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Short communication

Monitoring vegetation phenology using an infrared-enabled security camera

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ABSTRACT

Sensor-based monitoring of vegetation phenology is being widely used to quantify phenological responses to climate variability and change. Digital repeat photography, in particular, can characterize the seasonality of canopy greenness. However, these data cannot be directly compared to satellite vegetation indices (e.g. NDVI, the normalized difference vegetation index) that require information about vegetation properties at near-infrared (NIR) wavelengths. Here, we develop a new method, using an inexpensive, NIR-enabled camera originally designed for security monitoring, to calculate a "camera NDVI" from sequential visible and visible + NIR photographs. We use a lab experiment for proof-of-concept, and then test the method using a year of data from an ongoing field campaign in a mixed temperate forest. Our analysis shows that the seasonal cycle of camera NDVI is almost identical to that of NDVI measured using narrow-band radiometric instruments, or as observed from space by the MODIS platform. This camera NDVI thus provides different information about the state of the canopy than can be obtained using only visible-wavelength imagery. In addition to phenological monitoring, our method should be useful for a variety of applications, including continuous monitoring of plant stress and quantifying vegetation responses to manipulative treatments in large field experiments.

1. Introduction

The phenology of terrestrial vegetation is highly sensitive to climate variability and change (Rosenzweig et al., 2007; Migliavacca et al., 2012). In the context of climate change, phenology is important because it mediates many of the feedbacks between terrestrial vegetation and the climate system (Richardson et al., 2013a). From an ecological perspective, phenology plays an important role in both competitive interactions and trophic dynamics, as well as in reproductive biology, primary production, and nutrient cycling (Morisette et al., 2009).

Satellite remote sensing can provide global coverage of vegetation phenology, but suffers from tradeoffs between spatial and temporal resolution (Zhang et al., 2006; White et al., 2009). Thus, over the last decade, there has been great enthusiasm for increased on-the-ground monitoring of phenology (Betancourt et al., 2005; Morisette et al., 2009; Polgar and Primack, 2011). The general objective of these efforts is to better understand spatial and temporal variation in phenology, and how this variability is driven by environmental factors such as temperature, precipitation, and photoperiod (or insolation). Citizen science networks, such as the USA National Phenology Network (http://www.usanpn.org) and Project Budburst (http://budburst.org), are playing an important role in this monitoring, by engaging large numbers of motivated volunteers and establishing standardized protocols.

Instrument-based approaches (Richardson et al., 2013b) provide a compelling alternative to observer-based phenology, because of the potential for high frequency, automated data collection in a manner that is scalable for regional or continental monitoring. In this context, digital repeat photography (e.g. Richardson et al., 2007, 2009; Sonnentag et al., 2012) is an attractive option because images can be analyzed either qualitatively or quantitatively, and analysis can focus on individual organisms or integrate across the field of view to obtain a community- or canopy-level perspective. Compared to data collected by a human observer, which tend to focus on discrete phenophases, such as flowering or budburst, the entire seasonal trajectory of canopy greenness can be characterized from digital camera imagery. Additionally, the archived images provide a permanent visual record that can be reanalyzed as new tools and questions are developed. Camera-based monitoring (e.g. the PhenoCam network, http://phenocam.sr.unh.edu/) thus provides data

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at a spatial scale that is intermediate between ground observations of individual plants and satellite remote sensing.

To date, most camera-based monitoring of vegetation phenology has been conducted using standard, consumer-grade digital cameras (e.g. Sonnentag et al., 2012). These typically record a three-layer image (red, green and blue: RGB), which is sufficient for the representation of colors in the visible spectrum (VIS, λ = 400–700 nm) as perceived by the human eye. For quantitative analysis, the average value of each color layer for all pixels within a user-defined region of interest (ROI) is extracted from each image to yield a digital number triplet (R_{DN}, G_{DN}, B_{DN}). Then seasonal variation in the state of the canopy is characterized by the use of several color indices, such as the green chromatic coordinate (g_{CC}, Eq. (1a)) and excess green (G_{ex}, Eq. (1b)) (Sonnentag et al., 2012; Richardson et al., 2013b):

$$g_{CC} = \frac{G_{DN}}{R_{DN} + G_{DN} + B_{DN}} \tag{1a}$$

$$G_{EX} = 2G_{DN} - (R_{DN} + B_{DN}) \tag{1b}$$

Conversely, satellite remote sensing of vegetation has traditionally used both visible and near-infrared (NIR, λ = 700–1400 nm) wavelengths. The reason for this is that healthy vegetation can be distinguished from other land cover types by its unique spectral signature, which combines low reflectance in the VIS with high reflectance in the NIR. Thus, the camera indices presented above, which are based only VIS wavelengths, are not directly comparable to standard satellite vegetation indices such as NDVI (normalized difference vegetation index, Eq. (1c)), calculated from red band and NIR band reflectances (ρ_R and ρ_{NIR}, respectively) (Tucker, 1979).

