Selecting and Monitoring Hemlock Forest Reserves in the Great Smoky Mountains National Park: Buying Time for the Control of Hemlock Woolly Adelgid

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Introduction

The GSMNP occupies an area of 2,093 km^2 centered on the North Carolina-Tennessee border (Figure 1). It is interesting because it contains some of the highest and most varied terrain in the southeastern United States, which contributes to its status as a major North American biodiversity hotspot due to its vast array of available ecological niches. It is compelling as a focus for study because it is home to a wealth of rare species that thrive in hemlock-dominated cove forests, which are experiencing rapid decline due to an ongoing, devastating outbreak of hemlock woolly adelgid (HWA; *Adelges tsugae* Annand).

HWA is a small aphid-like insect native to Japan that was first detected in the GSMNP in 2002. It reproduces rapidly with 2 generations per year, is easily dispersed by wind, birds, mammals, and humans, can kill hemlocks regardless of age or size class, and is migrating at approximately 30 km/year. An estimated 26% of hemlock habitat in the US, including the GSMNP, has already been invaded by HWA (Koch *et al*. 2006). HWA threatens two species of hemlock, late-successional species that together form the structural backbone of the species-rich cove forest ecosystems in the GSMNP. Eastern hemlock (*Tsuga canadensis* (L.) Carriere) is one of the most abundant, long-lived shade tolerant species across its range, and plays a unique role in cove forest ecosystems that no other tree can fill. Carolina hemlock (*T. caroliniana* Engelmann) is the species native to the GSMNP area. Of the 2,093 km^2 area of the GSMNP, only 294 km^2 of that is composed of hemlock forest (Koch *et al*. 2006). However, some of these areas contain the highest levels of biodiversity in the entire park.

An ongoing question in GSMNP management involves deciding upon the best way to preserve threatened hemlock forest biodiversity. Tree removal as a protective measure has become commonplace, but is counterproductive to our hemlock conservation goals. Widespread pesticide application across all hemlock stands is infeasible due to cost and habitat sensitivity. Rather, biological control via imported predator species such as *Sasajiscymnus tsugae* Sasaji and McClure (Coleoptera: Coccinellidae) and *Laricobius nigrinus* Fender (Coleoptera: Derodontidae) has become accepted as the most effective approach for HWA management (Flowers *et al*. 2005). However, it takes time for these biocontrol agents to establish in a stand, while at the same time HWA could be causing irreversible damage (Cheah and McClure 1998).

Landscape Connectivity A Major Factor in HWA Spread

Human use of roads and trails can facilitate pest dispersal by accidental transport, or altering microhabitats in favorable ways for a pest (Jules *et al*. 2002). The study results of Koch *et al* (2006) suggest that long-distance dispersal of HWA by birds and humans is enabled by roads, major trails, and riparian corridors. Hemlock mortality due to HWA did not depend very strongly on landscape variables. The odds of infestation were lower at high elevations and on steeper slopes, but these are areas of low accessibility to humans. Distance to trail, road, and stream were the primary variables affecting hemlock mortality, with distance to trail being the most significant and elevation the least. Koch *et al* (2006) incorporated these variables into a logistic regression model, which was found to reliably and easily predict HWA distribution in the GSMNP for the first few years after initial infestation. This model predicted 85.4% of ground-confirmed infestations, which makes it useful for our reserve selection purposes by identifying locations that should not be in or near candidate reserve sites.

Similar to the findings of the above group on the low importance of landscape variables, Orwig *et al* (2002) found that the intensity of hemlock decline and mortality is only weakly correlated with stand and landscape variables such as canopy composition/structure, slope, and elevation, though stands with xeric aspects succumb faster. The duration of HWA infestation was found to be the primary determinant, causing mortality within 4-10 years. Thus, if stands can be prevented from encountering HWA in the first place, hemlock decline and mortality can be mitigated.

