et al. (2011) reported that RGB indexes could not detect the different characteristics between forest species in spring. Recently, Yang et al. (2014) have found that there was a mismatch of the maximum of Gcc value and the maximum of chlorophyll contents, but they have not quantified how to adjust camera-based indexes to reflect chlorophyll contents and other physiological variables. With the increasing use of cameras that can relatively easily collect numerous images to derive phenological patterns across various ecosystems, it is critically important to scrutinize how physiological information can be revealed by images.

In this study, we attempt to evaluate the applicability of color indices (Gcc and ExG) derived from the canopy images for the interpretation of the dynamic of leaf sizes, leaf area index (LAI) and chlorophyll contents, and to quantify how to match the development of chlorophyll contents with the curve of Gcc or ExG patterns during the leaf-expansion period in spring in a northern subtropical secondary oak forest in China.

Materials and Methods

Study site

The study was carried out in the spring of 2013 in a temperate forest (32°7′47.48″ N, 119°12′5.35″ E) dominated by sawtooth oak (*Quercus acutissima*) and cork oak (*Quercus variabilis*) located in Nanjing Forestry University's Xiashu Ecological Station on the Kongqin mountain of Jurong Country, Jiangsu Province, China. The site is part of the Chinese Forest Ecosystem Research Network (CFERN). The forest age was approximately 60 years afforested in 1950s. The area was characterized by humid subtropical climate. Based on the manual meteorological observation from March 2012 to February 2013, the curve of daily temperature showed an inverted "V" shape, which increased from March 2012 to August 2012, and peaked at August 18, 2012, then decreased to January 2013, and ranged between −4.1°C and 29.5°C. Monthly total precipitation varied from 10.9 to 195 mm, and was greater than 150 mm in June and July, but was less than 100 mm in other months. Besides, the range of monthly relatively humidity was from 74.0% to 93.4%, which peaked in August 2012 and stayed lowest point in October and November 2012.The soil is mainly composed of yellow brown soil (Liu et al. 2013).

Canopy images acquisition and processing

To monitor the temporal variations of trees phenology, we mounted a digital camera (Net-

Cam SC 1.3MP, StarDot, Buena Park, California, USA) on the top of 30-m tower (about 15 m above the canopy), facing north and angled 20° downward to get a widely visual view of forestry canopy in the Xiashu Ecological Station. Canopy images were captured hourly between 9:00 and 15:00 from March to June in 2013 and archived as JEPG format, with a resolution of 1296 × 960 pixels (Fig. 1). Images exposure and color balance were set to be automatic and manual, respectively. All captured images were downloaded and stored by a local server (TS-U100, USB Network Storage Server, TRENDnet, California, USA).

Continuous images were processed by the following four steps. First, following published methods (Richardson et al. 2007, 2009*b*), we defined the region of interest (ROI) that includes maximum amounts of trees (Fig. 1), then extracted and averaged each of the three color (red, green, and blue, or RGB) channel digital numbers (DN) for each ROI and transform the RGB DN to green chromatic coordinates (Gcc, Eq. 1) and excess green (ExG, Eq. 2) in order to suppress the influence of scene illumination (Gillespie et al. 1987, Woebbecke et al. 1995). Second, because the cloudy, sunny or other weather factors would generate uncertain reductions in daily Gcc and ExG, we used the 90th percentile of all the Gcc and ExG within a 3-day moving window to characterize canopy color change over time to get the smoothed time-serials of Gcc and ExG (Sonnentag et al. 2012). Third, in order to compare with the relative changes in leaf sizes, LAI, SPAD and greenness indices with the dynamical curve of Gcc and ExG, we selected maximum Gcc and ExG values during the leaf-expansion period in spring and calculated the ratio of Gcc and ExG values of each day to the maximum value of the season (Eqs. 3 and 4). Fourth, we analyzed the time of year when the trend of canopy color, leaf size and LAI changes their directions, as those dates could potentially be linked with significant plant functional change. In order to detect the phenological stages of deciduous trees in the spring, we used the Bayesian Change Point (BCP) analysis to identify these days along the time-series (Henneken et al. 2013, Pope et al. 2013). BCP fits the time-series with piece-wise linear regressions, and identifies the endpoints of each linear segmentation.

