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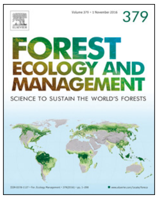

Herbaceous-layer diversity and tree seedling recruitment are enhanced following *Rhododendron maximum* shrub removal

Katherine J. Elliott*, Chelcy F. Miniat

Coweeta Hydrologic Laboratory, Center for Forest Watershed Research, Southern Research Station, USDA Forest Service, 3160 Coweeta Lab Rd, Otto, NC 28763, United States

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ABSTRACT

Forest ecosystems dominated by *Tsuga canadensis* are undergoing fundamental changes in function and composition from infestations by hemlock woolly adelgid (*Adelges tsugae*). We proposed that the first step to restoring southern Appalachian riparian forests following *T. canadensis* mortality would be eliminating the evergreen shrub, *Rhododendron maximum*. We hypothesized that removing *R. maximum* would increase light transmittance, soil moisture and temperature; and subsequently, enhance herbaceous-layer diversity and promote tree seedling recruitment and survival. We tested these hypotheses at two locations, (CWT, Coweeta Hydrologic Laboratory; WOC, White Oak Creek) in the Nantahala Mountain Range of western North Carolina, both with heavy *T. canadensis* mortality and a dense *R. maximum* subcanopy. The treatments were designed to remove only soil O-horizon (FF), remove only *R. maximum* (CR), remove *R. maximum* and soil O-horizon (CFFR), and untreated, reference (REF). We installed permanent plots across treatments and locations and measured light transmittance (Q_i/Q_o), soil water content (θ), herbaceous-layer cover and diversity (Shannon's index (H'_{cover}) and species richness), and tree seedling recruitment.

As expected, cutting the *R. maximum* subcanopy (CR and CFFR) immediately increased Q_i/Q_o in the spring months across locations, and it was sustained through the first growing season. θ was generally high across plots, averaging 26% during the growing season, and didn't vary over time. By the second growing season (2017) after treatments, herbaceous-layer cover and diversity increased on CR and CFFR. Herbaceous-layer cover was significantly related to Q_i/Q_o ($r^2 = 0.22, p < 0.001$) and θ ($r^2 = 0.13, p = 0.009$), while diversity was only related to Q_i/Q_o (H'_{cover}, $r^2 = 0.14, p < 0.001$; species richness, $r^2 = 0.21, p < 0.001$). Tree seedling density was related to Q_i/Q_o ($r^2 = 0.10, p = 0.001$) and θ ($r^2 = 0.26, p < 0.001$). Tree seedling density was low before treatment (1.4 ± 0.3 seedlings m^{-2}) and increased by 10-fold in CR and CFFR two growing seasons after treatment. In CR, species with the highest density ranked *Betula* spp. > *Acer rubrum* > *Quercus coccinea* > *Liriodendron tulipifera* > *Q. rubra*. In CFFR, tree seedling recruitment ranked *Betula* spp. > *A. rubrum* > *L. tulipifera*. These vegetation responses have important implications for potential recovery of riparian forests following *T. canadensis* mortality.

1. Introduction

Forest ecosystems dominated by *Tsuga canadensis* (L.) Carrière are undergoing fundamental changes in function and composition from infestations by hemlock woolly adelgid (HWA, *Adelges tsugae* Annand) (Ellison et al., 2005; Lovett et al., 2016). HWA is an invasive insect native to Japan, first documented in the eastern U.S. in the 1950s, that is attacking *T. canadensis* trees of all ages and sizes (Elliott and Vose, 2011), throughout much of the tree's range (Evans et al., 2012; Orwig et al., 2012; Foster et al., 2014; Morin and Liebhold, 2015; Case et al., 2017). In southern Appalachian forests, complete mortality of *T. canadensis* from HWA infestation typically occurs after six years (Elliott and Vose, 2011; Ford et al., 2012), and *T. canadensis* and *Rhododendron maximum* L. often co-occur (Elliott and Swank, 2008; Narayanaraj et al., 2010; Webster et al., 2012).

