Research, Monitoring, and Management of Eastern Hemlock Forests at Delaware Water Gap National Recreation Area

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Introduction

Delaware Water Gap National Recreation Area covers approximately 70,000 acres (28,300 hectares) along the Delaware River in northeastern Pennsylvania and northwestern New Jersey. Forests dominated by eastern hemlock (*Tsuga canadensis*) cover about 5% of the park, but they are disproportionately important to park ecology and recreation. A majority of these hemlock forests are recognized as "Outstanding Natural Features" having "high intrinsic or unique values" (NPS 1987). Trout streams and scenic waterfalls are associated with many of these hemlock stands, and recreational activities like hiking, fishing, bird watching, picnicking, and general "sight-seeing" are very popular and concentrated in these areas.

Hemlock woolly adelgid (HWA), *Adelges tsugae,* is a non-native (Asian) insect pest of hemlock, and was first detected in the park in 1989. HWA is active in the winter, and populations are often controlled by cold temperatures; warmer winters (climate change) reduce this control on HWA populations. Since 1993, we have conducted a program to address the threats that hemlock woolly adelgid and the decline of eastern hemlock poses to valued park resources and visitor experiences. This program has included annual monitoring of HWA populations and hemlock tree health in permanent hemlock forest plots in the park, a variety of intensive studies of ecosystem characteristics and biodiversity associated with hemlock-dominated forests, and efforts to manage HWA and maintain hemlock-dominated ecosystems and visitor use areas in the park. This paper summarizes monitoring results and management activities.

Monitoring methods

Annual monitoring. A total of 78 permanent hemlock plots, each with 10 hemlock trees, were established within 6 hemlock stands in the park. The health of plot trees have been assessed annually using the U.S. Forest Service "visual crown rating methods." HWA infestation levels and the amount of new twig growth on plot trees have also been measured annually. An index of HWA infestation level for each stand was calculated as the average proportion of sampled twigs infested with HWA. Similarly, an index of new twig growth for each stand was calculated as the average proportion of sampled twigs having new growth.

Predictive model of hemlock decline and mortality. A mathematical model was developed to simulate the spread of HWA infestations throughout the park and forecast the resulting hemlock decline and mortality. A logistic equation was used to model the cumulative percentage of hemlock trees in the park that become infested over time:

$$\text{Cumulative percent hemlocks infested up to the year ``y''} = \frac{100}{1 + e^{-r\,y}}$$

where e = 2.71828 (the natural logarithm), and r = the maximum rate of spread of HWA.

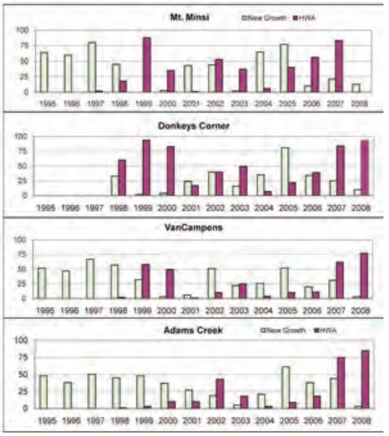
Data from research in the park (Eschtruth et al. 2006) was used to estimate r (r = 0.2608).

Hemlock trees decline and die in the model at assigned rates after having been infested with HWA. The model was set initially to fit the fact that in 1994, 93% of hemlocks in the permanent plots were "healthy," and none were dead. Hemlocks were removed from the "healthy" category in the model four years after HWA infestation. Hemlock mortality was modeled by assuming that 15% of hemlocks die 5 years after initial HWA infestation, 35% die after 10 years, 25% die after 15 years, 15% die after 20 years, 5% die after 25 years, and 5% survive indefinitely. The average time to hemlock tree mortality after HWA infestation in this model is just over 12 years.

Results

HWA populations and hemlock tree new growth. Figure 1 shows annual average HWA infestation levels and new twig growth at four stands during the past 14 years. Very high HWA infestation levels occurred in 1999–2000 (except at Adams Creek), and again in 2007 and 2008. Given the very high HWA infestation levels at these sites in 2007 and 2008, it is clear that the biological controls released in previous years (see below) have not been effective at suppressing HWA infestations to date.

Regression analysis of these data show that the amount of hemlock new twig growth in a given year declines systematically with higher HWA infestation levels in the preceding year (Figure 2). The equation describing this relationship is:



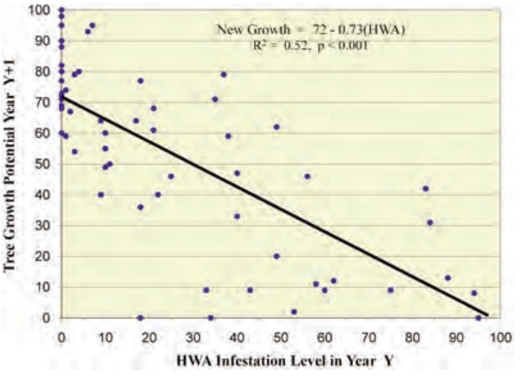


Figure 1 (left). Average annual hemlock new growth (percent of twigs producing new growth, light colored bars) and HWA infestation levels (percent of twigs infested with HWA, darker bars) at each of four monitoring sites, from 1995 through 2008. Data were not collected at Donkeys Corner before 1998.