$$\mathrm{Gcc} = \frac{\mathrm{greenDN}}{\mathrm{redDN} + \mathrm{greenDN} + \mathrm{blueDN}} \quad (1)$$

$$\mathrm{ExG} = 2\mathrm{greenDN} - \mathrm{blueDN} - \mathrm{redDN} \quad (2)$$

$$\mathrm{Gcc}(\%) = \frac{\mathrm{Gcc}}{\mathrm{MaxGcc}} \times 100 \quad (3)$$

$$\mathrm{ExG}(\%) = \frac{\mathrm{ExG}}{\mathrm{MaxExG}} \times 100. \quad (4)$$

Here, Gcc and ExG are the indices of Green Chromatic Coordinates and Excess Green, respectively; redDN, greenDN, blueDN represent the average digital number of each channel in pixel. MaxGcc and MaxExG are the maximum value of Gcc and ExG in the period of leaf expansion, respectively.

Leaf biophysical, biochemical properties and canopy structure

To examine the variation of Gcc and ExG during leaf-expansion, high time-resolution data of leaf sizes and chlorophyll were collected in situ from intact leaves. Daily measurements (lower frequency after April 21) were carried out on three sawtooth oak trees and one cork oak tree, both located in the ROI, from 30 March to 24 May. We used a ruler at the millimeter precision to measure the leaf length and width for every leaf on the labeled branches among these four oaks. The labeled branch height was about 9 m and the canopy height was between 8 and 13 m. Soil plant analysis development (SPAD) values were measured on the labeled leaves using the Chlorophyll Meter SPAD-502Plus (Konica Minolta, Osaka, Japan) in situ. The SPAD values are calculated through the amount of light transmitted by the leaf in red light (650 nm) and infrared light (940 nm), which have different absorbance induced by chlorophyll. Although the relationship between SPAD values and chlorophyll contents could be linear, exponential or polynomial correlations for various kinds of plants species have been reported; this relationship could be affected by light conditions, chloroplast distribution or the level of chlorophyll concentrations, but overall, the dynamic curve of SPAD values could be used as the indicator of leaf chlorophyll contents (Markwell et al. 1995,

