

AN ANISOTROPIC MODEL OF HEMLOCK WOOLLY ADELGID SPREAD

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Abstract

The hemlock woolly adelgid (HWA) (*Adelges tsugae* Annand) continues to spread through the range of eastern hemlock (*Tsuga canadensis* (L.) Carrière) leaving dead hemlocks in its wake. Current estimates are either isotropic, 20 - 30 km per year (McClure et al. 2001), or vary by cardinal direction, 3.6 km per year west and 5.8 km per year north and south (Morin et al. 2003). Decades of infestation records and regional geographic data offer the opportunity to model HWA spread as a dispersion that varies with site conditions. This paper is a preliminary attempt to create an anisotropic model of HWA spread within a geographic information system (GIS). The GIS includes both county and township level infestation records along with digital maps of geographic variables including plant hardiness zone, elevation, forest cover type, urbanization, precipitation, temperature, and hemlock range. I use three statistical approaches to explore the connections between the site variable and spread rate: cluster analysis, principal components analysis, and classification and regression tree (CART) modeling. The resulting estimates of past and predicted spread are preliminary and their failings may be as informative as the final results.

The first step in modeling future HWA infestations is to measure historic spread. The infestation records available to measure historic HWA spread are the U.S. Forest Service county records and township based records for Pennsylvania and northward (Anhold 1990, Bofinger 2003, Burnham 2003, Denham 2003, Ouellette 2003, Sior 2003, Teillon 2003, U.S. Forest Service 2003). Neither the county nor the township dataset is exact, because records of HWA infestation are not exact. HWA's passive dispersal and tree crown habitat make it hard to detect and record the date of first infestation. There are also inconsistencies between the two datasets, perhaps because the methods of recording and reporting infestation vary by state and surveyor. Unfortunately, these data sets are all that is currently available for estimating spread.

There are a number of ways of delineating the front of infestation and the rate of spread (e.g. Andow et al. 1990, Liebhold et al. 1995, Sharov et al. 1996). I will use a straightforward approach where the median Euclidean distance from the previous infestation front to the far edge of the newly infested township is the spread distance. Using this metric, the average rate of HWA spread since 1990 in North America based on county data is 16 km per year. Excluding two infestations in western New York where infested nursery stock cause HWA movement, the rate is 15 km per year. Employing the same spread metric for the township-based data the estimate of spread is 8.4 km per year. For comparison, measuring spread with the county-based data for the same geographic area (Pennsylvania and northward) the spread rate is 12 km per year. The township-based rates of spread for Pennsylvania and New York are 20 km and 7.7 km per year respectively. The variation in these rates of spread shows that the data scale and the geographic area used to calculate the rate of HWA spread have a large impact on the estimated rate. Although 15 km per year may be an improved estimate of regional HWA spread, on average only 8% of the counties within 15 km of a previous infestation have HWA the next year.

The 15 km per year rate of spread does not vary with geography and so is an isotropic model of HWA infestation. Distance from previous infestation is the only variable considered in predicting infestation. However, observed HWA dispersal appears to vary geographically. For example, HWA has spread more slowly in the northern edge of its range in New Hampshire than it has in Georgia. There are sociological and biological explanations for anisotropic spread. Two examples are humans assisted dispersal of HWA and reduced HWA survival in extreme cold (Parker et al. 1998, Costa 2004). This study attempts to translate these types of influences on HWA dispersal into an anisotropic model via regional geographic variables. The variables included in the GIS and in the modeling of spread are:

- List of states and counties with known HWA infestations (U.S. Forest Service 2003)
- USDA Plant Hardiness Zone Map (U.S. National Arboretum 1990)
- Global Land 1 km Base Elevation Digital Elevation Model (National Imagery and Mapping Agency 1996)
- Forest cover type (U.S. Geological Survey and U.S. Forest Service 2000)
- The National Atlas urbanization map (U.S. Geological Survey 2000)
- The National Atlas road map (U.S. Geological Survey 2000)
- United States annual maximum temperature, 1961-90 (Day & Taylor 2000)
- Population in 1990 per square mile (U.S. Census 1990)
- Distance from previous infestation
- Direction of spread from previous infestation

The geographic variables and the infestation records are not independent observations, which limits the number of analytical techniques appropriate to the data. The first statistical method I used to examine the data was cluster analysis. Cluster analysis makes a good first step in data analysis because it does not define relationships between variables, rather it groups data points based on their similarity. There are a number of algorithms available to build the groups of data points (SAS Institute Inc. 1999, McGarigal et al. 2000), but unfortunately none of them defined groups of counties or townships that match well with infestation history.

The next analysis I tried was principal components. The basic idea of principal components is to combine many variables into a few important axes of variation and then organize samples within these axes (SAS Institute Inc. 1999, McGarigal et al. 2000). The goal in using principal components analysis is to compare the axes of maximum variation with HWA spread gradients. However, the principal components analysis failed provide insight into the geographic variation in rates of HWA spread.

The most fruitful analytical technique for examining HWA spread was Classification and Regression Trees

(CART) (Brieman et al. 1984). CART is a modeling technique that uses a training data set to assign new data into groups. The training data defines a classification tree that then splits the new data into classes based on a series of attributes. Some of the advantages of CART modeling are that it does not make any assumptions about the distribution of the data, it is robust to outliers and misclassifications in the training data, and it combines both categorical and continuous data in its classifications (Brieman et al. 1984).

Those counties or townships that had HWA before 2001 and those counties well beyond the reach of HWA were the training data to build a classification tree. The geographic variables determined each split in the classification tree. The counties infested in 2002 provided a test of the classification tree. The CART model correctly predicted 92% of the uninfested counties and 88% of the infested counties in 2002. Prediction based on the pre-2003 data for 2003 infestations was much less good, showing the need for refinements in the model. The biggest modeling limitation is the historic HWA infestation data. Infestation records could be improved by gathering more township records of HWA from the south and by consistent regional surveys of current HWA locations. Adding other geographic variables and incorporating annual weather variation might also improve the model.

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