Figure 2 (right). HWA infestations reduce the growth potential of hemlock trees: Regression equation enabling prediction of the amount of tree new growth next year from the HWA infestation level this year. The higher the HWA infestation, the less growth of hemlock trees the following year; every 1% increase in HWA infestation level reduces hemlock tree new growth by 0.73% the following year. Each data point represents one hemlock stand in one year; data presented is from six hemlock stands from 1995–2008 (hemlock growth potential was determined by the 90th percentile of hemlock tree growth in a stand; that is, only 10% of the hemlock trees in a stand produced more than this amount of new growth).

Predicted new twig growth in year "Y + 1" = 72 – (0.73 x (HWA infestation level in year "Y")).

Hemlock decline and mortality. As of 2008, 30% of hemlock plot trees had died, and all the surviving plot trees were in substantial decline; no healthy trees remained (Figure 3). The predictive model of HWA spread and consequent hemlock decline and mortality has underestimated the rate of hemlock decline and mortality in our monitoring plots to date (Figure 4). Even so, the model predicts that 50% of park hemlocks will have died by 2014, and 80% by 2022. The high HWA infestation levels of 2007 and 2008 are likely to accelerate hemlock decline and mortality in coming years.

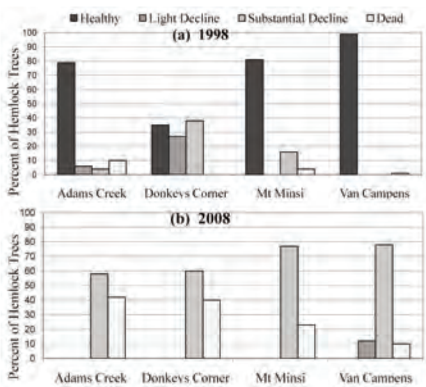
Management of HWA and hemlock

Our primary hemlock management concerns include the following:

- Increases in hazardous trees.
- Negative effects on aesthetics of visitor use areas.
- Negative effects on recreational activities.
- Invasions of alien plants.
- Impacts of white-tailed deer (*Odocoileus virginianus*) herbivory on vegetation.
- Alteration and disruption of micro-climates and ecosystem functions.
- Loss of native biodiversity, particularly losses of brook trout (*Salvelinus fontinalis*).
- Increased fire risk.

We've approached management of HWA and hemlock decline in the following ways:

- Identify and prioritize hemlock and HWA management concerns and goals.



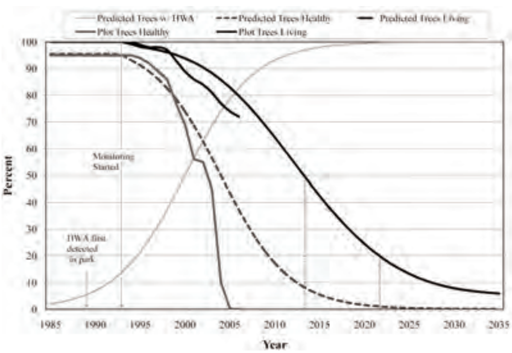


Figure 3 (left). Decline in hemlock tree crown vigor ratings in four stands between (a) 1998 and (b) 2008. No healthy trees remained at any of these sites in 2008, and all the trees at Adams Creek, Mount Minsi, and Donkeys Corner were either dead or in substantial decline.

Figure 4 (right). Hemlock health monitoring data compared to the predictive model of HWA spread and hemlock health decline (see text). The vertical dotted lines indicate the predicted dates when 50% of the hemlocks will be dead (2014), and 80% will be dead (2022).

- Identify visitor use and ecological values of individual hemlock stands.
- Prioritize individual hemlock stands for management actions, based on their visitor use and ecological values.
- Apply best available management practices to address specific concerns at prioritized hemlock stands.

Management actions we have taken in response to HWA infestations and hemlock decline include avoiding soil compaction from visitor use in hemlock forests, releasing biological control agents for HWA, chemical suppression of HWA, hazardous tree mitigation, installation of deer exclosure fences, planting native trees, and suppression of invasive alien plants in declining hemlock stands. To avoid soil compaction and damage to hemlock tree roots, elevated boardwalks were installed in high visitor use areas. Management actions have been matched with the specific ecological and visitor use values of each area. For example, at highly developed visitor use areas we have cut hazardous trees and applied insecticide to suppress HWA and keep hemlock trees alive. In contrast, in undeveloped hemlock stands that support a high diversity and/or rare native plants, we have worked to suppress invasive alien plants.