In addition to their study results, Koch *et al* (2006) also cite evidence from other sources that the heaviest HWA infestations have occurred along roads, while forest core areas were uninfested or only lightly infested. They also provide evidence that riparian corridors facilitate HWA spread by birds, though this is complicated by the frequent proximity of heavy-use hiking trails. Additionally, rather than greater hemlock density in an area being a major risk factor for hemlock mortality, they found that greater site accessibility by humans poses an even stronger risk.

Landscape Variables Affect Hemlock Health

Infested trees in mesic sites or deep ravines may experience slower mortality (Orwig and Foster 1998). Since the mortality rate is linked with the abundance of HWA on a tree, trees experiencing slower mortality may have lower populations of HWA available to spread to neighboring trees, and thus the spread of HWA may be slower across such sites. Thus, mesic sites and deep ravines located on or near candidate reserve sites would aid in their protection.

Bonneau *et al*. (2003) found that hemlock health was statistically better on northwestern through northeastern-facing, low valleys that contain deep, excessively drained, medium-textured entisols with a high infiltration rate. Hemlocks did worse on southwestern through western-facing slopes along ridges, that contain shallow, well-drained, coarse-textured inceptisols with a very slow infiltration rate.

Both these studies show that cooler, moister conditions are optimal for hemlock. Thus, candidate reserve sites should meet these criteria.

Objectives

While forest managers have a duty to protect this national and ecological treasure, they cannot do so without the best available information on which sites to prioritize for protection. The proposed research seeks to provide this. We believe the key issue in preserving hemlock stands and their dependent cove forest biodiversity is a landscape connectivity issue. The desired outcome would be to reduce connectivity for HWA while maintaining the maximum level of connectivity for hemlock stands. To achieve this, sites must be prioritized that will preserve the maximum amount of hemlock forest at the least cost.

Our goal is to design a system of hemlock forest reserves that have low landscape connectivity for HWA spread into those reserves. This would lessen the costs of special management against HWA (i.e. biocontrol agents) by selecting only the highest priority sites to receive such management. The objectives of this proposal are to:

- Implement the logistic regression model of Koch *et al* (2006) in a GIS to screen out sites that should not be candidate reserve sites

- Overlay aspect, elevation, and soil layers on a map of all hemlock stands in the GSMNP to narrow the list of candidate reserve sites further

- Produce a list of 25 reserve sites evenly distributed throughout the park that maximize connected area, distance from other hemlock stands, and distance from roads, streams, and trails. Given the intended isolation of these reserve sites, biocontrol efforts will be done by aerial release of predator beetles, with continued remote monitoring of forest health (Bonneau *et al*. 2003).

Study Area

Rationale: The Great Smoky Mountains National Park is an ideal area for reserve site selection given that it is currently at the front of an active outbreak of HWA that has been spreading southward across the park since 2002. Also, although hemlock forests exist throughout the Appalachian region that have been or are being infested by HWA, it would be more difficult to create reserves in areas that do not already receive special protection. The GSMNP is the most visited national park in the United States and has some of the highest levels of biodiversity in the eastern United States. Any special reserves created in the park for hemlock would certainly be well-maintained and monitored by Forest Service officials.

Disturbance Regimes: Fire has not been a major natural disturbance for many decades. Rather, the major natural disturbances in the GSMNP have largely been biotic. Balsam woolly adelgid has killed almost all stands of balsam fir, leaving large stretches of brown across the mountainous landscape (Allen and Kupfer 2001). Now there is the spread of hemlock woolly adelgid. These pest outbreaks are biotic processes that have been important agents of landscape pattern formation. Anthropogenic disturbances that have shaped the GSMNP landscape include land fragmentation due to logging, and road/trail construction.

As mentioned earlier, an important interaction exists between the presence of roads and trails, and biotic disturbances in the form of pest outbreaks such as HWA. This interaction exists because roads and trails aid in the dispersal of HWA. Judging from the literature on large, infrequent disturbances, the interaction of land fragmentation and HWA infestation will likely result in greater negative consequences for hemlock forest biodiversity than either disturbance alone (Paine *et al*. 1998).

