Using Landsat Imagery to Quantify Temporal and Spatial Patterns in Hemlock Decline

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Abstract

The purpose of this study was to detect and map temporal patterns of hemlock (*Tsuga canadensis*) health and decline over fourteen years, following infestation by the hemlock woolly adelgid (HWA) (*Adelges tsugae*) in northern New Jersey, a region of rugged terrain and heterogeneous, hemlock-mixed hardwood forests. Maps of estimated hemlock forest condition were derived using November/December scenes of Landsat Thematic Mapper data from the years 1984 (pre-HWA), 1992, 1994, 1996, and 1998. Each 30 m hemlock pixel, of 89,916 used for analysis (8,093 ha), was classified into one of four classes of hemlock forest health with 82% overall accuracy. The four health classes, based on the average percent defoliation of the canopy, are: Healthy/Light (<25%), Moderate (50%), Severe (75%), and Dead (100% defoliation). A GIS overlay analysis was performed on these five maps to detect temporal patterns in hemlock health. Each hemlock forest pixel in the resulting 119 unique patterns was classified into one of four general types. Type 1 pixels fluctuated between Healthy/Light and Moderate until 1998. Type 2 pixels declined to Severe, followed by an improvement to Healthy/Light or Moderate by 1998. Type 3 pixels declined to Severe, followed by an improvement to Healthy/Light or Moderate, and a second decline to Severe by 1998. Type 4 pixels declined steadily to death before or by 1998, though at different rates. The four types are scattered throughout the study area, but show heavy concentrations in some places. Pixels of each type also are clustered within hemlock stands. These four patterns correlate with ground data collected in eleven New Jersey hemlock Forest Health Monitoring plots.

This study shows that hemlock health, decline, and improvement can be monitored with remote sensing techniques. The resulting information on the spatial and temporal patterns of hemlock decline shows promise for developing models of vulnerability and monitoring the success of predator releases across spatial and temporal scales. In cooperation with the USDA Forest Service, we will test our methods and models in other mid-Atlantic states, refining the methodology as needed. Field data collected by state and federal agencies over many years throughout the Northeast will be invaluable for verifying and improving cartographic models of hemlock forest health.

Keywords:

Landsat, monitoring, patterns, spatial, temporal.

Introduction

Modeling the vulnerability of eastern hemlock, *Tsuga canadensis* (Carriere), to infestation by the hemlock woolly adelgid (HWA), *Adelges tsugae* (Annand), has become an important goal in hemlock research. To develop such a model, we must first detect and quantify spatial and temporal patterns in the decline process and identify any environmental factors associated with these patterns. This requires extensive spatial and temporal data of hemlock forest health. Landsat satellite data and image processing techniques provide the necessary information about the condition of hemlock forest over many years and over large areas (Royle and Lathrop 1997; Bonneau et al. 1999; Young and Morton 2002).

In earlier work, we modeled and mapped the health of hemlock forests in the New Jersey Highlands at the scale of a 30 m Landsat pixel using two scenes of Landsat imagery (1984 and 1994), change-detection techniques, and field data (Royle and Lathrop 1997). However, two scenes of Landsat data alone did not indicate how long a stand had been defoliating or reveal spatial and temporal patterns in hemlock decline. Multiple dates of imagery were used to track the spread of HWA-related damage and identify transition patterns in hemlock health in Connecticut (Bonneau et al. 1999). This Connecticut study was conducted on a small number of hemlock stands in landscapes of limited heterogeneity. The remote sensing of hemlock-mixed hardwoods forests across a region of rugged, highly heterogeneous landscapes, however, poses many challenges (Royle and Lathrop 2002). For the past several years we have continued to improve and refine our methodology for monitoring and mapping hemlock forest health throughout all of northern New Jersey for a wide range of hemlock habitats spanning fine to coarse scales.

The purpose of this study was to detect, quantify, and map temporal patterns of hemlock decline over a 14-year period across northern New Jersey.

Methods

The majority of New Jersey's estimated 10,522 hectares of hemlock forest stands occur in the northern half of the state in the Ridge and Valley and in the Highlands physiographic provinces. Hemlock woolly adelgid dispersed into New Jersey from neighboring states during the 1970s, causing widespread hemlock defoliation and mortality by the mid-1990s. The methodology used to prepare the data for analysis is described elsewhere (Royle 2002; Royle and Lathrop 2002). In summary, hemlock health was modeled and mapped throughout northern New Jersey using two leaf-off scenes (1984 and 1994) of Landsat Thematic Mapper imagery, a digital elevation model, 1995 field data, and discriminant function analysis. All hemlocks were assumed healthy in the 1984 image, because mortality did not occur in natural stands until the late 1980s. Based on changes in the spectral qualities of hemlock forest from 1984 to 1994, each 30 m hemlock pixel was classified

into one of four discrete classes of hemlock canopy defoliation with 82% overall accuracy. The four health classes are: Healthy/Light (< 25%), Moderate (50%), Severe (75%), and Dead (100% defoliation). The discriminant function was applied to three other Landsat 5 TM scenes to produce a total of five raster (grid) maps of hemlock forest health spanning 14 years: 8 November 1984, 14 November 1992, 22 December 1994, 27 December 1996, and 1 December 1998.

