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SHORT COMMUNICATION

Digital herbarium archives as a spatially extensive, taxonomically discriminate phenological record; a comparison to MODIS satellite imagery

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Abstract This study demonstrates that phenological information included in digital herbarium archives can produce annual phenological estimates correlated to satellite-derived green wave phenology at a regional scale ($R=0.183$, $P=0.03$). Thus, such records may be utilized in a fashion similar to other annual phenological records and, due to their longer duration and ability to discriminate among the various components of the plant community, hold significant potential for use in future research to supplement the deficiencies of other data sources as well as address a wide array of important issues in ecology and bioclimatology that cannot be addressed easily using more traditional methods.

Keywords Phenology · Plant ecology · Herbarium records · Remote sensing · Landscape ecology

Introduction

In the face of growing concerns about the effects of changes in climate, phenology, or the study of the timing of seasonal biological events, has emerged as one of the clearest and most responsive mechanisms for exploring the relationship between climate conditions and the biosphere (Schwartz 2003). However, as phenological science progresses toward the development of long-term assessments and predictive models of regional and continental phenological change, the limitations of existing phenological records are becoming increasingly apparent.

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Satellite imagery—the predominant source of data for phenological modeling at regional or continental scales (Reed et al. 2009; White et al. 2009)—is limited both by its inability to discriminate among plant taxa and by the comparatively recent development of satellite systems capable of phenological monitoring. The other robust source of spatially extensive phenological data in North America, the lilac-honeysuckle network established by Caprio, provides data as far back as 1957, but includes only three non-native taxa and is restricted to regions with a sufficient chilling period for those species to grow (Schwartz 2003). Thus, neither data source is able to discriminate among specific components of the plant community. While additional phenological records exist that are capable of analyzing the different phenological responses of multiple species (Abu-Asab et al. 2001; Cook et al. 2007), they are typically local in scale and are of limited utility in addressing regional phenological variability.

Herbaria, or collections of pressed plant samples collected to document taxonomic diversity, represent an increasingly popular phenological record uniquely suited to address both of these concerns. Many previous studies have indicated that herbarium records within highly localized, well-sampled locations produce similar estimates of long-term phenological changes to those produced by in-situ observation (Bolmgren and Lunnberg 2005; Miller-Rushing et al. 2006; Primack et al. 2004; Robbirt et al. 2011). However, the process of assessing the phenological status and location of each sample is extremely time consuming. With the exception of the few studies that use digital herbarium databases (Gallagher et al. 2009; Neil et al. 2010) or consider only intra-annual phenological patterns without incorporating interannual changes, (Boulter et al. 2006; Zalamea et al. 2011), the resulting limitations in sample size have restricted most phenological studies using herbarium data to either single species (Lavoie and Lachance 2006; Gaira et al. 2011; Robbirt et al. 2011), or highly local

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areas (Primack et al. 2004). Additionally, this has thus far limited herbarium-based studies of interannual phenological variation to a decadal or multi-decadal resolution. The advent of digital archiving efforts among an increasing number of herbaria will facilitate analysis of the vast wealth of phenological data they represent and allow the full usage of such records for spatially extensive, taxonomically discriminate examinations of phenological change. Further, this may also allow a finer temporal resolution than has previously been considered possible with such records.

However, as most samples are collected during flowering, herbarium records are useful primarily in evaluating that phenophase. Additionally, most databases include simple binary notation as to whether each sample is flowering/not flowering and fruiting/not fruiting, severely limiting their utility in estimating the timing of specific events such as date of first flower. Spatial information is also rarely registered in a standardized fashion below county level, restricting the spatial resolution possible when utilizing large numbers of records. Additionally, many annual gaps occur at a county level, and some spatial collection biases may occur in highly heterogenous areas (Loiselle et al. 2007). While these records do include virtually all species documented in an area, some groups of plants, such as graminoid (grasslike) species, are unsuitable for assessment through digital herbarium records due to a lack of accurate phenological assessment among those taxa, and species of particular taxonomic interest or those having charismatic blooms may be collected more commonly than other co-occurring species.

Despite these issues, such records provide a unique window into the responses of the plant community to climate variation, and may facilitate the use of herbarium records as a measure of overall ecosystem phenology capable of detecting variations not only at a multidecadal scale, but also at interannual resolutions that require evaluation of a previously prohibitive number of samples each year. This study will demonstrate that (1) digital herbarium records retain a significant amount of explanatory power over wide spatial scales even when pooled across a broad array of species, and (2) interannual variations in phenological timing derived from digital herbarium records are sufficiently correlated to other ecosystem-wide measures of phenological variation (in this case, MODIS derived greenup estimates) to represent a robust measure of ecosystem-level plant phenology across a wide range of plant species.

Data and methods

Herbarium records were acquired with permission from the herbaria of Clemson University, the University of South Carolina, and Florida State University, for a total of 5,949 observed flowering specimens collected from 2000 to 2009. Satellite imagery consisted of all MODIS 5 leaf area index (LAI) 8-day composite images within South Carolina from the years 2000–2009 (507 images in total) from the Land Process Distributed Archive Center (https://lpdaac.usgs.gov/). As this work crosses a wide array of vegetation types, MODIS LAI algorithms were considered preferable to NDVI or EVI as they account for qualitative differences in vegetation structure (Knyazikhin et al. 1999; Myneni et al. 2002), and provide a more structural measure of vegetation.

Image preparation and estimation of greenup timing

After exclusion of cloud-contaminated pixels, all images were overlaid with a vector-based 3 km fishnet grid. Each grid cell was assigned to the county in which its center fell, and mean LAI values in each cell were computed for each image.