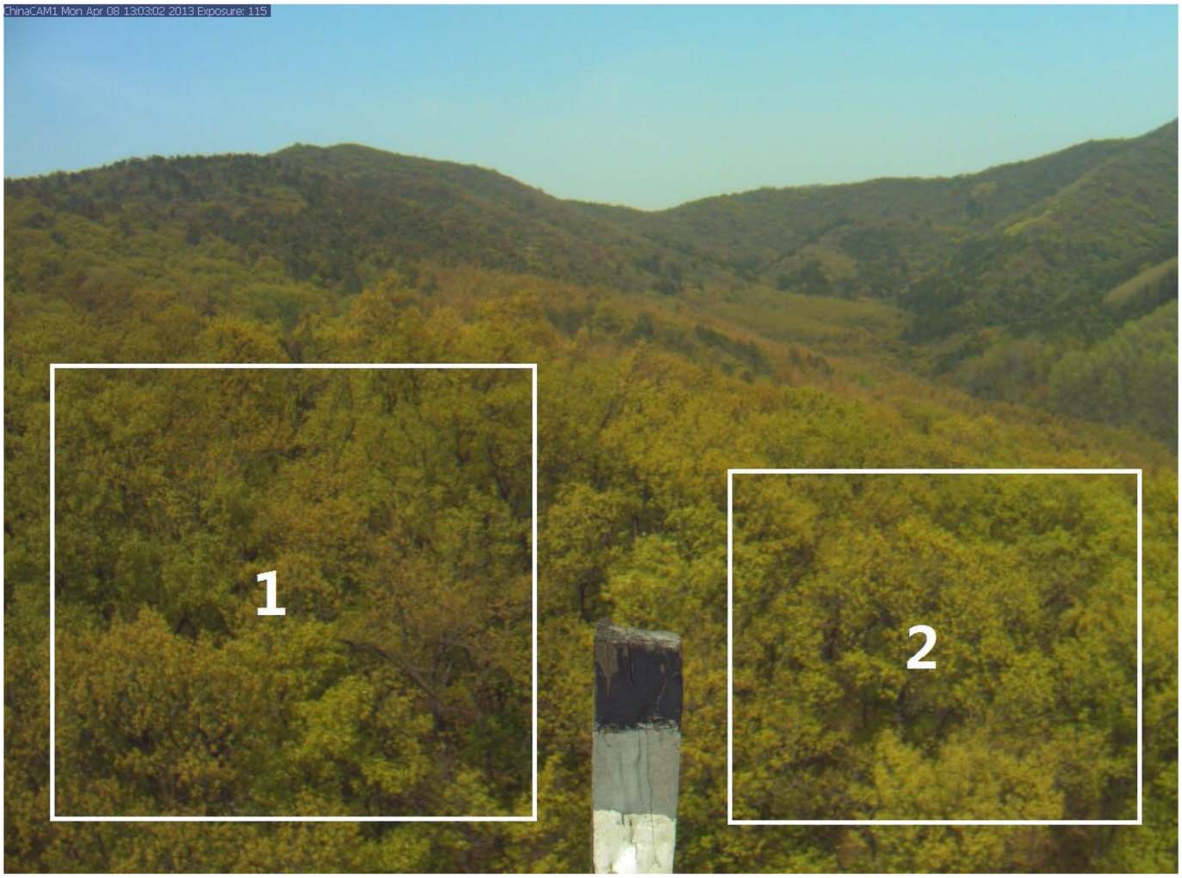

Fig. 1. A digital camera canopy image was taken in day of year (DOY) 98. White rectangle 1 and 2 are the region of interest (ROI) used to calculate the color indices (Gcc and ExG)

Muraoka and Koizumi 2005, Uddling et al. 2007, Naus et al. 2010, Ling et al. 2011, Nagai et al. 2011, Djumaeva et al. 2012, Scattolin et al. 2013, Riccardi et al. 2014). Furthermore, the daily leaf area index (LAI) values (lower frequency after the end of leaf expansion) within ROI were collected with the leaf area meter LAI-2200 (Li-COR, Nebraska, USA) at the same time with other measurements.

In order to show the relative changes of leaf size, SPAD values and LAI values over time, we selected the last day we recorded as the maximum values during the leaf-expansion period, and then calculated the percentage of leaf size, SPAD values and LAI value to the maximum value, similar to the method of calculating the percentage of ExG and Gcc.

Results

The spring peak of Gcc and ExG was 18 days earlier than the 90% maximum SPAD value, suggesting a mismatch between the peak of color indices and the maximum of chlorophyll contents during the spring leaf expansion period. The Gcc and ExG peaked on 18 April 2013 (Day-of-Year [DOY] 108) based on the visual inspection and Bayesian multiple change point analysis (Fig. 2c). Meanwhile, the leaf SPAD value just reached the 65% of their maximum level. The date of 90% maximum SPAD value, which indicated the end of fast development of chlorophyll, was on DOY 126 (Fig. 2b).

The spring curves of Gcc and ExG before their peaks were highly synchronous with the expansion of leaf size and the development of LAI value. Based on the Bayesian analysis for the Gcc

