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Remote sensing of spring phenology in northeastern forests: A comparison of methods, field metrics and sources of uncertainty

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ABSTRACT

Current remote sensing studies of phenology have been limited to coarse spatial or temporal resolution and often lack a direct link to field measurements. To address this gap, we compared remote sensing methodologies using Landsat Thematic Mapper (TM) imagery to extensive field measurements in a mixed northern hardwood forest. Five vegetation indices, five mathematical fits to model a continuous temporal response, and a suite of threshold estimates for "start of spring/season" (SOS) assessments were compared to field measurements of bud burst stage and hemispherical photo derived canopy structural metrics (transparency, leaf area index, greenness). Results indicated that a four-parameter logistic model based on at least five spring coverages of the Enhanced Vegetation Index (EVI) and a SOS threshold of 0.3 was most closely related to field metrics and most accurate in predicting the date of full leaf out. Plot level SOS was predicted with a mean absolute error of 11 days for all species and elevation combinations, but improved to 9 days for hardwood dominated plots and 7 days for sugar maple dominated plots. Mean absolute error was improved to 8 days when forest type (mixed, conifer hardwood) was used to refine predictions. The consistency of prediction errors across forest types indicates that while overall accuracy across pixels may be low, inter-annual comparisons of changes in phenology on a pixel basis may provide accurate assessments of changes in phenology over time. This was confirmed by application to seven years of independent phenology data predicted with 12 days of mean absolute error. However, image availability will be a limiting factor in areas of frequent cloud cover.

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1. Introduction

With an increasing interest in how climate impacts forest ecosystems, studies of plant phenology have become more common, spanning from single site field studies (Badeck et al., 2004) to continental remote sensing assessments (White, Thornton, & Running, 1997). In the northeastern United States and northern latitudes these studies indicate that warming trends have extended the growing season, with both an earlier spring and later autumn (Badeck et al., 2004; McNeil, Denny, & Richardson, 2008; Menzel, 2002; Tucker et al., 2001; White, Running, & Thornton, 1999; Zhang, Friedl, Schaaf, & Strahler, 2004), with implications for productivity (Badeck et al., 2004; White et al., 1999), carbon cycling (Cleland, Chuine, Menzel, Mooney, & Schwartz, 2007), nutrient and water cycling (McNeil et al., 2008), species interactions (Badeck et al., 2004), and disturbance regimes (Dukes et al., 2009; Kramer & Hänninen, 2009).

The majority of remote sensing efforts across the region have fit vegetation growth curves to temporal composites using coarse spatial resolution satellites, such as AVHRR and MODIS (deBeurs & Henebry, 2010; Fisher, Mustard, & Vadeboncoeur, 2006; Liang, Schwartz, & Fei, 2011). White et al. (1997) compared AVHRR derived Normalized Difference Vegetation Index (NDVI) to lilac leaf out with a mean absolute error of 26 days. A MODIS derived Enhanced Vegetation Index (EVI) was used by Zhang, Friedl, and Schaaf (2006) to predict full canopy cover at Hubbard Brook with a mean absolute error of 10 days. Liang et al. (2011) improved accuracy to a mean absolute error of 2 days using MODIS derived EVI and weighting field observations by dominant forest community type. While these studies offer a regional perspective, there are several scale-based limitations. Because of the large degree of heterogeneity in species composition, soil type, forest fragmentation, land use (mixed pixels) and elevation found in northeastern forests, the use of such coarse resolution assessments limits the evaluation of spatial variability in phenology (Fisher et al., 2006; Ibanez et al., 2010; Kramer & Hänninen, 2009). The success and interpretation of such efforts are also limited by the difficulty in linking plot level field measurements to satellite derived pixel values; as well as uncertainty in which phenological field metrics match sensor reflectance metrics (Fisher et al., 2006).

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The use of higher resolution imagery, such as from the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+), offers both the spatial resolution necessary to address these limitations, with the added advantage of a two decade archive that can provide a context for changes in phenology (Reed, Schwartz, & Xiao, 2009). While Landsat has been utilized for many vegetation applications, assessments of phenology are limited. In southern New England, Fisher et al. (2006) used an 18-year sequence of Landsat imagery to quantify spatial patterns in phenology. While they found a strong relationship between field measured phenological stage and satellite derived vegetation greenness, analyses were limited to hardwood dominated plots only. Most recently, Melaas, Friedl, and Zhu (2013) used a historical archive of Landsat TM imagery to examine patterns and variability in phenology at the Harvard Forest. While their results were promising ($r^2 = 0.80$), their assessment was limited to highly variable inter-annual assessments on a subset of trees contained within one Landsat pixel.

The goal of this study is to test previously published approaches to quantify phenology in northeastern hardwood and mixed forests using Landsat TM/ETM+ imagery, including the ability to differentiate subtle differences in phenology driven by species demographics and topographical variability. Because there is no standard method for phenology assessment using satellite imagery, and even less exploration of methodological options using Landsat, this paper focuses on the comparison of many reflectance products, curve fits, threshold values and field metrics in order to identify the most accurate approach to quantify the start of spring across a heterogeneous landscape. Our specific objectives include to:

- Identify the most accurate vegetation index, logistic model, and threshold for detecting the start of spring (SOS).
- Assess the impact of temporal frequency of imagery on SOS predictions.
- Examine the relationships between vegetation indices and various phenological field metrics to better understand what the sensor is characterizing and which phenological stages are most accurately predicted.
- Characterize potential sources of error in remote sensing SOS estimates.