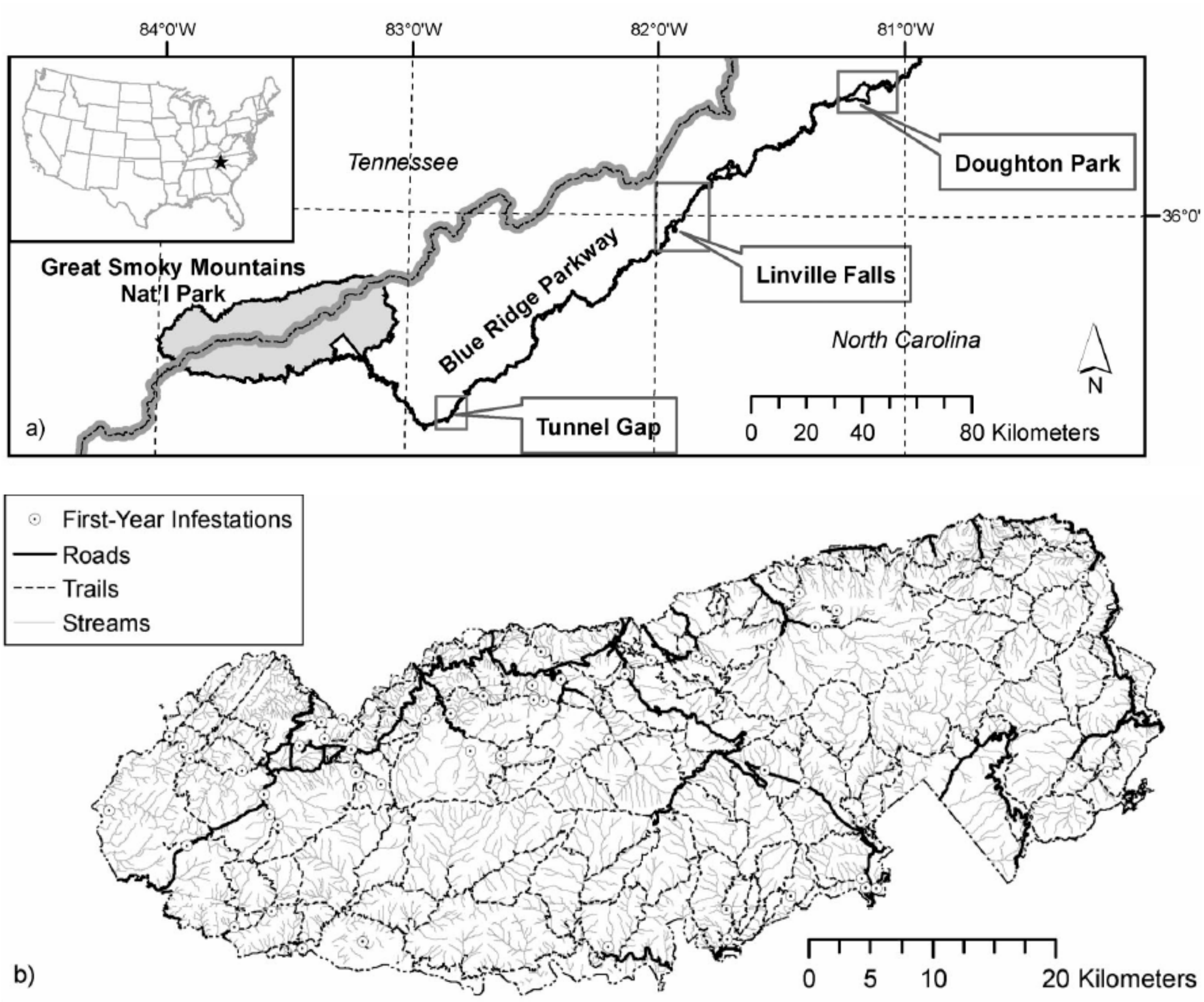

Figure 1. General location of the study area. Adapted from Koch *et al* (2006). A) Great Smoky Mountains National Park. B) Close-up of the study area, showing proximity of 2002 infestations to roads, trails, and streams.