Rate of change in LAI was determined by calculating a linear slope for each 40-day period (five successive images) using a rectangular window function. For each cell, greenup was estimated to occur at the midpoint of the 8-day composite image located in the center of the 40-day time series producing the highest positive slope, with an implicit 4-day uncertainty. County-level averages of greenup timing were then calculated across all counties and years. Due to false estimations of LAI increase in late fall caused by cloud contamination, only 40-day windows with at least one uncontaminated pixel in four out of the five composite images were considered.

Herbarium data preparation and correlation analysis

First, observations of spore-bearing and graminoid (grasslike) species were excluded from analysis due to unreliable phenological assessments. Average observed flowering dates among all observations were then calculated for each remaining species. In order to exclude winter-flowering species and remove errors caused by occasional second flowering in fall by some spring flowering species (I.W.P., personal observation), all flowering samples collected more than 150 days after median flowering were removed, as were taxa with average flowering prior to day 45 or after day 310. Remaining samples included 5,949 samples across 1,185 species, which represented the majority of non-graminoid species found within South Carolina across all growth habits and counties in South Carolina. Average flower timing was then calculated within each county for each year, and correlation analysis was conducted between MODIS-derived greenup estimates and average flowering blocked by county and year. Data was present within all counties for at least one year of the study period (Fig. 1). In order to identify the correlation of the two metrics across spatial and interannual variation independently, correlation

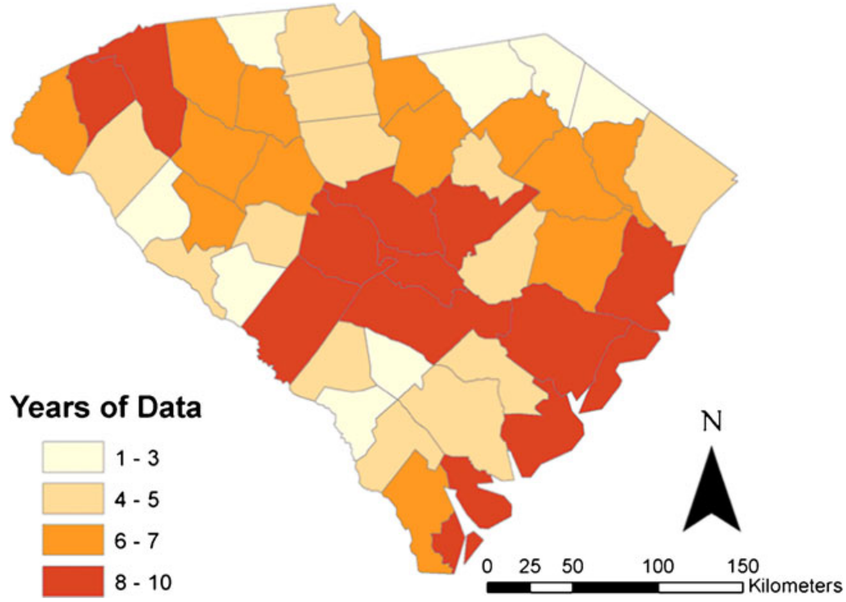

Fig. 1 Years of herbarium data among South Carolina counties from 2000 to 2009

analyses were also conducted when pooled among counties and years.

Results

MODIS-derived greenup timing was correlated significantly with herbarium-derived flower timing over 2000–2009 (R= 0.183, P=0.03, df =267). Although similar correlation was detected when only interannual variation was considered, (R=0.221, P=0.568 df =9, Fig. 2), when considered singly, neither interannual nor spatial correlation (R=0.107, P=0.107 df =46) were statistically significant due to the reduction in degrees of freedom in these cases.

Discussion

These results indicate that multi-taxa analysis of herbarium records are capable of detecting interannual changes in phenological timing despite the various limitations inherent in herbarium records. Given the paucity of samples in 2008 along with the extreme estimated phenology from that year (Fig. 2), smoothing or exclusion of poorly sampled years may be required. However, such deficiencies may be somewhat comparable to data quality issues present in other data sources, such as the cloud contamination of satellite imagery. While the limited span of satellite records and the large number of missing years within the herbarium records for some counties (Fig. 1) prevented useful analysis of spatial variation, additional work incorporating the full duration of herbarium collections will address this issue.

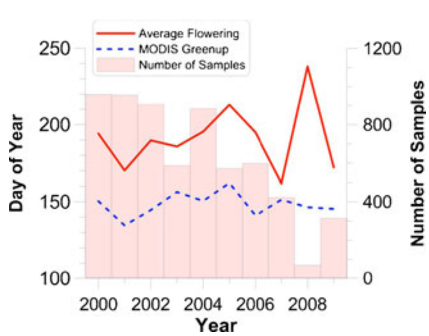

Fig. 2 *Solid lines* Average flowering time estimated from herbarium records, *dotted lines* MODIS-derived greenup estimates. *Bars* Number of herbarium samples collected in flower each year

Given the promising nature of this preliminary study, future work should expand to address a variety of important issues that cannot be addressed easily by existing techniques. First, herbarium records may be used in conjunction with life history and physiological data to determine the relative importance to patterns of historical phenological variations of factors such as phylogeny, morphology, drought and shade tolerance, or annual or perennial life cycles. Consideration of various components of the plant community may also be used to contextualize the relationship of other phenological measures such as satellite imagery to specific components of the plant community. Because of their ability to evaluate myriad species' phenology independently and examine phenology over wide areas, these records also possess a unique capability to evaluate the relative roles of inter- and intra-species phenological plasticity on regional and continental patterns of landscape phenology. Finally, as many collections date back to the late 1800s, such records may be used to extend our historical record of North American phenology. As more herbaria across the country digitize their holdings, such records may play a unique role in the development of a continental, and eventually global, assessment of the history of our biosphere's relationship to changes in climate.

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