2. Methods

2.1. Study area

Sampling a variety of sites is important in the northeast because of the heterogeneity of species composition and site characteristics across the landscape. To this end, we established 32 0.1 ha plots that were assessed every 2–4 days from March to July of 2011 across north/central Vermont (Fig. 1). This region was selected based on the overlap of Landsat paths 13 and 14 (row 29), effectively doubling the frequency of image dates available for analysis. Plot selection was designed to capture a range of elevations (60 to 780 m), forest cover types, and landscape positions while still providing repeated sampling of dominant canopy compositions. This included 19 northern hardwood stands (dominated by *Acer saccharum* Marsh., *Acer rubrum* L., *Betula alleghaniensis* Britton and *Fagus grandifolia* Ehrh.) and 12 mixed stands (including the species listed above and *Quercus rubra* L., *Pinus strobus* L., *Tsuga canadensis* L., and *Abies balsamea* L.). One pure conifer plot (*Pinus strobus*) was included as a reference, to see how vegetation index curves appear for species that retain foliage year-round. At each site, stand composition and topography were consistent across a larger 100 m area to minimize noise from misregistration of plot locations to image pixels.

2.2. Field phenology assessments

Field phenology methods were adapted to match as closely as possible guidelines from several active phenology monitoring programs conducted by the Vermont Department of Forest Parks and Recreation, Vermont Monitoring Cooperative, Proctor Maple Research Center, and Hubbard Brook Experimental Forest. Our modified approach categorized a tree into one of five phenology field rank (PFR) categories, from dormancy to full leaf out (Table 1) based on the dominant phenological stage assessed across the entire canopy. We recorded observations for all dominant, codominant and understory trees within 20 m of plot center. To scale PFR from individual trees to the plot level we calculated a plot average based on a species average weighted by its plot percent basal area. This ensured that variation within trees of the same species and variation among species on a plot were captured. While the initial tree level phenology rankings are ordinal in scale, both plot average PFR and vegetation indices are continuous in scale and therefore allow a potentially more precise comparison between field and satellite metrics (Reed et al., 2009).

To include canopy structural metrics, we collected digital images at each plot using a Nikon D90 digital camera with a Sigma 8 mm 180 degree circular fisheye lens. In order to minimize common errors reported in canopy closure estimates due to contrast confusion, slope or time of day (Breda, 2003; Frazer, Fournier, Trofymow, & Hall, 2001; Jonckheere et al., 2004; Sonnentag et al., 2012), each photo was taken at a fixed height and location over plot center, under cloudy conditions or early morning/late afternoon, with consistent auto focus, aperture, and ISO settings.

We used Gap Light Analyzer (GLA) (v2.0) software (Simon Fraser University (SFU), Burnaby, British Columbia, Canada and Institute of Ecosystem Studies (IES), Millbrook, New York, USA) to calculate percent canopy openness and Leaf Area Index (LAI 4 ring – effective leaf area index integrated over zenith angles 0–60°, and LAI 5 ring – effective leaf area integrated over the zenith angles 0–75°) (Frazer, Canham, & Lertzman, 1999). Images were isolated to the blue color plane in order to improve the contrast between foliage and sky (Frazer et al., 1999; Leblanc, Chen, Fernandes, Deering, & Conlye, 2005), with canopy/sky thresholds optimized using SideLook 1.1 (Jarčuška, Kucbel, & Jaloviar, 2010; Minkova & Logan, 2007; Nobis & Hunziker, 2005). Canopy "greenness" was approximated using software available from Digital Earth Watch (http://www.globalsystemsscience.org/software/download). This approach utilizes a normalized color channel brightness (percent red, green and blue) to quantify "green-up" associated with spring phenology (Richardson, Braswell, Hollinger, Jenkins, & Ollinger, 2009; Richardson et al., 2007).

2.3. Image processing

We downloaded Level 1T Landsat TM and ETM+ imagery from the USGS Global Visualization Viewer (U.S. Department of the Interior, 2012) for all image dates between March 10 and July 25, 2011 with less than 60% cloud cover. In order to maximize image availability, all scenes from the overlap of paths 13 and 14 were reprojected to UTM zone 18N for use in this study. This resulted in 15 images (out of 37 possible dates) for analyses. However, because of partial clouds across the study area, the highest number of image dates at any of our established field plots was 12. Level 1T processing includes an orthorectification, but to ensure consistency across image dates in our region of high terrain variability, each image was georegistered to a cloud-free, mid-summer 2002 control image using a 3rd order polynomial warping transform and nearest neighbor resampling. Reported fit of registration was below 0.2 pixels (RMSE 6m), based on a minimum of 50 ground control points located across the full extent of each image.

Raw DN values for bands 1–5 and 7 were converted to reflectance using ENVI's Landsat TM calibration tool (ITT Visual Information Solutions, 2009). This transformation accounts for solar illumination angle, minimum/maximum radiance and gain for each band, and scene specific atmospheric path length (Chander, Markham, & Helder, 2009). In order to minimize differences in atmospheric conditions between image acquisition dates we applied a dark object subtraction in ENVI that used the lowest DN that first represents a sharp increase in the number of pixels (Chavez, 1988; Soudani, Francois, Le Marie, Le

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