Methods

Approach

The design of nature reserves, as conducted by The Nature Conservancy (TNC) and others, assesses multiple criteria in prioritizing sites. The main criteria for TNC, besides ecological uniqueness and feasibility, are viability and threats. Our proposal concentrates on the latter two. *Viability* considers the likelihood that hemlock forests and their associated species would persist on the site if protected. Contributing factors to the viability of our selected reserves will include reserve size and site connectivity. *Threats* are agents that would reduce the site's long-term viability or value as a reserve. The primary threat in our case is HWA.

Our general approach will build on previous research. Koch *et al*. (2006) suggested that a fruitful direction for future research would be to incorporate traditional landscape metrics such as inter-patch distance. This was omitted from their study because they reasoned that the slower invasion of more isolated hemlock patches would be of secondary significance to the density of roads and other dispersal corridors for HWA spread. However, to select potential hemlock forest reserves to target for longer-term biocontrol efforts, it is necessary to identify isolated patches that will be more slowly invaded. To do this, we will use GIS analysis to identify the most suitable sites for hemlock reserves, combined with a site selection algorithm that uses distance between sites (inter-patch distance), as well as distance between sites and potential HWA sources. Then, once these sites are identified and created as reserves, a remote monitoring program will be implemented to assess the efficacy of biocontrol efforts.

Data

We will use the following sources of data in our analysis:

1) Existing GSMNP land cover data created from 1:12,000 scale aerial photographs that depicts the distribution of hemlock stands within the park (Welch *et al*. 2002)
2) HWA infestation data, provided by the USFS
3) GSMNP trail, road, stream, soil, aspect, and elevation data, provided by the USFS
4) 2001 and 2006 Landsat TM imagery for the GSMNP
5) The following logistic regression model created by Koch *et al*. (2006) identifies the most important variables that control HWA spread. This model can identify 85.4% of first-year infestation sites, with the benefit of low levels of overprediction compared with using discriminant analysis, *k*-nearest neighbor, or a CART model. This will aid in narrowing the number of sites to prioritize for management. All variable values are in meters. Figure 2 is a GIS implementation of the model that shows all areas that are likely to be infested by HWA, and thus would not be considered for candidate reserve sites.

$$\begin{gathered}\log\,(\text{odds of infestation}) = 5.3321 - 0.00497 \\ \times\ \text{stream\_distance} - 0.00072 \\ \times\ \text{road\_distance} - 0.00264 \\ \times\ \text{trail\_distance} - 0.00150 \times \text{elevation} \\ - 0.0242 \times \text{pct\_slope}\ (1)\end{gathered}$$