The five maps of estimated hemlock health provided the data for analysis of temporal changes in hemlock forest health from 1984 to 1998. In this paper we report the results of the transition pattern analysis. We define a transition pattern as the sequence of change in health over time. For example, from 1984 to 1998 hemlocks could change in health according to the transition pattern H-L-M-S-D. To detect all possible transition patterns occurring in the study area, we conducted GIS overlay analysis on these five maps, using the MATRIX function in ERDAS Imagine 8.5. The count of pixels per transition pattern was obtained from the final overlay map. The resulting patterns were examined, classified into four general patterns, and mapped throughout the study area. Of the estimated 10,522 ha of hemlock forests in New Jersey, 89,916 pixels (8,093 ha) of snow- and cloud-free Landsat TM data were available for analysis.

Results

The amount of Healthy hemlock forest in the study area decreased dramatically from 1984 to 1994 (Figure 1). By 1994 only 43% of all hemlock pixels remained in a healthy to lightly defoliated condition, 32% were moderately defoliated, 18% were severely defoliated, and 6% were dead. In 1992, 82% of the original hemlock forest pixels retained at least half of their foliage (Healthy/Light or Moderate classes). The percentage of HLM forest remained fairly constant (75 to 76%) from 1994 to 1998. However, from 1994 to 1998 there was a dramatic shift in the proportion of Healthy/Light to Moderate defoliation. Moderate decreased from 32% in 1994 to 7% in 1998. The transition matrix (not shown) reveals that large percentages of the Moderate and Severe classes shifted back into healthier classes during the three

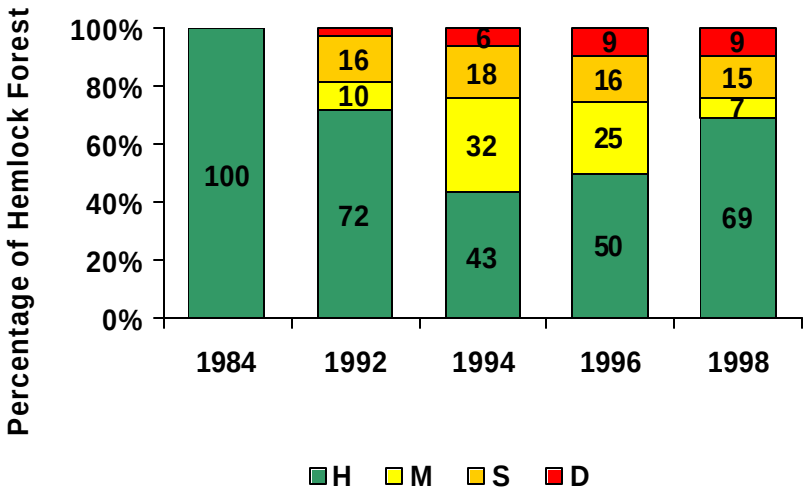

Figure 1. The percentage of hemlock forest per health class for each of the five years of Landsat TM imagery. All 8,093 ha of hemlock forests used in this analysis were assumed to be healthy in 1984. The health classes (HL, M, S, and D) are Healthy/Light (< 25% canopy defoliation), Moderate (50% defoliation), Severe (75% defoliation), and Dead (100% defoliation).

latter time intervals (1992 to 1994, 1994 to 1996, and 1996 to 1998).

The GIS overlay analysis reveals 119 unique patterns of change in hemlock health from 1984 to 1998, but 100 of these patterns each contain less than 1% of the total hemlock forest. The 119 transition patterns fall into four general types (Figure 2). Hemlock forest pixels in Type 1 remained somewhat healthy throughout the study period, and encompassed the largest percentage of hemlock forest (58.1%). These sites may have fluctuated between Healthy/Light and Moderate during the 14-year period, but they did not decline beyond Moderate condition at any time. Type 2 (17.5%) declined to Severe by 1992, 1994, or 1996, but then improved to the Healthy/Light or Moderate classes by 1998. Type 3 (5.9%) is similar to Type 2, but the improved hemlocks declined once again to Severe or Dead by 1998. Type 4 declined to Severe or Dead at some time by 1998 in a generally continuous fashion with little or no improvement at any time. Some patterns within each type maintained their health class for one or two intervals over the course of the decline period. The four types are generally scattered throughout the study area with heavier concentrations in some places. Pixels of each type are clustered with others of the same type within hemlock stands.

