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Linking remote sensing and various site factors for predicting the spatial distribution of eastern hemlock occurrence and relative basal area in Maine, USA

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ABSTRACT

Introduced invasive pests are perhaps the most important and persistent catalyst for changes in forest composition. Infestation and outbreak of the hemlock woolly adelgid (*Adelges tsugae*; *HWA*) along the eastern coast of the USA, has led to widespread loss of hemlock (*Tsuga canadensis* (L.) Carr.), and a shift in tree species composition toward hardwood stands.

Developing an understanding of the geographic distribution of individual species can inform conservation practices that seek to maintain functional capabilities of ecosystems. Modeling is necessary for understanding changes in forest composition, and subsequent changes in biodiversity, and one that can be implemented at the species level. By integrating the use of remote sensing, modeling, and Geographic Information Systems (GIS) coupled with expert knowledge in forest ecology and disturbance, we can advance the methodologies currently available in the literature on predictive modeling.

This paper describes an approach to modeling the spatial distribution of the less common but foundational tree species eastern hemlock throughout the state of Maine (~84,000 km^2) at a high resolution. There are currently no published accuracy assessments on predictive models for high resolution continuous distribution of eastern hemlock relative basal area that span the geographic extent covered by our model, which is at the northern limit of the species' range. A two stage mapping approach was used where presence/absence was predicted with an overall accuracy of 85% and the continuous distribution (percent basal area) was predicted with an accuracy of 84%. Overall, these findings are quite good despite high variability in the training dataset and the general minor component that eastern hemlock represents in the primary forest types in Maine.

Eastern hemlock occurs along the southern half of the state stretching the east-west span with little to no occurrence in the northern regions. Several environmental and site characteristics, particularly average yearly maximum and minimum temperatures, were found to be positively correlated with hemlock occurrence. Eastern hemlock dominated stands appeared predominantly in the southwest corner of the state where HWA monitoring efforts can be focused. Given the importance of climate variables in predicting eastern hemlock, forecasts of future range shifts should be possible using data generated from climate scenarios.

1. Introduction

1.1. Motivation

We are experiencing a significant loss in biodiversity worldwide, this is considered to be important for a variety of reasons (Randall, 1991; Rolston, 2000), but recent attention has focused on its potential importance for the adequate functioning of the Earth's ecosystems (Schulze and Mooney, 1994; Heywood and Watson, 1995). Forest ecosystems are losing biodiversity through a variety of disturbances that are numerous, including land use, climate change, fire, and wind. In particular, invasive introduced species are disturbance agents to which temperate forests appear to have relatively little resistance (Richardson, 1998, but see Simberloff et al., 2002 for a treatment of tropical forests). As many as 19 introduced insect pests and pathogens are causing changes to

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forest structure, species composition, and ecosystem function of North American forests and it is anticipated that a warming climate will amplify the effects of these forest pests (Dukes et al., 2009).

In the northeastern United States, mean annual temperatures have increased by 0.8 °C over the last century with estimates that they will continue to increase from 2.1 to 5.3 °C by 2100 (Campbell et al., 2009). Changes in our climate will precipitate changes in biogeochemical cycling, resulting in potentially dramatic changes in forest composition and productivity (Weiskittel et al., 2011). These climate driven alterations will be coupled with the effects of other disturbances such as forest pathogens and forest management strategies (e.g., harvesting). Consequently, it is important to understand and forecast both current and future potential species habitat.

In particular, New England forests are currently experiencing a decline in eastern hemlock (*Tsuga canadensis* (L.) Carr.) due to the hemlock woolly adelgid (*Adelges tsugae*; HWA), an invasive, aphid-like pest introduced to the United States from Asia (Ellison et al., 2005). HWA can be found in 15 states along the eastern seaboard from Georgia to Maine (Stadler et al., 2005) including several counties in southern and mid-coast Maine (Maine Forest Service, 2014). Albani et al. (2010) predict that HWA will continue to move northward and will be established throughout the eastern hemlock range in Maine in the next 30 years.

Eastern hemlock is a late-successional conifer that, because of its deep shade and acidic litter, shapes stand microclimate and influences community and ecosystem characteristics (Eschtruth et al., 2006; Orwig et al., 2002). This strong influence on microclimate affects vegetation organization, successional dynamics, species diversity, and microenvironmental characteristics (Orwig and Foster, 1998). Eastern hemlock dominated forests represent unique characteristics that serve as critical wildlife habitat (Orwig et al., 2002).