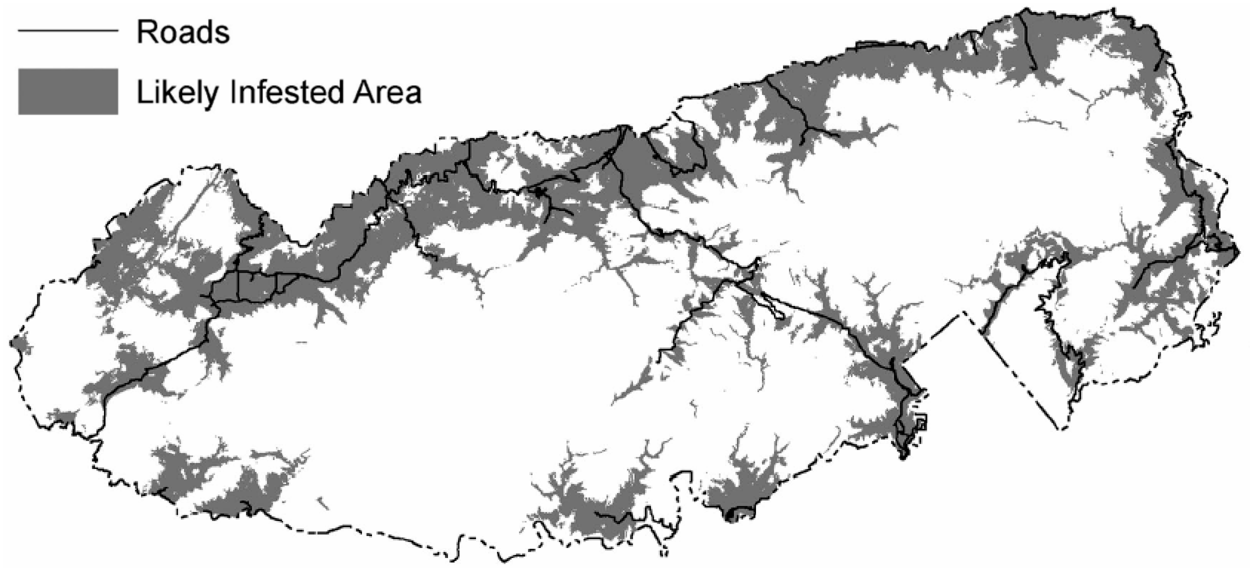

Figure 2. Map of GSMNP showing areas predicted by the above logistic regression model as likely to be infested by HWA. From Koch *et al* (2006).

Analysis

Task 1: Removing Infested Sites from Consideration as Potential Reserves

The logistic regression model of Koch *et al* (2006) can be used to predict sites most likely to be infested. Implementation of this model in GIS can then allow creation of useful maps showing HWA infestation risk. These areas will be subtracted from the hemlock distribution map provided by the USFS using ArcGIS 9.2.

Task 2: Using GIS to Identify Environmentally Favorable Reserve Sites

Taking the remaining distribution of hemlocks from Task 1, we will narrow the list of candidate reserve sites further by using GIS to select sites with the most favorable conditions for hemlocks. Since hemlocks thrive in cool, moist conditions (Orwig and Foster 1998, Bonneau *et al*. 2003), we will perform a weighted overlay of aspect, elevation, and soil layers, and select approximately 100 sites with the highest rankings.

Task 3: Using a Modified Version of PORTFOLIO for Final Site Selection

Hemlock stands that have the largest connected area and the greatest isolation from HWA sources are ideal candidates for reserves and should receive high site priority. Thus, we propose to modify the PORTFOLIO reserve design program to include the ability to incorporate Euclidean distances to various HWA dispersal routes such as trails, roads, and streams. This would allow us to select a list of 25 reserve sites with maximum connected area and maximum isolation from potential sources of HWA.

Presently, PORTFOLIO uses four input files – candidate reserve sites, a species census file, a between-site distance file, and a file containing a list of species. We will modify the program to use three input files. The first lists the candidate reserve sites, indexed by its area and core area (a proxy for habitat quality). The second summarizes pairwise distances between sites. The third summarizes distance to trails, roads, and streams, which will be calculated using ArcGIS.

The PORTFOLIO program iteratively computes seven metrics on which candidate sites can be compared. We will borrow two and add one more. The two metrics we will borrow are (1) total area, and (2) core area. Following MacArthur and Wilson's theory of island biogeography, larger sites generally support more species, and sites with proportionately more core area have more species than expected for their size. Thus we will focus on preserving connected hemlock forest area to capture the maximum number of associated animal and plant species. We do not want to preserve connected area or connected core area, since our goal is to select reserve sites that are isolated from each other to decrease the potential spread of HWA. We will also add a metric that takes into account the distance of each of these candidate sites from trails, roads, and streams. The farther the candidate sites are from these three features, the lower the risk of HWA dispersal. In tie-breaker cases, the site with greater area will be sacrificed in favor of the one with the greatest distance from trails, roads, and streams.