Rhododendron maximum is an evergreen, ericaceous shrub that is largely self-replacing due to its clonal reproduction strategy (Elliott and Vose, 2012). It occurs primarily in riparian or cove forests, it is highly shade tolerant, forms a dense subcanopy layer that strongly attenuates light incident on the forest floor (Clinton, 2003), and reduces soil moisture and temperature (Cofer et al., 2018). As a result, it has little to no herbaceous or woody cover (henceforth, herbaceous-layer) below its

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* Corresponding author.
E-mail address: kelliott@fs.fed.us (K.J. Elliott).

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canopy (Clinton, 1995; Beckage et al., 2000), and it strongly reduces tree seedling recruitment (Hille Ris Lambers and Clark, 2003; Beier et al., 2005). Over time, a thick recalcitrant organic soil layer accumulates under these shrubs (Monk et al., 1985), soil zinc concentrations can be high (Nilsen et al., 2001), and soil nitrogen availability to non-ericaceous species decreases (Wurzburger and Hendrick, 2007, 2009). Recent evidence suggests that this shrub expands considerably following canopy disturbances, such as the *Castanea dentata* (Marsh.) Borkh. mortality in the mid-1930s due to the chestnut blight (Elliott and Vose, 2012), and *T. canadensis* mortality more recently (Ford et al., 2012; Pfennigwerth et al., 2018a,b). While tree seedling recruitment has also responded positively to these canopy disturbances (Ford et al., 2012), over the long-term *R. maximum* has limited recruitment of these trees into the canopy. Thus, in the southern extent of the HWA infestation range, forest dynamics following *T. canadensis* mortality may become increasingly dominated by *R. maximum* (Ford and Vose, 2007; Kincaid and Parker, 2008; Roberts et al., 2009; Ford et al., 2012), likely leading to permanently altered forest structure.

Active and adaptive management strategies will be required to transform degraded riparian forests into more diverse future forests (Folke et al., 2004, 2010; Vose et al., 2013; Messier et al., 2015; Kern et al., 2017; Webster et al., 2018). Science-based restoration methods to aid land-managers in the recovery of forest structure, function, and diversity are needed. Responding to this need, we conducted a *R. maximum* and organic soil (soil O-horizon) removal experiment in riparian corridors once dominated by *T. canadensis*. We hypothesized that the removal of *R. maximum* would: (1) increase incident light on the herbaceous-layer, and soil temperature and moisture; (2) increase understory plant diversity, with a more rapid response in sites with removal of both the shrub layer and the soil O-horizon; and (3) increase tree seedling and herbaceous species recruitment due to greater light and soil moisture. We explored these hypotheses using two approaches: one, a replicated experimental plot-level test; and the other, an operational implementation trial at the stream reach scale (3 ha).

2. Methods

2.1. Site descriptions

We conducted our study at two locations, representing two different spatial and sampling scales, Coweeta Hydrologic Laboratory (replicated plots) and White Oak Creek watershed (300-m stream reaches). Both lie in the Nantahala Mountain Range of western North Carolina, USA, within the Blue Ridge Physiographic Province, near the southern end of the Appalachian Mountain chain (Fig. 1). Soils are deep sandy loams and are underlain by folded schist and gneiss. Two soil orders are found within both locations, immature Inceptisols and older developed Ultisols. Soil types include the Cullasaja-Tuckasegee complex along the stream channel and the Edneyville-Chestnut complex and Plot fine sandy loams on the uplands (Thomas, 1996). Both locations had similar characteristics in terms of high density of *R. maximum* < 3 m height and dead *T. canadensis* (Table 1); all *T. canadensis* trees were dead at the time of this study. The remaining live overstory included deciduous trees of *Acer rubrum* L., *Liriodendron tulipifera* L., *Betula lenta* L., *Quercus montana* Willd., *Quercus rubra* L., and *Carya* spp.

For the replicated plot-scale experiment, we selected areas within the Coweeta Hydrologic Laboratory (CWT, latitude 35°03′N, longitude 83°25′W). Prior to mortality, *T. canadensis* comprised 52% of the overstory basal area (Table 1). Plots were located in mesic, riparian areas with low-to-moderate slopes ($< 30\%$) and across an elevation range from 760 to 1060 m (Fig. 1a, inset). Mean annual temperature is 12.6 °C; and seasonally ranges 3.3–21.6 °C, with abundant rainfall (ca. 1800 mm annual mean) (Laseter et al., 2012).

