ISPRS Journal of Photogrammetry and Remote Sensing 142 (2018) 151–161

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Intra-annual phenology for detecting understory plant invasion in urban forests

Kunwar K. Singh*, Yin-Hsuen Chen[1], Lindsey Smart, Josh Gray, Ross K. Meentemeyer

Center for Geospatial Analytics, North Carolina State University, Raleigh, NC 27695, USA
Department of Forestry & Environmental Resources, North Carolina State University, Raleigh, NC 27695, USA

ARTICLE INFO

Keywords:
Biological invasion
Vegetation indices
Vegetation phenology
Normalized difference vegetation index
Ligustrum sinense
Chinese privet
Random forest

ABSTRACT

Accurate and repeatable mapping of biological plant invasions is essential to develop successful management strategies for conserving native biodiversity. While overstory invasive plants have been successfully detected and mapped using multiple methods, understory invasive detection remains a challenge, particularly in dense forested environments. Very few studies have utilized an approach that identifies and aligns the acquisition timing of remote sensing imagery with peak phenological differences between understory and overstory vegetation types. We investigated this opportunity by analyzing a monthly time-series of 2011 Landsat TM data to identify acquisition periods with the highest phenological differences between understory and overstory vegetation for detecting the spatial distribution of the exotic understory plant *Ligustrum sinense* Lour., a rapidly spreading invader in urbanizing regions of the southeastern United States. We used vegetation indices (VI) to establish intra-annual phenological trends for *L. sinense*, evergreen forest, and deciduous forest located in Mecklenburg County, North Carolina, USA. We developed Random Forest (RF) models to detect *L. sinense* from those time steps exhibiting the highest phenological differences. We assessed the relative contribution of VI and topographic indices (TI) to the detection of *L. sinense*. We compared the top performing models and used the best overall model to produce a map of *L. sinense* for the study area. RF models that included VI, TI, and Landsat TM bands for March 13 and 29, 2011 (the periods with highest detected phenological differences), produced the highest overall accuracy and Kappa estimates, outperforming the combination of VI and TI by 8.5% in accuracy and 20.5% in Kappa. The top performing model from the RF produced a Kappa of 0.75. Our findings suggest that selecting remote sensing data for a period when phenological differences between *L. sinense* and forest types are at their peak can improve the detection and mapping of *L. sinense*.

1. Introduction

Biological invasions have become a major non-climatic driver of global change (Ricciardi, 2007). They pose serious threats to native biodiversity, ecosystem services, and human health and well-being (Pejchar and Mooney, 2009; Pimentel et al., 2000). Successful management requires accurate and repeatable mapping of biological invasions at regional scales. Methods like species distribution models and predictive modeling have addressed biological mapping and invasion problems (Davis et al., 2016; Nielsen et al., 2008), but costs of field data collection are high and implementation at regional scales is often challenging. Remote sensing technologies have shown great potential for mapping invasive plants because of their broad spatial extent and moderate- to fine- spatial and temporal resolution (Bradley, 2014; Huang and Asner, 2009; Shouse et al., 2013). While methods that combine remote sensing data and advanced algorithms are often the first choice to overcome the limitations of traditional species distribution modeling, applications utilizing remote detection of understory invasive plants remain limited due to the interference of overstory canopies and a lack of plant-specific methodologies (Tuanmu et al., 2010). Multiple vegetation factors limit the successful mapping of understory invasive plants. For example, the complex and non-linear interactions between the spectral signatures of over- and understory components are difficult to separate (Eriksson et al., 2006). Forest characteristics, such as canopy closure, canopy shadow, density of invasive plants, and terrain variability, can also hinder successful mapping (Asner et al., 2008). The characteristics of the biological invaders themselves, such as variable height, and evergreen to semi-deciduous

* Corresponding author.
E-mail addresses: kksingh@ncsu.edu (K.K. Singh), eisen520@ufl.edu (Y.-H. Chen), lssmart@ncsu.edu (L. Smart), jmgray2@ncsu.edu (J. Gray), rkmeente@ncsu.edu (R.K. Meentemeyer).
[1] Department of Geography, University of Florida, Gainesville, Florida, USA

https://doi.org/10.1016/j.isprsjprs.2018.05.023
Received 15 February 2018; Received in revised form 27 May 2018; Accepted 31 May 2018
Available online 15 June 2018

leaves, make it harder to track their spread at both the desired scale and cost. However, intra-annual phenology, estimated using remote sensing data, might allow for improved mapping of understory invasive plants.

A variety of solutions for accurate, repeatable, and efficient invasive plant detection and mapping have been proposed and studied, including phenological approaches from optical imagery, imaging-spectrometry, LiDAR (light detection and ranging), or some combination of the aforementioned methods (Ghulam et al., 2014). Both active and passive remote sensing data have been utilized in biological invasion detection and mapping. For example, active remote sensing technologies like LiDAR have been used alone, and in conjunction with passive remote sensing data, to quantify a diverse array of invasive species representing different growth forms (Chance et al., 2016; Peerbhay et al., 2016; Singh et al., 2015). LiDAR and its combination with passive remote sensing data can be effective in accurate detection of invasive plants, but the cost and resources required to acquire and process LiDAR data often limit the utility of these data for regional analyses (Singh et al., 2012). LiDAR and other high-resolution remote sensing data (e.g., IKONOS) are often not available for intra-annual time scales and rarely match spatial extents and temporal resolutions fine enough to capture the important biophysical characteristics of vegetation and phenological changes. Moderate-resolution multispectral satellite imagery, such as Landsat-series data, offers an appropriate spatial and spectral resolution at relatively fine temporal scales and are freely available.

