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Another Challenge to Eastern Forests of North America: Hemlock Wooly Adelgid, Climate Change, and the Loss of Hemlock

95th ESA Annual Meeting, August 1-6, 2010, Pittsburgh

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Impacts of eastern hemlock mortality on ecosystem function: A guide to restoration strategies in the southern Appalachians

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Background/Question/Methods Despite the implementation of various biological and chemical controls, eastern hemlock trees (*Tsuga canadensis* (L.) Carr.) are declining throughout much of the eastern US due to hemlock woolly adelgid (HWA). The decline is especially rapid in the southern Appalachian region of the US. We used a combination of intensive measurements and monitoring at the Coweeta Hydrologic Laboratory in western N.C. to (1) determine the spatial distribution of hemlock in southern Appalachian ecosystems, (2) monitor the rate of spread and decline of HWA infested tress, and (3) quantify the impacts of HWA induced hemlock mortality on water, carbon, and nutrient cycling pools and processes. Our primary objective was to use our understanding of the impacts of hemlock decline on ecosystem structure and function to guide restoration strategies.

Results/Conclusions Eastern hemlock is present in mixed stands within riparian zones in the southern Appalachians; highest hemlock densities occur within 50 m of streams and hemlock can occupy as much as 50% of the basal area. HWA was first detected in a few scattered trees in the Coweeta basin in 2003. However, by 2005, HWA was detected in 100% of hemlock trees across a network of vegetation plots. By 2008, average crown loss of infested trees exceeded 80%. Sapflow measurements and modeling approaches showed that annual stand level transpiration has been reduced by 10%, with greater reductions (up to 30%) in the spring and fall. Carbon cycle components were impacted within three years of infestation. We observed a rapid decrease in stem growth in hemlocks, increased growth of co-occurring hardwoods, and decreased fine root biomass and soil respiration. Changes in nutrient cycling were not detected, suggesting that some of the impacts of hemlock mortality on ecosystem processes make take several years to manifest. While we anticipate a substantial pulse of coarse woody debris (CWD) as hemlock trees fall, likely replacement species (*Betula* and *Acer*) decompose quickly. Restoring hydrologic processes, forest structure, and CWD are the highest priorities for ecological restoration. In particular, establishing evergreen tree cover will be necessary to restore soil moisture dynamics and establishing species with recalcitrant CWD will be necessary to maintain temporal CWD dynamics in the forest floor and streams.

Potential changes in transpiration with shifts in species composition following the loss of eastern hemlock in southern Appalachian riparian forests

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Background/Question/Methods
Eastern hemlock (*Tsuga canadensis* (L.) Carr.) is declining throughout much of its range in the eastern US due to hemlock woolly adelgid (HWA) infestation. The loss of this foundation species will impact the hydrologic cycle in these systems. To estimate the impact on the hydrologic budget, we quantified transpiration over six years for *T. canadensis*, and over three years for co-occurring species *Acer rubrum*, *Betula lenta*, and *Rhododendron maximum* using sapflow probes. These three species represent the likely woody species that will dominate the trajectory of succession following the loss of eastern hemlock. In areas where *R. maximum* is a dominant component of the shrub layer, regeneration of overstory tree species is severely restricted. We developed relationships between transpiration and climate for all species. Given the loss of *T. canadensis* from the ecosystem, we modeled implications on transpiration from two succession scenarios: one in which hemlock is lost from the canopy and a *R. maximum* subcanopy results, and one in which eastern hemlock is replaced in the canopy by *A. rubrum* and *B. lenta*.

Results/Conclusions
Transpiration was shown to decline since 2004 for *T. canadensis*, and no such decline was observed for the other species. We found that with the loss of hemlock leaf area, light levels in the subcanopy increased almost 17-fold, and we estimated that *R. maximum* would increase transpiration by over 4-fold. Although *R. maximum* transpiration increased, this increase was not enough to make up for the loss of *T. canadensis'* contribution to transpiration. For example, estimated sap flow of *R.*

maximum during days 142–285 in 2005 was found to be 4.78 g s^{-1} while sap flow of *T. canadensis* under healthy conditions during several days of the growing season in 2004 was 14.78 g s^{-1}. By contrast, if species composition shifted from *T. canadensis* to 100% *A. rubrum*, 100% *B. lenta*, or a 50/50 mixture of the two species, stand sap flow increased by 38%, 71%, and 55% respectively. Although actual post-mortality scenarios are uncertain, the loss of *T. canadensis* will result in changes in the structure and function of this ecosystem.