Predicting eastern hemlock occurrence is complicated by the fact that it is difficult to distinguish from other conifers by spectral response alone (Doucette et al., 2009) particularly in mixed conifer stands, which is where it tends to occur in Maine. Ancillary GIS data representing environmental characteristics are often used in conjunction with satellite imagery to define patterns in vegetation cover (Kong et al., 2008). Narayanaraj et al. (2010) found strong relationships between eastern hemlock density (# ha^{-1}), basal area ($m^2\ ha^{-1}$) and elevation, distance to streams, and soil moisture. Boyce (2000) also found a strong relationship between the location of eastern hemlock trees and elevation, slope, and NW aspect. These previous analyses highlight the importance of topographic variables in describing the distribution of eastern hemlock, but acknowledge the diverse array of factors that influence it. Given the geographic extent of the study area in this present study, several potential predictors should be evaluated to find the most robust model. A working hypothesis for this analysis was that remote sensing, climatic, and topographic variables would be equally important for predicting both eastern hemlock occurrence and abundance.

1.2. Objectives

Developing an understanding of the geographic distribution of individual tree species can inform conservation practices that seek to maintain biodiversity of ecosystems. Mapping eastern hemlock in Maine will be crucial to response efforts by anticipating where HWA infestations will occur. The methodology developed and used here can also be applied to other species level inquiries in northern forests. The primary objectives for this paper were to: (1) predict the occurrence of a less common tree species, eastern hemlock across a large geographic extent that includes the species' northern range, (2) predict percent basal area of eastern hemlock where it occurs, and (3) map the species occurrence and percent basal area at a high resolution.

2. Methods

2.1. Study area

The state of Maine (~84,000 km^2) is located in the northeast corner of the New England region of the U.S. It is bordered by the Canadian provinces of Quebec and New Brunswick, the Atlantic Ocean, and by New Hampshire (see Fig. 1). It falls within mapping zone 66 (42°58′N to 47°28′N and 66°57′W to 71°5′W). Maine is nearly 90% forested and dominated by mixed northern hardwood stands comprised of over 62 tree species. The most prevalent of these species being balsam fir (*Abies balsamea* L.) Mill.), red maple (*Acer rubrum* L.), red (*Picea rubens* Sarg.), white (*Picea glauca* (Moench) Voss), and black spruce (*Picea mariana* (Mill.) B.S.P.), sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britton), and American beech (*Fagus grandifolia* Ehrh.) (Maine Forest Service 2013). Maine forests are bordered by Boreal Forests in the north and Central Hardwood Forests to the south and are sometimes referred to as "Acadian Forests".

2.2. Spatial database

A relatively comprehensive spatial database was compiled for the state of Maine comprised of satellite imagery, digital elevation models, and ancillary GIS data. Most of these data can be found and downloaded from the Natural Resources Conservation Services (NRCS) Geospatial Data Gateway (http://datagateway.nrcs.usda.gov). Over 30 different spatial data layers depicting ecological (e.g., biomass) or environmental (e.g., precipitation) phenomenon were explored to find good predictors for eastern hemlock. Predictor variables were selected by evaluating the coefficient of determination and variable importance plots produced by the randomForest algorithm with a threshold mean decrease in accuracy value of 20%. Preliminary analysis indicated eleven predictors that were most influential in describing eastern hemlock distribution, these were used in the final model and are described in detail below.

2.2.1. Remote sensing and Google Earth Engine

The use of satellite imagery and remote sensing in ecological and resource management research has been increasing steadily since the 1990s (Fassnacht et al., 2006). Multi-spectral imagery is helpful in discerning land cover types as different wavelengths of electromagnetic energy are reflected differently from different types of land cover. In choosing a remote sensing system some important considerations for researchers are: (1) cost, (2) temporal resolution (frequency of image acquisition), (3) spatial resolution (cell size), and (4) spectral resolution (number of wavebands detected). We chose Landsat-5 thematic mapper (TM), which is, arguably, the most popular mid resolution, passive remote sensor used in natural resource applications prior to the launch of Landsat 8 OLI in February 2013, a similar sensor that has replaced TM. For the study area the size of Maine, Landsat TM offers cost-effective imagery that has a revisit period of 16 days, 30 m pixel resolution (cell size), and is multi-spectral with 7 wavebands detected (3 visible, 1 near infrared, 2 mid-infrared, 1 thermal infrared). An individual Landsat TM scene covers approximately 26,000 km^2.

For complete coverage of the state of Maine, nine individual scenes are needed from 3 paths and 4 rows (listed here as Word-wide Reference System path/row: 10/29, 11/27, 11/28, 11/29, 11/30, 12/27, 12/28, 12/29, 12/30). Acquiring Landsat TM imagery