Despite the availability of a variety of passive remotely-sensed data, methodological approaches using intra-annual phenology to detect understory invasive plants are still evolving (Barbosa et al., 2016). Various characteristics of understory invasive plants (e.g., variable height, canopy cover, vegetation density, and shadows) not only hamper detection but also make the application of passive remote sensing data more challenging than for overstory species. Few studies have explored the applicability of both moderate-resolution satellite imagery and high-resolution aerial imagery for understory invasive species detection. Perroy et al. (2017) explored the impacts of overstory vegetation cover, imagery resolution, and camera look angle on invasive detection using an unmanned aircraft system. Using a combination of oblique and nadir look angles, researchers detected understory invasive plants, but only within a particular threshold of overstory vegetation density. Barbosa et al. (2016) used spectral unmixing methods and a single-class classification approach along with imaging spectrometer data to detect the understory invasive strawberry guava (*Psidium cattleianum*).

Studies have also used phenological approaches in combination with passive remote sensing data for both overstory and understory invasive species detection. Plant phenological development can be established with time-series remote sensing data by estimating the intra- and inter-annual phenology that can then be used for improved detection and mapping of understory invasive plants. Tuanmu et al. (2010) used phenology metrics generated from a time-series of MODIS (Moderate Resolution Imaging Spectroradiometer) data to successfully map understory bamboo by characterizing the phenological features of forests in Wolong Nature Reserve, China. Ji and Wang (2016) successfully mapped saltcedar (*Tamarix* spp.) invasions by identifying the peak coloration and using this fall phenological trait with Landsat TM imagery in their mapping efforts. Wilfong et al. (2009) extended these methods further using Landsat imagery and derived vegetation indices (VI) to detect differences in leaf phenology between Amur honeysuckle (*Lonicera maackii*) and native woody species and estimate the cover of Amur honeysuckle in forest understories. Clinton et al. (2010) studied the interaction between time-series of NDVI, derived from MODIS data, and precipitation to measure differences between native grasses and the invasive downy brome (*Bromus tectorum*) for estimating the geographical distribution and abundance of downy brome in the Great Basin rangelands. Dymond et al. (2002) suggest that multi-temporal satellite images can be used to detect phenological variation between species. Broadly, these results demonstrated that, if the phenology of an understory invasive plant differs from native forest species for any part of the year, the difference might offer spectral remote sensing opportunities for detection and mapping. However, most of the studies previously mentioned relied on *a priori* information or expert knowledge to determine periods that capture a plant's unique phenological signature. Additionally, studies have not taken full advantage of the fall phenology of forests to capture the spectral characteristics of the understory invasive plants while they are exposed. To address the limitations in previous studies, we used optical remote sensing data to (1) detect the unique phenological signatures of understory invasive plants regardless of the availability of *a priori* information, and (2) used this information to map the extent and distribution of invasive species. Although this methodological approach has potentially broad applications, it is still underutilized for understory species detection.

Using *Ligustrum sinense* Lour. as a case study, commonly known as Chinese privet, we focused on forests of Mecklenburg County, North Carolina, USA, to explore the utility of intra-annual time-series analyses of Landsat TM imagery for detection and mapping by identifying time periods of peak phenological differences between *L. sinense* and dominant forest types (e.g., deciduous and evergreen). Spectral indices from those periods were then used with the Random Forest (RF) algorithm to map the extent and distribution of the invasive plant. We quantified the contribution of VI, topographic indices (TI), and spectral bands from periods of peak and non-peak phenological differences to understand the added benefit of this methodological approach. We answered the following research questions: (1) can the phenology of *L. sinense* be differentiated from evergreen and deciduous forest; (2) if yes, what part of the year is the phenological difference at its peak; and (3) which indices derived from Landsat TM imagery and elevation data are most successful at detecting and mapping *L. sinense*? By developing the top performing models with data from the peak phenology difference, and understanding the relative contributions of remote sensing predictors, we can more accurately map the occurrence of *L. sinense* across the study region. In addition, by evaluating the benefits of the added time-series analysis, we provide a practical approach for invasive plant detection in diverse and heterogeneous landscapes.

2. Material and methods

2.1. Study area

This study focuses on an exotic understory plant, *L. sinense,* in forests of Mecklenburg County, North Carolina, USA. The county is located within the Piedmont physiographic province in the center of the Charlotte Metropolitan Area of North Carolina, covering an area of 1415 km^2 (Fig. 1). The region is characterized by rolling topography with a forest-farmland mosaic comprising a mix of secondary growth oak-hickory-pine forests that have developed on former timber plantation sites as well as through natural regeneration on abandoned farmland. Rapid urbanization has converted the forest and farmland mosaic into an array of developed land-use types. Extensive anthropogenic activities, such as repeated disturbance and fragmentation, have provided suitable conditions for the colonization and spread of invasive species (Davis et al., 2016). As such, occurrence of *L. sinense* at forest edges throughout the county is common. In recent years, *L. sinense* has invaded over one million hectares of forests throughout the southeastern United States (Miller et al., 2008). Its ability to tolerate a wide range of environmental conditions makes it well suited to grow in varied habitats, such as abandoned farmlands, disturbed areas, floodplains, and riparian zones of forests (Brown and Pezeshki, 2000). Often, it forms impenetrable thickets with a typical height range of 1–5 m,