$$\text{NDVI} = \frac{\rho_R - \rho_{NIR}}{\rho_R + \rho_{NIR}} \tag{1c}$$

Intriguingly, the CCD (charge-coupled device) or CMOS (complementary metal-oxide-semiconductor) imaging sensors used in most digital cameras are sensitive to wavelengths in the NIR portion of the spectrum. An infrared cut filter is typically used to block these wavelengths from reaching the imaging sensor, as they are beyond the spectral range to which the human eye is sensitive and are thus not necessary for conventional color photography. Customized cameras have been used in the past to leverage this NIR sensitivity (Shibayama et al., 2009, 2011; Sakamoto et al., 2010, 2012; Nijland et al., 2013). For example, using a two-camera system Sakamoto et al. (2012) calculated an NDVI-style index that was more akin to the conventional NDVI than either g_{CC} or G_{EX}. The two-camera approach allows for simultaneous recording of information about the VIS and NIR properties of vegetation, but creates challenges related to camera alignment, cross-calibration, and synchronization of image capture. Very recently, relatively low-cost NDVI cameras have become available (e.g. MaxMax, Event-38, and Regent brands), but these have not been produced with long-term monitoring in mind, and such cameras are unable to also produce conventional RGB imagery—that is, infrared wavelengths are recorded at the expense of information in one of the RGB channels.

Here, we show that a commercially available, network-enabled camera ("webcam") with a software-controlled infrared cut filter overcomes the above limitations. With the cut filter in place, standard 3-layer RGB imagery is recorded; with the filter removed, a monochrome RGB + NIR image is obtained. We develop a method to compute an NDVI-style vegetation index, which we call "camera NDVI", from this imagery. A lab experiment, conducted under controlled conditions, is used as a proof-of-concept. We then apply the method to a one-year archive of images from the Harvard Forest to demonstrate the feasibility of employ this method for field monitoring of vegetation phenology, where day-to-day variation in weather and lighting cause additional challenges. As a final test, we compare the seasonality of camera NDVI from the Harvard Forest

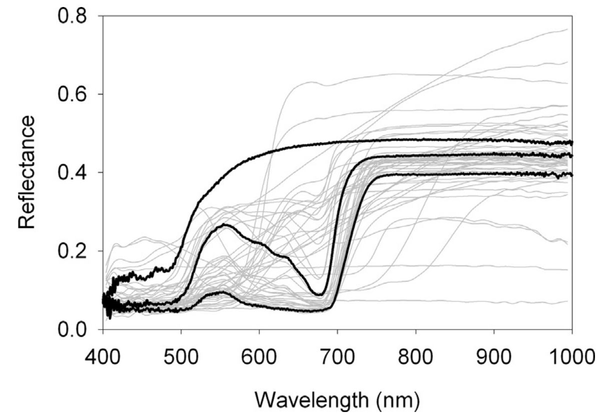

Fig. 1. Reflectance spectra of the 51 samples (thin gray lines) used in the laboratory experiment. The heavier black lines indicate representative spectra from a healthy green leaf (bottom), a yellowing leaf (middle), and a red (top) leaf.

data with that obtained using co-located narrow-band radiometric instruments and from satellite sensors. Data from our camera system will be of value for quality assessment of phenology products derived from satellite imagery (e.g. White et al., 2009).

2. Materials and methods

2.1. Camera

We used a NetCam SC IR (StarDot Technologies, Buena Park, CA) camera, featuring a Micron ½″ CMOS active-pixel digital imaging sensor and configured for 1.3 megapixel (1296 × 976) output. The camera was set at manual (fixed) white balance and, unless otherwise noted, automatic exposure. With a built-in uClinux operating system, the camera operates as a standalone system with Internet connectivity. Command scripts running on the camera controlled the infrared cut filter, image capture, and image upload to a remote server via FTP. The customized scripts used here are available in the "Tools" section of the PhenoCam project page (http://phenocam.sr.unh.edu/webcam/tools/) or from the corresponding author.

2.2. Proof-of-concept lab experiment

We conducted a lab experiment to evaluate whether camera imagery can be used to accurately characterize the broadband spectral properties of different materials. We used the StarDot camera to record sequential color RGB and monochrome RGB + NIR images of materials with a wide range of spectral signatures (Fig. 1). Each sample was illuminated from above with a 50 W Halogen lamp designed for indoor diffuse reflectance measurements (ASD Pro-Lamp, Analytical Spectral Devices Inc., Boulder, CO). The StarDot camera was mounted on a tripod to the side of the sample and inclined downward at an angle of about 45°. Each sample filled approximately one-quarter of the camera's field of view. For quality assurance, we included a multi-color reference panel in each image, made by painting red, green, blue, white and gray strips on a flat piece of plastic. We recorded four images of each sample: one image at fixed exposure (1/300 s) for both color RGB and monochrome RGB + NIR images, and one image at automatic exposure for both color RGB and monochrome RGB + NIR. Automatic exposure values were determined by the camera. The mean automatic exposure for the color RGB images was 1/30 s (minimum 1/120 s), compared with 1/200 s (minimum 1/350 s) for the monochrome RGB + NIR images. Thus the fixed exposure images were almost always underexposed compared to the automatic exposure images.