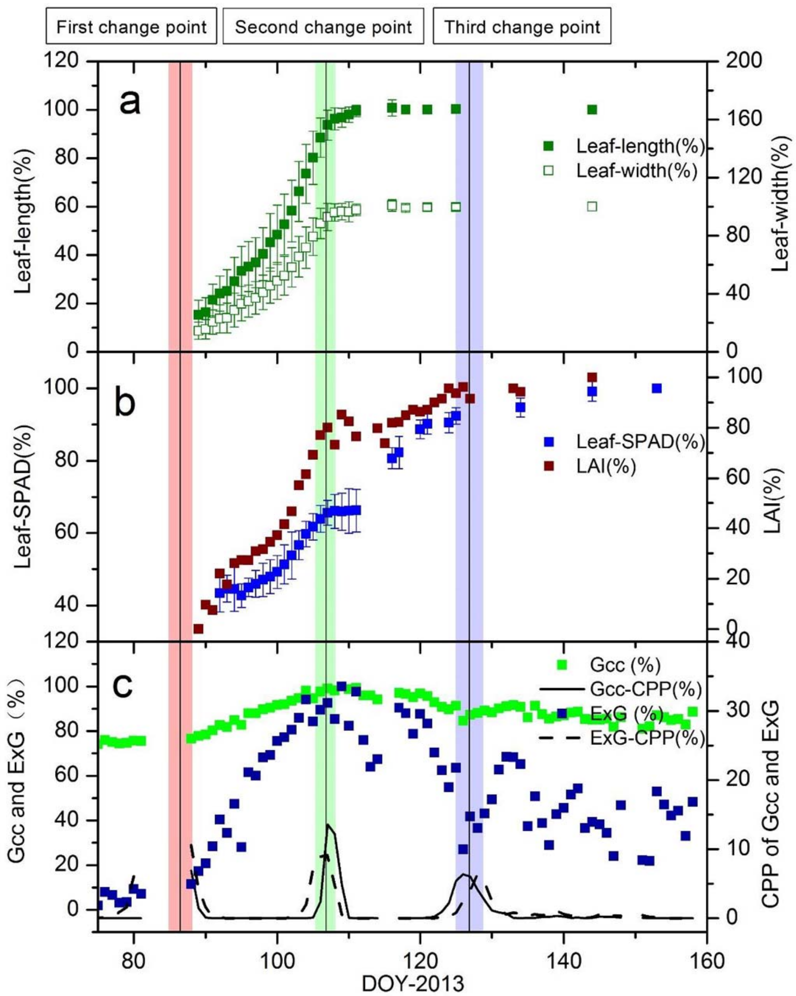

Fig. 2. Comparison among canopy color indices, leaf sizes, leaf chlorophyll contents and leaf area index (LAI). The measurement of leaf sizes and chlorophyll contents were carried out in-situ by ruler and soil plant analysis development (SPAD) which was used as the indicator of leaf chlorophyll concentration, respectively. (a) The curves of leaf length and width. Dots represented the percentage of the measured values to the average of respective maximum from the labeled leaves each time. The average of all leaves length and width maximum was 11.63 cm, 4.20 cm, respectively. The whiskers are the standard deviations. (b) The percentage of labeled leaf SPAD values over the maximum SPAD value from DOY 92-153, and the percentage of LAI value over the maximum LAI value from DOY 89-153. (c) Green chromatic coordinate (Gcc) and Excess green (ExG) curve derived from the camera time-series, and their change point probability (CPP) based on the Bayesian multiple change point analysis.

and ExG, the first change point of Gcc and ExG occurred on 31 March 2013 (DOY 89 $\pm$ 0.9886) when Gcc and ExG started to increase (Fig. 2c). Meanwhile, the leaves of ROI began to expand along with the steady increases in Gcc, ExG and LAI values. Bayesian analysis then detected the second change point of Gcc and ExG on DOY 108.6 $\pm$ 1.1 and DOY 106.1 $\pm$ 2.8, respectively, when Gcc and Exg started to decrease over time. Meanwhile, leaf sizes and LAI value reached approximately 95% and 85% of the maximum, respectively, and experienced a similar increasingly pattern before the DOY 108 (Fig. 2b), supporting that Gcc and ExG are highly synchronous with leaf sizes and LAI value during the leaf expansion period.

The third change point date of Gcc, ExG and their probability, which means the probability of occurrence of a change point, occurred on DOY 128.73 $\pm$ 4.8 (29.4%) and DOY 131.0 $\pm$ 7.2 (27.4%), respectively. Meanwhile, the curve of SPAD values showed that chlorophyll ended the phase of the fastest-growing and reached about 90% of its maximum (Fig. 2b), which implied that the third change point date of Gcc's and ExG's curves represented the end of rapid increase of chlorophyll contents.

Discussion

We found that during the leaf expansion period in spring, Gcc, ExG, and leaf size increased synchronistically until the end of rapid increase within the DOY 108.6 $\pm$ 1.1, while leaf chlorophyll levels continuously increased until about 18 days after the peaks of Gcc, ExG and leaf size. If the chlorophyll level measured by SPAD is a real indicator of leaf phenology and leaf photosynthesis capacity, camera-based Gcc and ExG may overestimate the duration of the growing season if we do not consider the potential mismatch in the spring. The mismatch of the peak Gcc (ExG) and chlorophyll could be reconciled as the peak chlorophyll coincided with the change point of Gcc (the third one from the start of the growing season) from a decreasing to a stabilized trend detected by the Bayesian analysis. Thus we might adjust the camera-based phenology by using the above change point as the peak of photosynthesis capacity, replacing the potential bias by simply using the peak Gcc (ExG) value. Besides, we found that the spring curve of Gcc and ExG before their peaks was highly synchronous with the expansion of leaf size and the development of LAI value, suggesting the usefulness of Gcc and Exg as a proxy for leaf size and LAI.

Our findings suggest that there is a mismatch in timing between the peak of greenness index and chlorophyll concentration in an oak forest in China, supporting the recent report conducted at Harvard Forest in eastern U.S. (Yang et al. 2014), and emphasize the strength and weakness of phenology derived from the greenness index, which is obtained by digital cameras and commonly used in worldwide "near remote" plant phenological studies (Ahrends et al. 2009, Richardson et al. 2009*a*, Ide and Oguma 2010, Sonnentag et al. 2012).

