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Research Paper

Fine-scale perspectives on landscape phenology from unmanned aerial vehicle (UAV) photography

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ABSTRACT

Forest phenology is a multi-scale phenomenon, arising from processes in leaves and trees, with effects on the ecology of plant communities and landscapes. Because phenology controls carbon and water cycles, which are commonly observed at the ecosystem scale (*e.g.* eddy flux measurements), it is important to characterize the relation between phenophase transition events at different spatial scales. We use aerial photography recorded from an unmanned aerial vehicle (UAV) to observe plant phenology over a large area (5.4 ha) and across diverse communities, with spatial and temporal resolution at the scale of individual tree crowns and their phenophase transition events (10 m spatial resolution, ~5 day temporal resolution in spring, weekly in autumn). We validate UAV-derived phenophase transition dates through comparison with direct observations of tree phenology, PhenoCam image analysis, and satellite remote sensing. We then examine the biological correlates of spatial variance in phenology using a detailed species inventory and land cover classification. Our results show that species distribution is the dominant factor in spatial variability of ecosystem phenology. We also explore statistical relations governing the scaling of phenology from an organismic scale (10 m) to forested landscapes (1 km) by analyzing UAV photography alongside Landsat and MODIS data. From this analysis we find that spatial standard deviation in transition dates decreases linearly with the logarithm of increasing pixel size. We also find that fine-scale phenology aggregates to a coarser scale as the median and not the mean date in autumn, indicating coarser scale phenology is less sensitive to the tails of the distribution of sub-pixel transitions in the study area. Our study is the first to observe forest phenology in a spatially comprehensive, whole-ecosystem way, yet with fine enough spatial resolution to describe organism-level correlates and scaling phenomena.

1. Introduction

Forest phenology has gained wide recognition as a sensitive indicator of global change, and determines the timing of ecosystem processes that may elicit feedbacks within the earth system (Morisette et al., 2009; Polgar and Primack, 2011; Richardson et al., 2013). The advance of spring onset in temperate forests in recent decades (Ault et al., 2015; Miller-Rushing and Primack, 2008; Schwartz et al., 2006), and earlier canopy activity in the spring time, have been linked to increased carbon sequestration in forest ecosystems (Badeck et al., 2004; Keenan et al., 2014b; Richardson et al., 2010). Autumn extension of the growing season has also been shown to increase net annual productivity (Dragoni et al., 2011; Keenan et al., 2014b). As understanding of the causal factors of forest phenology develops, both global scale observations from satellite remote sensing, and plot scale studies of trees, will play crucial roles in linking phenological processes to ecosystem function (Cleland et al., 2007; Ibáñez et al., 2010; Menzel et al., 2006; Morisette et al., 2009; Vitasse et al., 2009).

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Harmonizing such diverse scales of information presents distinct challenges to the characterization of phenology. Investigators rely on satellite remote sensing for a complete view of the earth system, but at the expense of spatial resolution, which is typically in the hundreds of meters for global phenology data (Cleland et al., 2007; Verger et al., 2016; White et al., 2009; Zhang et al., 2006, 2003). Discerning the plant physiological processes governing phenology transitions relies on plot scale observations and experiments with individuals, which must be scaled up to represent ecosystem processes (Jarvis, 1995; Stoy et al., 2009); heterogeneous landscapes, composed of diverse plant communities, complicate the scaling process (Doktor et al., 2009; Hufkens et al., 2012; Klosterman et al., 2014). Even within one plant community type, limited ground-based observations may not accurately represent variability in ecosystem dynamics, if there is significant microclimatic variation (Fisher and Mustard, 2007).

These challenges highlight the need for phenology observation at intermediate scales, such as the canopy scale of phenocams (Richardson et al., 2007). These tower-mounted digital cameras can be used to obtain high temporal resolution, near-surface phenology data, akin to the vegetation indices of satellite remote sensing (Huete et al., 2002; Verger et al., 2016). Phenophase transition dates estimated from digital images have been shown to correlate with plant life cycle features, such as spring budburst and autumn senescence, carbon assimilation, and leaf physiology parameters (Keenan et al., 2014a; Toomey et al., 2015; Wingate et al., 2015; Yang et al., 2014).

While the low cost and familiar technology of digital cameras makes the phenocam method popular (Brown et al., 2016), their stationary, tower-mounted perspective limits the area of observation. Aerial photography is a natural extension of the phenocam technique. The recent technological revolution in unmanned aerial vehicles (UAVs), also known as drones, makes it feasible to collect aerial images with the temporal resolution necessary to monitor plant phenology events (Anderson and Gaston, 2013; Berra et al., 2016; Dandois and Ellis, 2013; Lisein et al., 2015). A low cost approach is possible (total hardware and software cost ~\$2000), using a consumer grade digital camera mounted on a UAV, and photogrammetry software to create georeferenced mosaic images, similar to imagery available from platforms such as Google Maps. UAVs continue to find new applications in plant science and ecology, including detailed characterization of the 3D structure of individual tree crowns (Gatziolis et al., 2015), 3D structure and color properties of forest canopies (Dandois and Ellis, 2013), and micro-topography of Antarctic mosses (Lucieer et al., 2014). In the context of tree phenology, recent studies used UAV photography in a validation study showing that ground-based observations of spring budburst are correlated with individual tree-scale analyses of digital photography (Berra et al., 2016), and presented phenological analyses of individuals as a method for identifying tree species (Lisein et al., 2015).

