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Essays and Perspectives

Introducing digital cameras to monitor plant phenology in the tropics: applications for conservation

Bruna Alberton[a,*], Ricardo da S. Torres[b], Leonardo F. Cancian[a], Bruno D. Borges[a], Jurandy Almeida[c], Greice C. Mariano[b], Jefersson dos Santos[d], Leonor Patricia Cerdeira Morellato[a]

[a] *Universidade Estadual Paulista (UNESP), Instituto de Biociências, Departamento de Botânica, Laboratório de Fenologia, Rio Claro, SP, Brazil*
[b] *Universidade de Campinas (UNICAMP), Institute of Computing, RECOD Lab, Campinas, SP, Brazil*
[c] *Universidade Federal de São Paulo (UNIFESP), Institute of Science and Technology, São José dos Campos, SP, Brazil*
[d] *Universidade Federal de Minas Gerais (UFMG), Department of Computer Science, Belo Horizonte, MG, Brazil*

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A B S T R A C T

The application of digital cameras to monitor the environment is becoming global and changing the way of phenological data collection. The technique of repeated digital photographs to monitor plant phenology (phenocams) has increased due to its low-cost investment, reduced size, easy set up installation, and the possibility of handling high-resolution near-remote data. Considering the widespread use of phenocams worldwide, our main goals here are: (i) to provide a step-by-step guide for phenocam set up in the tropics, reinforce its appliance as an efficient tool for monitoring tropical phenology and foster networking, (ii) to discuss phenocam applications for biological conservation, management, and ecological restoration. We provide the concepts and properties for image analysis which allow representing the phenological status of the vegetation. The association of a long-term imagery data with local sensors (e.g., meteorological stations and surface-atmosphere flux towers) allows a wide range of studies, especially linking phenological patterns to climatic drivers; and the impact of climate changes on plant responses. We show phenocams applications for conservation as to document disturbances and changes on vegetation structure, such as deforestation, fire events, and flooding and the vegetation recovery. Networks of phenocams are growing globally and represent an important tool for conservation and restoration, as it provides hourly to daily information of monitored systems spread over several sites, ecosystems, and climatic zones. Moreover, websites enriched by vegetation dynamic imagery data can promote science knowledge by engaging citizen science participation.

Introduction

The use of digital cameras to document plant changes is not novel. Photographs have been used to monitor landscape since 1965 by Hastings and Turner to verify changes in the ecosystem dynamics and structure of the arid southwest region of the US. Thompson et al. (2002) used photographic registers for the long-term study of glacial retreat in the Antarctic ice sheet. Repeated digital images have been used to document changes in cultural landscapes (Peñuelas and Boada, 2003; Webb et al., 2007); to measure vegetation growth and biomass (Crimmins and Crimmins, 2008; Graham et al., 2009); to detect plant stress and nitrogen status (Wang et al., 2004) and to monitor crops (Slaughter et al., 2008). More recently, the application for monitoring leaf exchanges patterns or leafing phenology (Richardson et al., 2007, 2009; Nagai et al., 2011) has brought the technique to the agenda of global change research and conservation (Richardson et al., 2013; Morellato et al., 2016).

Phenology is an integrative environmental science focused on monitoring, understanding, and predicting recurrent life cycles events of organisms, which are mainly related to climate (Morellato et al., 2016). Leafing is the plant phenological event that defines the growth season and controls crucial ecosystems processes such as, nutrient cycling, water storage, regulates productivity in terrestrial ecosystems, and the dynamics of carbon sequestration (Reich, 1995; Baldocchi et al., 2005).

Phenological studies have been efficiently applied to track effects of environmental changes on plants and animals in temperate regions, answering questions about the current scenario of

* Corresponding author.
E-mail address: brualberton@gmail.com (B. Alberton).

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global climate change and stimulating the search for innovative tools of plant monitoring (Polgar and Primack, 2011). Detect plant responses to environmental changes across tropical systems, especially in the Southern Hemisphere, is an important question on the global agenda since few studies have addressed trends related to global warming (Rosenzweig et al., 2008; Morellato et al., 2013, 2016; Chambers et al., 2013). However, the tropical high diversity of species precludes the observation of many species across several sites due to the intense human labor and costs (Alberton et al., 2014; Morellato et al., 2016).

The technique of repeated photographs to monitor plant phenology may overcome those difficulties. The application has increased due to its low-cost, reduced size, easy set up, and the possibility of handling high-resolution data, making digital cameras reliable tools for a wide range of ecological applications (Crimmins and Crimmins, 2008; Morisette et al., 2009; Graham et al., 2010; Nasahara and Nagai, 2015; Brown et al., 2016). Digital cameras for plant phenology observation, also called phenocams, have allowed the detection of leaf phenological events through the analysis of color changes along time. By quantifying the red, green, and blue (RGB) color channels, it is possible to estimate, for instance, leaf flushing and senescence, using the green and red channels, respectively (Ahrends et al., 2009; Morisette et al., 2009; Richardson et al., 2009).