For the operational stream reach-scale, we selected three perennial 2nd order streams within the White Oak Creek watershed (WOC, 35°20′N latitude, 83°58′W longitude), approximately 21 km north-west of CWT (Fig. 1). For each stream reach, sampled areas were along a 300 m reach. For these stream reaches, dead *T. canadensis* comprised 40% of the overstory basal area and the *R. maximum* subcanopy was dense (Table 1, Fig. 2a). The three stream reaches were located on Holloway Branch, Split Whiteoak Branch, and Kit Springs. Across reaches, slopes are moderate (30–60%) and elevation ranges from 1160 to 1390 m. The climate at WOC is similar to CWT, but cooler and with more precipitation (ca. 1900 mm annual rainfall, mean annual temperature is 10.8 °C).

2.2. Experimental design

We used a Before–After/Control–Impact experimental design (BACI) (van Mantgem et al., 2001) with four treatments implemented at the replicated plot-scale at CWT and three treatments implemented at the stream reach-scale at WOC. Only three treatments were implemented at WOC because of adverse weather conditions. The four treatments were designed to (1) remove only the soil O-horizon (i.e., forest floor, hereafter, FF), (2) remove only the *R. maximum* subcanopy (hereafter, CR), (3) remove *R. maximum* subcanopy and soil O-horizon (hereafter, CFFR), and (4) untreated, no removal (reference, hereafter, REF). The CR and CFFR treatments included cutting *R. maximum* followed by immediate application of herbicide on cut stumps (Romancier, 1971; Esen and Zedaker, 2004; Harrell, 2006). The herbicide was a triclopyr amine (Garlon 3A®, DOW AgroSciences, Indianapolis, IN) formulation (44.4% Triclopyr Triethylamine Salt) with an aquatic label mixed to a ratio of 50% herbicide/50% water. *Rhododendron maximum* cutting (CR, CFFR) occurred in spring (March–May) 2015 (Fig. 2b), and the prescribed fires (FF, CFFR) were implemented in spring (March) 2016 (Fig. 2c). Prescribed fires were hand lit across plots at CWT and across the entire delineated stream reach (3 ha) at WOC (see below). The fire technique included backfires along the upper ridge and ignitions at 10–25 m intervals depending on slope steepness during weather conditions specified in the USDA Forest Service, Nantahala National Forest, Prescribed Burning Plan (USFS, 2011).

For the CWT location, we established sixteen 20 m × 20 m plots across the 2185 ha Coweeta Basin (Fig. 1a, inset). Six of the 16 plots have been monitored for vegetation dynamics, carbon and nutrient pools and fluxes, and soil solution chemistry since 2004 (Nuckolls et al., 2009; Knoepp et al., 2011; Ford et al., 2012). We established 10 additional plots with similar characteristics, and then, randomly selected among the 16 plots to apply the treatments resulting in four replicates of each treatment.

For each of the stream reaches at the WOC location, we delineated a 300 m length, 50 m width on each side of the stream as the treated area (3 ha, Fig. 1b, inset). Each stream reach received one of three treatments: Holloway (CR), Split Whiteoak (CFFR), and Kit Springs (REF). WOC did not have a FF treatment. Within each stream reach, we established six transects (three on each side of the stream) extending from stream edge to the 50 m boundary. Transects were arrayed perpendicular to, and on each side of, the stream; and at least 50 m apart. We placed two 20 m × 20 m plots along (or near) each transect line with 10 m distance between plots, for a total of 12 plots per stream reach. A fourth stream reach was selected for this study to receive a prescribed fire (Rocky Bald, FF); however, the fire was not implemented due to adverse weather conditions.

2.3. Microenvironment measurements

To characterize microenvironmental responses to treatments, we measured incident light, i.e., photosynthetically active photon flux density (Q_i, µmol m^{-2} s^{-1}) and soil water content (θ, %) in each plot in the growing season months (June–August) of each year. At CWT, automated sub-hourly θ and soil temperature (T_{soil}, °C) measurements were taken and averages were recorded hourly (CS655, Campbell Scientific Inc., Logan, UT). Probes were placed in the soil to span