Biological control of HWA. Biological control agents provide the only hope in the foreseeable future of limiting the damaging effects of HWA in large or remote hemlock forests over the long-term. Since the year 2000, we have released a total of 75,700 black "Japanese lady beetles" (*Sasajiscymnus tsugae*), 4,500 *Scymnus sinuanodulus* beetles, and 5,512 *Laricobius nigrinus* beetles. We know these beetles have survived and reproduced to some extent in the park. However, the high HWA infestation levels observed in 2007 and 2008 (Figure 1) indicate that, at least to date, these beetles have had little or no meaningful effects on HWA infestation levels.

Chemical suppression of HWA. Judicious use of insecticides is the only practical method of HWA suppression, and of keeping individual trees alive in the immediate future. With support from the Forest Service, we've applied insecticide (imidacloprid) to suppress HWA infestations at priority visitor use areas in 2006, 2007, and 2008. This insecticide has proven to suppress HWA for several years after application (Evans 2009), although the insecticide must be applied to one individual tree at a time. To date, a total of about 2,000 hemlock trees have been treated by soil injection, and 650 hemlock trees by stem injection of imidacloprid. Each treated tree was tagged to document the year and season (spring or fall) of treatment. Soil injection has been the preferred method of application, because stem injection is more costly, requires more time, and is most effectively applied during limited hours in the morning. However, use of stem injection is required in wet areas and where trees are growing within 75 feet of surface waters.

Invasive plant suppression. We selected fourteen hemlock stands as priorities for invasive plant suppression, based on the following: stand size, location, and landscape setting; park management zoning; botanical resources (including rare species); and recreational use. All but one of these stands are within the "Outstanding Natural Feature" zone in the park. Targeted invasive alien plants include Japanese barberry (*Berberis thunbergii*), tree-of-heaven (*Ailanthus altissima*), multiflora rose (*Rosa multiflora*), garlic mustard (*Alliaria petiola-*

ta), and Japanese stiltgrass (*Microstegium viminium*). Prior to treatment, we conducted surveys to assess invasive plant populations and to identify treatment areas.

Invasive plants have been suppressed in 300 acres in 10 hemlock stands in the park to date. Park staff, NPS Exotic Plant Management Teams, and private contractors have been involved in this effort. A combination of mechanical removal and herbicide (glyphosate and imazapyr) treatments has been used.

Reforestation "demonstration" project. In 2005, numerous hazardous hemlock trees had to be cut within the Raymondskill Falls visitor use area in the park. A Reforestation Project was initiated at this area in 2006 to inform and demonstrate to visitors the effects of HWA and hemlock decline, and park management concerns and responses. The objectives of this project are the following:

- Eliminate or minimize populations of invasive plants.
- Maintain existing hemlock trees.
- Foster regeneration of eastern hemlock and other native trees.
- Minimize erosion and maintain good soil conditions for reforestation.
- Inform and educate the public.

These objectives have been addressed in a number of ways: treatment of most hemlock trees at this site with insecticide; installation of high-tensile, eight-foot high woven-wire fencing to ensure protection of native plants from deer browsing (Eschtruth and Battles 2008, forthcoming); planting a variety of native trees; elimination or major reduction of most invasive plant species at the site by applications of herbicide or mechanical removal; and posting educational signs at the site.

It is worth noting that the trees cut in 2005 were left on site to help minimize erosion, maintain good soil conditions, and foster regeneration of hemlock and other native plants. Although the downed trees may be perceived as un-attractive by some people, this is a temporary condition, and the aesthetic concern is far outweighed by the ecological benefits of leaving the downed trees on-site.

Conclusion

Hemlock woolly adelgid is only one example of problems caused by introductions of invasive alien species. The consequences of the introduction and spread of HWA are complicated and exacerbated by other environmental changes, such as the presence of invasive alien plants, elevated deer populations, and climate change. Efforts to control HWA infestations and mitigate the numerous effects of widespread hemlock decline and mortality on ecosystems, native biodiversity, and immediate human concerns (safety, aesthetics, recreation) are extremely difficult and costly, and have had limited success to date. Given such circumstances, how can we achieve the NPS mandate to conserve the parks "in such manner and by such means as will leave them unimpaired for the enjoyment of future generations"?

> Nature in the 21st century will be a nature we make; the question is the degree to which this molding will be intentional or unintentional, desirable or undesirable (Botkin 1990).

Acknowledgments

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