Discussion

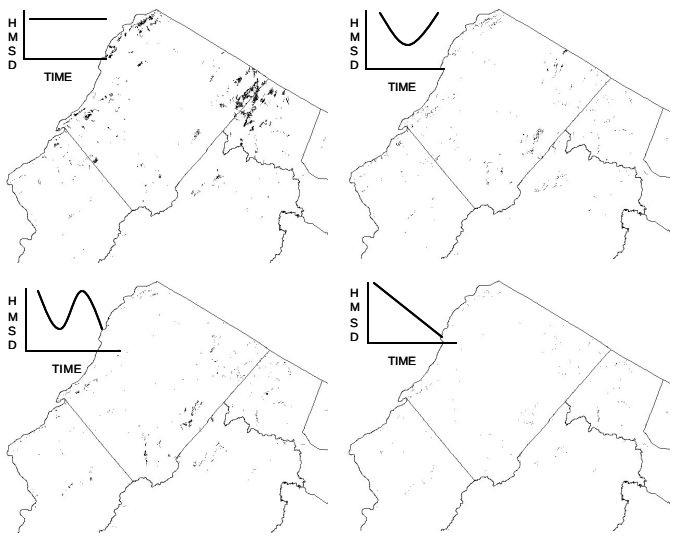

Figure 2. The location of each transition type within the study area. Hemlock pixels of each type are shown in black. The inset diagrams portray the general change in

Although the presence of HWA in New Jersey was documented as early as 1974 in voucher specimens (Stoetzel 2002), hemlocks in natural stands did not begin to die until the late 1980s (Ward et al. 1992). It is not unusual that the hemlock patches in the northern part of the study area show less damage than patches farther south, because they have been infested for a shorter time. And the overall decline in health from 1984 to 1994 is not surprising, given the nature of the infestation and lack of natural predators. What is surprising, however, is the remarkable shift from

the more damaged classes toward the healthier classes from 1994 to 1998. A flush of new growth over a few years does not mean that infested trees are "healthy," per se, but it does mean that enough new foliage grew on the trees to be detected by the satellite sensors. Improvements in hemlock health have been observed in some of the eleven hemlock Forest Health Monitoring plots established in 1994 in hemlock stands throughout northern New Jersey; trees can remain in an infested condition for many years, only to decline and die at some later time (Scudder et al. 2000). Similar transition patterns of decline and recovery occurred in Connecticut during the same time period in the mid-1990s, and were detected with Landsat imagery and change-detection techniques (Bonneau et al. 1999).

Some of the known hemlock stands in the study area may contain pine or other conifers, thus appearing as "healthy" hemlock forest. Wherever pine is a natural component of the hemlock-mixed hardwoods forest type, the mixed spectral signatures tend to shift estimated hemlock health toward that of healthier classes (Royle and Lathrop 1997). In the New Jersey Highlands, non-hemlock conifers are not a major component of hemlock forests, but this is not the case to the north and west of New Jersey. However, we are hopeful that the presence of other conifers will not thwart our efforts to monitor hemlock health with the highest possible accuracy.
There are advantages and disadvantages in the use of satellite data to monitor hemlock health. The disadvantages are that Landsat data are not always available during the leaf-off months due to clouds and snow. And, although we can detect declining hemlock health, by the time we detect a decline in health with sufficient accuracy, the canopy has already experienced significant defoliation. The advantages are that hemlock health can be discriminated at four levels of defoliation using Landsat imagery, field data and statistical methods with relatively high accuracy (80%+), and that we can detect recovery as well as decline.

We are in the process of assessing the accuracy of our model in estimating current hemlock health with recent imagery (December 2001). Historic and current field data collected throughout eastern Pennsylvania and northern New Jersey by state and federal agencies will be used to evaluate the utility of our hemlock health model across time and space within the study area. In cooperation with the USDA Forest Service, we will test our methods and models in other mid-Atlantic states, refining the methodology as needed. Historic and current field data will provide the necessary documentation to improve and assess our maps across the region. We emphasize that long-term efforts by state and federal agencies to monitor hemlock health in permanent plots have not been in vain. Because Landsat 4 and 5 TM data have been archived since the early 1980s, we can model hemlock condition using historic and current field data along with archived and current Landsat imagery. The statistical model can then be applied to other Landsat scenes to provide multi-temporal maps of hemlock health at the landscape and regional scales.

This study shows that hemlock health, decline, and improvement can be monitored with remote sensing techniques. The resulting information on the spatial and temporal patterns of hemlock decline shows promise for developing models of vulnerability and monitoring the success of predator releases across spatial and temporal scales. The clustering of temporal patterns suggests that underlying site and/or weather factors may be involved. In future research, we will be analyzing temporal patterns with regard to underlying soils and terrain, weather and climate, and the health status of neighboring hemlock forest stands.

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