Task 4: Design and Validation of an Image Classification Technique for Reserve Monitoring

Given the intended isolation of these reserve sites, biocontrol efforts will have to be done by aerial release of predator beetles, with continued remote monitoring of forest health. Our proposed method for remotely monitoring the health of the 25 forest reserves follows from earlier work on HWA infestation monitoring done by Bonneau *et al*. (2003). First, since dead or dying hemlock forests do not have the same visible and IR light reflectivity as normal coniferous forest, a 2001 Landsat Thematic Mapper (TM) image will be classified to develop a baseline of once healthy hemlock stands. Then, radiance normalization and masking of non-hemlock areas (as determined from the map of GSMNP hemlock stands supplied by the USFS) will be used to pre-process a 2006 TM image. The difference of these two images will show 2006 hemlock stands, at various levels of health. Next, three image enhancement techniques will be compared to see which performs best at measuring vegetation vigor. These are the Normalized Difference Vegetation Index (NDVI), the Modified Soil Adjusted Vegetation Index-2 ($MSAVI_2$), and the Tasseled Cap transform. These techniques differ in the number of Landsat bands that are used and how, and can provide differing types of image contrast. Finally, cluster analysis will be used to separate hemlocks into 4 levels of tree vigor.

Task 5: Field Sampling to Assess Image Classification Accuracy

To measure the accuracy of our health classification technique, we will sample 600 trees within 150 hemlock forest stands across the GSMNP using the USFS Crown Condition Rating Guide (CCRG), which measures forest health using 5 tree vigor indicators. This will only be done once to ensure we have an accurate technique to use for assessing reserve health in future years. Stands will be identified using a virtual pilot study to ensure trees of all vigor classes will be sampled. Each site will be a circular plot of 15 m radius, and within each one, 4 dominant or co-dominant hemlocks will be selected. The five indicators that will be measured on these are live crown ratio, crown density, crown diameter, crown dieback, and foliar transparency. The CCRG indicator data will be averaged for the four trees at each site, and each indicator classified as condition 1, 2, or 3 based on a range of CCRG values (Table 1). Finally, the indicator condition codes will be combined to determine the health rating (Table 2).

Table 1. CCRG tree vigor indicators and classification thresholds. Adapted from Bonneau *et al*. 2003.

	Condition 1	Condition 2	Condition 3
Live crown ratio	40% or more	20–35%	5–15%
Crown diameter	55% or more	26– 54%	1–25%
Crown density	55% or more	25–50%	5–20%
Dieback	0–5%	10–25%	30% or more
Foliar transparency	0–45%	50–70%	75% or more

Table 2. Rules for determining the health rating of a tree based on tree vigor indicator condition codes. From Bonneau *et al*. 2003.

Good	All factors are class 1, or only one class 2, and no class 3
Average	Not as good as above; many combinations of classes 1 and 2, but none are class 3
Poor	At least one factor is class 3, but never all factors
Very Poor	All factors are class 3; living trees that do not have live branches larger than 1″ diameter are included here

Classification accuracy will be measured by overlaying the health ratings measured on the ground with those on the classified images (Figure 3), and counting the number of points that have the same health class as the 30 m pixel in the underlying image. A 15 m buffer will be placed around each field point to allow for GPS location error. If the buffered field point intersects an area on the image in the same health class, the point will be classified as an accurate match.