Here, we use a lightweight UAV to identify spring and fall phenophase transition events on a landscape scale (5.4 ha area) corresponding to a MODIS pixel, with fine spatial resolution (10 m, dividing the MODIS pixel in to 540 micro-pixels). We break this area down into plant communities, and use a detailed map of tree species and *in-situ* phenology observations to explore variance between and within communities. Then, by using several resolutions of image analysis, as well as medium and coarse resolution remote sensing (Landsat and MODIS), we describe the nature of spatial scaling in phenophase transition dates. Specifically, we answer these questions:

- What is the timing of phenology events between and within plant communities in a mixed forest ecosystem (deciduous trees, evergreen trees, wetlands) and how do they scale up to aggregate measures of ecosystem phenology?
- What is the biological interpretation of phenophase transitions derived from UAV photography, and how well does *in-situ* observation of a small set of individuals (3–5) represent the larger deciduous community?
- To what degree does spatial variation in phenology correlate to differences in species assemblage?
- What are the statistical relationships of landscape phenology transition dates across different spatial resolutions?

2. Methods

2.1. Study site

We conducted our study at Harvard Forest in Petersham, MA. The study area is a mixed deciduous-evergreen forest, with some woody wetlands, annual mean precipitation of 110 cm, and a temperate climate with mean annual temperature 7.1 °C. Deciduous trees in the study area include predominantly red oak (*Quercus rubra*) and red maple (*Acer rubrum*), but also yellow birch (*Betula alleghaniensis*), American beech (*Fagus grandifolia*), and black oak (*Quercus velutina*).

2.2. Digital image acquisition and processing

Within Harvard Forest, our primary study area was a 250 m MODIS pixel (ground area 5.4 ha) containing the PhenoCam mounted on the Environment Measurement Station tower (EMS; 42.5378, −72.1715; the 'harvard' PhenoCam, see http://phenocam.sr.unh.edu/). We obtained aerial photography over the primary study area using a UAV (3DR ArduCopter Quad-C Frame, 3D Robotics, Berkeley, CA) equipped with a Canon Powershot A3300 camera. The camera took photos continuously throughout each flight, using an intervalometer script programmed with the Canon Hack Development Kit (CHDK, http://chdk.wikia.com/wiki/CHDK). Images were taken at a minimum shutter speed of 1/1000 s, with constant exposure during each flight. The same color balance was used for all acquisition dates, as consistent color balance has been shown to be important for reliable digital camera observations of phenology (Richardson et al., 2009). We recorded images in the JPEG file format, as opposed to RAW, for faster image capture time and increased frequency of photos during flight. The utility of JPEGs for plant phenology study has been thoroughly demonstrated (Ahrends et al., 2008; Keenan et al., 2014a; Sonnentag et al., 2012; Toomey et al., 2015). We used the same camera and image settings for all flights, and took pictures of a gray reference square (ColorChecker classic, X-rite, Grand Rapids, MI) before each flight on all but the first date of image acquisition. Frequency of flights was roughly every five days during spring leaf out and every week during fall senescence and abscission in 2013, depending on weather conditions (acquisition dates shown in Fig. 1G). We programmed the UAV to fly between waypoints that covered the study area in two flights of approximately 10 min each (example flight logs shown in Fig. S1, with flight plan description in caption).

We combined camera imagery (~400 photos per acquisition date) into orthophotos covering the study area, using the PhotoScan software package (Agisoft, St. Petersburg, Russia). Initial estimates of camera location for each photo were derived from flight logs of the GPS on board the UAV, and timestamps of image files, using custom scripts written in Matlab (The Mathworks, Natick, MA). We used the following steps and options in PhotoScan:

1. Align Photos: Accuracy, High; Pair preselection, Ground Control; Point limit, 40000; Constrain features by mask, No.
2. Build Dense Cloud: Quality, Medium; Depth filtering, Moderate; Reuse depth maps, No.
3. Build Mesh: Surface type, Arbitrary; Source data, Dense cloud; Interpolation, Enabled; Face count, Medium.

We exported orthophotos from PhotoScan and performed final georeferencing in ERDAS IMAGINE AutoSync (Intergraph, Huntsville, AL) using aerial photography obtained from the Massachusetts Office of