Responses of eastern hemlock dependent songbirds to hemlock woolly adelgid infestation in Appalachian riparian forests

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Background/Question/Methods
Invasive insects pose a significant threat to biodiversity, often affecting entire ecological communities through destruction of foundation species. This situation is currently unfolding in eastern hemlock (*Tsuga canadensis*) forests of the northeastern United States which are severely threatened by the invasive hemlock woolly adelgid (*Adelges tsugae*). Among the many organisms dependent on hemlock stands are several species of birds including Acadian flycatcher (*Empidonax virescens*), blue-headed vireo (*Vireo solitarius*), black-throated green warbler (*Dendroica virens*) and blackburnian warbler (*Dendroica fusca*). The extent of their dependency varies and is at least partially the result of foraging and/or nesting requirements. Here we ask to what extent will the degradation and perhaps eventual elimination of hemlocks affect populations of these bird species in the northeastern United States using studies from infested and pristine hemlock stands across Pennsylvania. Bird population levels were determined using detections along linear transects and spot-mapping techniques in hemlock stands with varying levels of infestation. Studies involving the Acadian flycatcher also investigated nesting success parameters in relation to severity of infestation.

Results/Conclusions
Correlations between detections of vireo and warbler species and measures of adelgid impact involving branch terminal infestation were not significant. Infestation levels using measures of branch condition were significantly positively correlated with detections of blue-headed vireo and black-throated green warbler. This unexpected positive relationship between detections of these species and more severe infestation levels could be the result of the influence of secondary insect infestation on foraging opportunities but this remains a topic for future exploration. Conversely, Acadian flycatcher breeding density declined by 70% in heavily infested sites although nest survival rates were not affected. The apparent differences in response to varying infestation levels between vireos/warblers and the Acadian flycatcher may be the result of different strategies of exploitation of the hemlock-dominated environment.

Potential plant community shifts in eastern hemlock-dominated ravines on the front of the hemlock woolly adelgid invasion in Ohio

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Background/Question/Methods Across the central and southern Appalachian Mountains and unglaciated Allegheny Plateau, eastern hemlock (Tsuga canadensis L.; hereafter hemlock) dominates ravine and riparian forests. In these ecosystems, hemlock is a foundation species that regulates important ecosystem processes. Thus, the loss of hemlock due to the invasive non-native pest, the hemlock woolly adelgid (HWA), will result in shifts in vegetation composition and structure that will alter ecosystem function. For this study, we examined hemlock-dominated riparian forests in the unglaciated Allegheny Plateau of southeastern Ohio, which is currently on the front of the HWA invasion. These areas are important for natural history and native diversity, as well as recreational activities. A greater understanding of the composition and function of these hemlock-dominated riparian forests should provide Ohio land managers to develop planning options prior to widespread mortality of eastern hemlock.

Results/Conclusions In southeastern Ohio, hemlock is particularly dominant in the overstory immediately adjacent to streams, with few other species in the overstory and understory layers. Non-metric dimensional scaling (NMDS) ordination analyses indicate distinct associations of deciduous hardwood species along environmental gradients within riparian forests. Specifically, lower slope positions are characterized by interspersed sweet birch (Betula lenta L.) and tulip-poplar (Liriodendron tulipifera L.). At upper slope positions, overstory species richness is higher, with increasing abundance of maples (Acer rubrum L., A. saccharum Marsh) and oaks (Quercus alba L, Q.rubra L. and Q. prinus). This may indicate that moving upslope, communities similar to adjacent upland ecosystems may develop should widespread hemlock mortality occur. At the same time, greater shifts in composition will occur at positions immediately adjacent to streams. We believe it

is therefore reasonable to expect that in these systems, ecosystem function across riparian and headwater stream areas will experience the greatest change. Managers may want to prioritize HWA strategies in headwater riparian areas to mitigate impacts from hemlock mortality including nitrate leaching, loss of habitat for migratory birds and cold water fishes, and the spread of invasive plant species in large hemlock gaps.