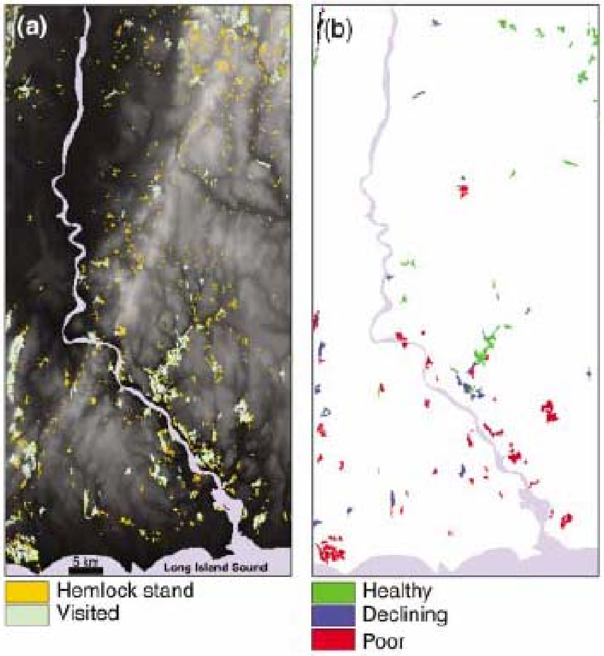

Figure 3. Representative image of what the resulting classification map may look like. Adapted from Orwig *et al*. 2002. A) Location of all hemlock stands obtained from the USFS, and the 150 stands that will be visited. B) Mean overstory hemlock vigor resulting from HWA infestation.

Task 6: Biocontrol Treatment and Monitoring of Reserves

Biocontrol efforts can begin as soon as we have an accurate image classification model, and GSMNP officials agree on the proposed reserve selection and monitoring plan. Aerial releases of predator beetles over reserve sites can be done using cost-effective small aircraft such as those used in crop dusting and fighting wildfires, given that enough predator beetles can be supplied. Then, each year a new Landsat TM image containing the 25 reserve sites will be classified using the same method, and compared to the previous year's image. Using adaptive management, sites that show a small decline in health will be targeted for increased releases of predator beetles as a preventive measure, since drought or other forms of stress can increase susceptibility to HWA. Sites that show greater declines in health will be targeted for tree removal to protect uninfested areas of the reserve. Unfortunately, sites may be lost with time. However, the initial goal of establishing this system of hemlock reserves was to buy time for biocontrol efforts to begin working in other areas of the park, while attempting to save biodiversity in the largest forest tracts that otherwise would be lost.

Schedule

The first two years of this research will focus on reserve planning, while the third and subsequent years will involve ongoing treatment and monitoring efforts.

Activity	**Year 1**		**Year 2**		**Year 3**	
	1-6	**7-12**	**1-6**	**7-12**	**1-6**	**7-12**
Database Development – Integrating hemlock forest distribution layer, road layer, stream layer, and trail layer	X					
Implement logistic regression model to eliminate infested sites from consideration as potential reserves	X	X				
Use weighted overlay of aspect, elevation, and soil layers to identify the 100 largest optimal sites for hemlock		X				
Calculate nearest road, stream, and trail distances for each of the 100 sites and save to a text file		X				
Modify PORTFOLIO to incorporate the road, stream, and trail distance file into a metric to aid with the selection of 25 final reserve sites			X			
Use Landsat TM imagery and cluster analysis to classify existing hemlock stands into 4 levels of vigor				X		
Conduct field sampling to test accuracy of image classification				X		
Begin aerial releases of predator beetles on each of the 25 reserves, to be done once a year					X	
Begin implementation of remote monitoring process using a new Landsat TM image each year					ongoing	

Anticipated Results

The product to be provided from this work are a map of 25 reserve sites on which HWA biocontrol efforts can be focused, allowing scarce management resources to be applied where they will have the greatest ecological benefits. We anticipate that the selection of these 25 reserve site will be the best way to preserve threatened hemlock forest biodiversity. Biocontrol will have to be an ongoing management regime on these reserves, at least until both hemlock species evolve resistance to HWA. Closing some roads or trails may also be effective in limiting the spread of HWA and could be done alongside the release of biocontrol agents, though further research will need to be done to identify which road or trail closures would have the greatest impact and whether such closures would be feasible.

We also anticipate that the biocontrol program will be effective, despite the remoteness of the reserve sites. The efficacy of these treatments in preventing HWA infestation can then be assessed by satellite monitoring, which saves the heavy cost of sending out field crews to remote terrain (and risking the accidental introduction of HWA).

If all goes well, we hope to see something different than the near-total decimation of balsam fir in the GSMNP and hemlock stands elsewhere. We hope that at least on 25 sizable sites in the GSMNP, hemlock forests and their associated communities can be preserved intact, alive, and well.

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