The later peak of chlorophyll contents than the greenness indexes and leaf size could be explained by the mechanism that many species tends to delay chloroplast development and keep relative low chlorophyll contents until the leaf size reach its full level in order to reduce herbivorous damage (Kursar and Coley 2003, Coley et al. 2005). The chlorophyll concentration has high relationship with the photosynthesis rate and the gross primary productivity (GPP) (Field and Mooney 1986, Morecroft et al. 2003). Therefore, the peak GPP may not synchronize with the peak of the greenness indices, such as Gcc and ExG, during the growing season (Richardson et al. 2007, Ahrends et al. 2009, Mizunuma et al. 2013). On the other hand, Richardson et al. (2007) evaluated the relationship between broadband normalized difference vegetation index (NDVI) and the greenness index in the canopy scale, and showed that the peak of NDVI and Gcc, ExG have highly time-serial synchronization (Richardson et al. 2007). This suggests that NDVI may not synchronize with GPP during the leaf expansion period. Therefore, the potential mismatch between peak GPP and peak ExG/Gcc values based on ground-observation or NDVI data based on the satellite-monitor should be carefully calibrated before these indices are used to estimate the growing season length and the annual sum of GPP.

After the third change point of Gcc and ExG when leaf chlorophyll and possibly GPP peaked, we still observed a slight increase in SPAD values. The reason could be induced by the change of light conditions and the development of leaf structure. The SPAD values were measured on the labeled branches that were located below the forest canopy because of the restriction of field condition. Light intensity of this position would decrease when closed canopy was gradually formed. The chloroplast would move from the side position (along cell walls parallel to the incoming light) to the facing position (along cell walls perpendicular to incoming lights), and SPAD reading increased when the light intensity changed from the high to low (Naus et al. 2010). In addition, based on the field observation, the surface of oak leaves would form a wax layer and the leaves would gradually thicken after leaves sizes reached their maximum, which could lead SPAD values to increase.

We observed that there was a gradual increase of LAI after the leaf sizes maximized, explained by two reasons. First, LAI values were measured above 1.5 m of the ground, so it can be affected by the development of shrubs with heights over 2 m. Second, LAI was measured by the LAI-2200 plant canopy analyzer, which rejects any radiation >490 nm and assumes the foliage is dark, and the transmission of blue radiation would show a distinct decrease with the increase of chlorophyll after the peak of Gcc or ExG, suggesting that the increase of LAI after maximum leaf size is probably a result of the decrease of blue radiation transmission.

Our results are consistent with that of Nagai et al. (2011), who also reported the earlier peak of the greenness index and LAI than SPAD values in *Quercus crispula*, *Betula ermanii* and *Acer rufinerve* forests in Takayama research site where is a cool-temperate, deciduous, broad-leaved forest research site in central Japan. Other studies also reported an inflection point in about 3 weeks after the peak Gcc or ExG (Ahrends et al. 2008, Richardson et al. 2009*a*, Graham et al. 2010, Sonnentag et al. 2012, Ide and Oguma 2013). The date of this inflection point could point to the highest chlorophyll content as we found in our study. Although our conclusions need to be validated in various kinds of forest species with multiple years of datasets, we clearly show that during the leaf expansion period in spring, the date of maximum Gcc (ExG) is not the date of maximum concentration of chlorophyll, but the date of the maximum leaf sizes and the date of highest canopy LAI value.

Commercial digital cameras are increasingly installed as an effective and inexpensive method to monitor the dynamic pattern of plants phenology and to examine the response to climate change in recent decades (Morisette et al. 2009, Richardson et al. 2009*a*, 2013, Nagai et al. 2013). It is critically needed to ensure a reliable correlation between color indices, which are extracted from the continuous plants images, and plants physical and chemical properties. Our study showed the relationship among indices, phenological and ecological characters during the leaf expansion, and tried to explain the mismatch between SPAD values and greenness indices. Particularly, using the Bayesian Change Point analysis (the third change point of Gcc/ExG), we provide a quantitative method to identify the peak chlorophyll content from camera-based Gcc/ExG time-series data. However, any generalization of these results needs to be proved by more works from different plant species and regions. To better understand what greenness indices are the best representativeness in the future "near-remote sensing" phenological study, we need to connect phenological and ecological properties, such chlorophyll contents, photosynthesis, solar induced fluorescence (Yang et al. 2015), with color indices across different scales, from the leaf to canopy, regional, and global scales.

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