The term "Near-surface remote phenology" consists in the use of sensors installed on the ground, as the phenocams, with the objective of monitoring ecosystem-scale vegetation changes. Digital cameras monitoring canopy vegetation has an important role by filling the "gap of observations" between satellite monitoring and the traditional on-the-ground phenology (Alberton et al., 2014; Brown et al., 2016; Morellato et al., 2016; Morisette et al., 2009). The use of imagery data over the traditional phenological observations allows simultaneous multi-sites monitoring, long-term monitoring collecting high-frequency data (daily, hourly), and reduced human labor fieldwork for data acquisition. Phenocams networks are already covering a wide range of ecosystems in the world (Richardson et al., 2013; Brown et al., 2016). The main networks websites are the Phenocam Network in the United States (http://phenocam.sr.unh.edu – as of January 2017), the EuroPhen in Europe (http://european-webcam-network.net – as of January 2017) and the Phenological Eyes Network (PEN) in Japan (http://pen.agbi.tsukuba.ac.jp – as of January 2017). Together these initiatives combine more than 250 outdoor cameras (Brown et al., 2016; Nasahara and Nagai, 2015). For the tropics, we have the Tropidry project as a successful example of ecological project with intense multidisciplinary data collection, including the use of phenology towers with phenocams, covering dry tropical sites (http://tropi-dry.eas.ualberta.ca/ – as of May 2017). In Brazil, the *e*-phenology Network (http://www.recod.ic.unicamp.br/ephenology – as of January 2017) introduced in this paper, target the challenge of monitoring different vegetation types from dry forest, grasslands, and cerrado savannas to rainforests.

Therefore, considering the worldwide applications of phenocams in ecological studies, our main goals here are: (i) to provide a step-by-step guide for phenocam set up in the tropics, reinforce its appliance as an efficient tool for monitoring tropical phenology, (ii) to show how phenocams can provide key contributions to biological conservation, and (iii) to encourage this promising research field in Brazil and tropical areas based on the *e*-phenology project experience, and foster networking and *e*-science collaborative research.

Phenocams as tools for the monitoring of plant phenology

Digital images are typically based on the RGB color model (red, green, and blue color channels). These channels encode the brightness values of the scene and can be combined in more than 16 million of colors, representing basically all the colors perceived by humans (Cheng et al., 2001). Through the quantification of the RGB color channels, it is possible to calculate vegetation indices, which are related to leaf color changes representing the phenological status of the vegetation (Richardson et al., 2007; Sonnentag et al., 2012) (Fig. 1).

By capturing daily digital images of a given site, we derivate time series encoding RGB color changes over time. Thus, the leaf patterns can be described based, for instance, on the proportion of the green fraction in the images (Richardson et al., 2007). The association of digital imagery data with local sensors (e.g., meteorological stations and surface-atmosphere fluxes) uncovers a wide range of research opportunities, especially linking phenological patterns to climatic drivers, and analyzing long-term data to detect phenological shifts due to the impact of anthropogenic changes (Polgar and Primack, 2011; Brown et al., 2016; Morellato et al., 2016).

The collection of daily vegetation color changes has been motivated also by the need to understand ecosystem-scale energy fluxes (Baldocchi et al., 2005; Richardson et al., 2007). Studies from temperate vegetation have found the start of the vegetation greenness controls the gross primary productivity (GPP) curves (Richardson et al., 2010; Migliavacca et al., 2011; Keenan et al., 2014). Therefore, temporal changes in the vegetation drive carbon exchange processes via influencing the photosynthesis process, respiration, and litter production (Peichl et al., 2014).

Most of the studies using phenocams have been developed in the Northern hemisphere, covering mainly deciduous forests (Richardson et al., 2007, 2009; Nagai et al., 2011). However, the application of repeated digital photographs is also efficient for the phenology monitoring of temperate grasslands (Inoue et al., 2015; Julitta et al., 2014), peatland (Peichl et al., 2014), and evergreen forest (Toomey et al., 2015). Its reliability for tropical vegetation was recently validated for woody cerrado savanna (Alberton et al., 2014) and applied for tropical forest (Nagai et al., 2016; Lopes et al., 2016). The use of camera-derived vegetation indices in association with leaf demography-ontogeny models has been recently applied in the Amazon forest to investigate ecosystem-scale photosynthetic seasonality (Wu et al., 2016). However, there is still little focus on the species level analysis and on grasslands, mountains and other tropical vegetation.

Procedures for phenological monitoring using digital cameras

Digital cameras are reliable tools for the monitoring of vegetation because they have low price and easy setup, while providing high frequency and resolution data. Here, we introduce the main steps for phenology camera set up and basic information about image processing for data analysis (Fig. 1). A detailed protocol is available in the Supplementary Material.

Camera set up and image settings

In general, the camera is placed in a tower built in the middle of vegetation (Fig. 2a and b). The choice of the site and the field of view must maximize the vegetation to be monitored. Hemispherical lens cameras are reliable for capturing images of the canopy, reducing crown cover among individual species (Fig. 2c). Cameras should be positioned facing North – Northeast to maximize the light over the canopy and to minimize lens flare. Cameras can be set up on small towers, close to the ground, to capture landscape images (Fig. 2d and e) when the focus are shrublands, grasslands, or other vegetations with short canopies and across heterogeneous landscapes as rupestrian grasslands (Fig. 2f).

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