The rise and fall of eastern hemlock: perspectives from the Northwoods and Appalachia

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Background/Question/Methods Eastern hemlock (*Tsuga canadensis*) is a wide-ranging species that occurs throughout the Appalachian Mountains and across the northern Great Lakes region. Using historical accounts, vegetation surveys, field experiments, and remeasurements of long-term vegetation plots, we examined the historic importance and contemporary regeneration dynamics of hemlock at distal points in its range, the Northwoods of the Great Lakes region and the southern Appalachian Mountains. From this examination, we identified historic and contemporary factors that have resulted in the greatly differing, but converging, fates of hemlock in the two regions.

Results/Conclusions In the late 19th century, hemlock was a regional dominant in the Northwoods, but now only occurs across a small fraction of sites it formerly occupied. Regeneration failures have been noted in the Northwoods since the 1940s. In areas with low deer abundance, hemlock is a persistent understory species that is favored by small canopy gaps. However, in areas of higher deer abundance, similar-sized gaps are generally captured by maple species (*Acer* spp.). In a study that examined regeneration in 39 stands across the Upper Peninsula of Michigan, variation in seedling abundance was associated with the availability of suitable microsites, whereas recruitment into larger size classes was closely associated with the level of winter deer use. The balance of this work suggests that deer use of hemlock stands creates a feedback with maple that is detrimental to the establishment of hemlock.

Conversely, hemlock was widely distributed in forests of the southern Appalachians that survived logging in the early 20th century. Long-term plot data show that hemlock expanded with fire suppression into forest types where it was previously uncommon. In these forests, it created a dense understory layer that excluded competitors and allowed hemlock to persist and create more mesic understory conditions. However, the hemlock woolly adelgid (HWA, *Adelges tsugae*) was first found in the southern Appalachians in 2002, and by 2008 data from long-term vegetation plots revealed heavy decline of trees and the initiation of a wave of mortality that continues. HWA mortality occurred first in the understory, resulting in a scarcity of hemlock regeneration as trees in the overstory began to decline. This heavy mortality of regeneration suggests that successful chemical treatments of overstory hemlock will only preserve the current generation of trees. If the range of HWA extends northward with predicted warming trends, the long-term persistence of hemlock across much of its range is precarious at best.

17 years of integrated research, monitoring, and management of HWA and hemlock ecosystems at Delaware Water Gap National Recreation Area

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Background/Question/Methods
Delaware Water Gap National Recreation Area (“the park”) covers 28,000 ha along the Delaware River in Pennsylvania and New Jersey. Eastern hemlock forests cover 2,200 ha (8%) of the park, and are associated with trout streams and scenic waterfalls. Activities like trout fishing, bird watching, and hiking are concentrated in hemlock forests, and many of these areas are officially designated as “Outstanding Natural Features” having “high intrinsic or unique values." In 1989 hemlock woolly adelgid (HWA) was detected in the park, and since 1993 the park has conducted a program to address the threats that hemlock woolly adelgid and hemlock decline poses to park resources. This program includes annual monitoring of HWA populations and hemlock tree health in permanent plots, studies of hemlock ecosystems and associated biodiversity, and efforts to suppress HWA infestations and maintain hemlock ecosystems in the park. Questions addressed include: What are the distinctive characteristics of hemlock ecosystems in the park? What effects do HWA infestations have on hemlock health? What is the rate and extent of hemlock decline and mortality? How effective are insecticides and biological controls at suppressing HWA infestations and sustaining hemlock health? What are the ecological effects of hemlock decline?

Results/Conclusions
Sustained monitoring and research in the park during the past 17 years have provided answers to these questions and informed management. Streams draining hemlock forests are $1^{o}C$–$2^{o}C$ cooler in summer, hydrologically more stable, three times more likely to support trout, and typically support 30% more species of aquatic insects than streams draining hardwood

forests. Birds such as blackburnian warblers, black-throated green warblers, and blue-headed vireos are very strongly associated with hemlock forests in the park. Permanent plot trees first became infested with HWA in 1998, and by 2008 no healthy hemlocks remained, and 30% had died. A dendrochronology study in the park concluded that every 1% increase in average plot HWA infestation level resulted in an 8% increase in the likelihood of a tree being in decline. Mathematical models indicate that hemlock mortality in the park will reach 50% by 2015, and 80% between 2020 and 2030. Although we have released over 90,000 biocontrol beetles in the past ten years, they have not controlled HWA populations. Insecticides effectively suppress HWA populations and sustain tree health, and we have treated about 10,000 individual trees to date. Continued hemlock decline will have major effects on park ecosystems and biodiversity.